Ecology, management, and use of aspen and balsam poplar in the prairie provinces

E.B. Peterson and N.M. Peterson

Northwest Region • Special Report 1

Forestry Canada Forêts Canada

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Although individual stems of an aspen clone are not long-lived when compared to other tree species, old and large specimens of aspen are candidates for heritage designation and for genetic research. This aspen was photographed near Nojack, Alberta, in 1968.

ECOLOGY, MANAGEMENT, AND USE OF ASPEN AND BALSAM POPLAR IN THE PRAIRIE PROVINCES, CANADA

E.B. Peterson[1] *and N.M. Peterson*[1]

SPECIAL REPORT 1

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ABSTRACT

Aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) are major components of the forest resource in the prairie provinces and in northeastern British Columbia. The uses and economic importance of this resource increased dramatically in the last half of the 1980s. Much has been learned about these hardwood species since the last Canadian syntheses of available information over 20 years ago. An up-to-date review is provided for managers and field foresters involved with management and use of aspen and balsam poplar. The regional focus is Alberta, Saskatchewan, and Manitoba, although available information is also drawn from other regions where these species are managed. The emphasis is on aspen because it is the dominant of the two species and because balsam poplar has been studied in less detail. Although ecology, management, and use are the three main subsections in the text, it is emphasized that these topics must be integrated by the manager seeking sustainable use of this resource. A summary of knowledge gaps and research needs is presented in the conclusion.

RÉSUMÉ

Le peuplier faux-tremble (*Populus tremuloides* Michx.) et le peuplier baumier (*Populus balsamifera* L.) sont d'importants constituants des ressources forestières des provinces des Prairies du nord-est de la Colombie-Britannique. Les utilisations et l'importance économique de cette ressource ont augmenté de façon dramatique au cours de la seconde moitié des années 80. On a appris beaucoup au sujet de ces espèces de feuillus depuis les derniers comptes rendus canadiens d'information disponibles, rédigés il y a plus de 20 ans. Voici un compte rendu à jour pour les gestionnaires et les travailleurs forestiers s'occupant de la gestion et de l'utilisation du peuplier faux-tremble et du peuplier baumier. Ce compte rendu porte surtout sur les provinces de l'Alberta, de la Saskatchewan et du Manitoba, bien que des informations disponibles proviennent également d'autres régions où on s'occupe de gestion de ces espèces. On met l'accent sur le peuplier faux-tremble, parce qu'il s'agit de la principales des deux espèces, et parce que les études sur le peuplier baumier sont moins détaillées. Bien que l'écologie, la gestion et l'utilisation constituent les trois principales parties du texte, il faut remarquer que celles-ci doivent faire l'objet d'une approche intégrée par le gestionnaire visant une utilisation durable de cette ressource. Un résumé des lacunes des connaissances et des besoins en recherche est présenté dans la conclusion.

ACKNOWLEDGMENTS

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Ross M. Waldron, Northern Forestry Centre, who was among Forestry Canada's earliest aspen researchers in the prairie provinces, was Scientific Authority for this project. The authors thank him for his support for this publication. Several sections of this report were reviewed by specialists. The section on ecology was reviewed by J.S. Rowe, R.E. Farmer, J.D. Johnson, Y. Hiratsuka, M.J. Apps, W.J.A. Volney, I.G.W. Corns, and S. Navratil; the management chapter by W.J. Ball, D. D'Amico, D.A. Perala, and G.A. Steneker; and the section on uses of aspen and balsam poplar by L. Bach, R. Bohning, B.W. Karaim, M.M. Micko, and E.M. Wengert. A near-final version of the entire text was reviewed by H.J. Johnson and P.M. Morley. Suggestions of these reviewers resulted in substantial improvements to the text.

The editorial review and production of the publication was overseen by a Northern Forestry Centre committee made up of J.K. Samoil, B.L. Laishley, D.D. Lee, D.A. Leroy, E. Schiewe, J.M. Simunkovic, and P.S. Debnam. The authors thank M. Peterson, Cadboro Bay Business Centre, Victoria, for the large task of word processing several early versions of the report, B. Laishley for editorial review and production coordination, E. Schiewe for her excellent typesetting of such a complex manuscript, and D. D. Lee for the graphics and artwork. The organizations and individuals who contributed photographs for this publication are acknowledged where the photographs appear in the text. The assistance of S. Lux, Northern Forestry Centre, who contacted researchers for photographs of publication quality is greatly appreciated. A relatively large number of color plates in this report are reproduced from previously published reports of the Northern Forestry Centre; the assistance of those who originally prepared the plates is acknowledged with thanks.

A computer search of aspen-related references in the Weyerhaeuser database was consulted, as was a database of aspen references assembled by J.S. Gephart, Natural Resources Research Institute, Duluth, Minnesota. E.S.L. Hambly, Ontario Ministry of Natural Resources, made her 1985 aspen literature review available before its publication. The authors thank Dr. I.K. Edwards and Dr. M.J. Apps, Northern Forestry Centre, for their contract support of earlier aspen-related work, which led to the original assembly of much of the information used in this report. The work on behalf of Dr. Apps resulted in interviews in 1988 with about 60 researchers and managers involved with boreal mixedwood forestry in the prairie provinces and northeastern British Columbia; some of the ideas received from those interviews are used in this report as personal communications.

Last, and most importantly, the authors gratefully acknowledge the many balsam poplar and aspen researchers in Canada and the United States whose cited publications are the main foundation for this review.

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NOTE

The exclusion of certain manufactured products does not necessarily imply disapproval nor does the mention of other products necessarily imply endorsement by Forestry Canada.

Most Canadian foresters, in their professional training, learned little about the two hardwood species, aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.), which make up nearly one-quarter of the 4327 million ovendry tonnes of forest standing crop in the prairie provinces (Bonnor 1985). These two species are now recognized as commercially important species and are expected to play a central role in twenty-first century forestry in the prairie provinces. The recent report of the Expert Panel on Forest Management in Alberta (1990) is an example of the change in attitude that has resulted in these hardwoods being recognized as an integral part of boreal forest management. The 1990–95 strategic plan for Forestry Canada's Northwest Region also emphasizes the importance of these boreal hardwoods by the proposed development of an Aspen Innovation Centre that will serve as a clearing house for information on aspen management and utilization.

This report was written for forest managers and field foresters whose professional work involves decisions affecting ecosystems dominated by aspen or balsam poplar. The report does not deal with these two species in separate sections. The emphasis is on aspen because it is the dominant of these two *Populus* species in western Canada. Where appropriate, balsam poplar is referred to in context, often to identify a feature or a response that distinguishes it from aspen. Within the prairie provinces, the focus is on the Mixedwood Section (B.18a) of the Boreal Forest Region (Rowe 1972). A small portion of this forest section also extends into northeastern British Columbia.

The main goal of this report is to summarize information on the ecology, management, and use of aspen and balsam poplar in the ecosystems of the main zone of commercially important aspen–balsam poplar from southern Manitoba to northeastern British Columbia (Fig. 1).

Related Reviews and Other Information Sources

The most recent review of aspen information is the comprehensive report by DeByle and Winokur (1985),

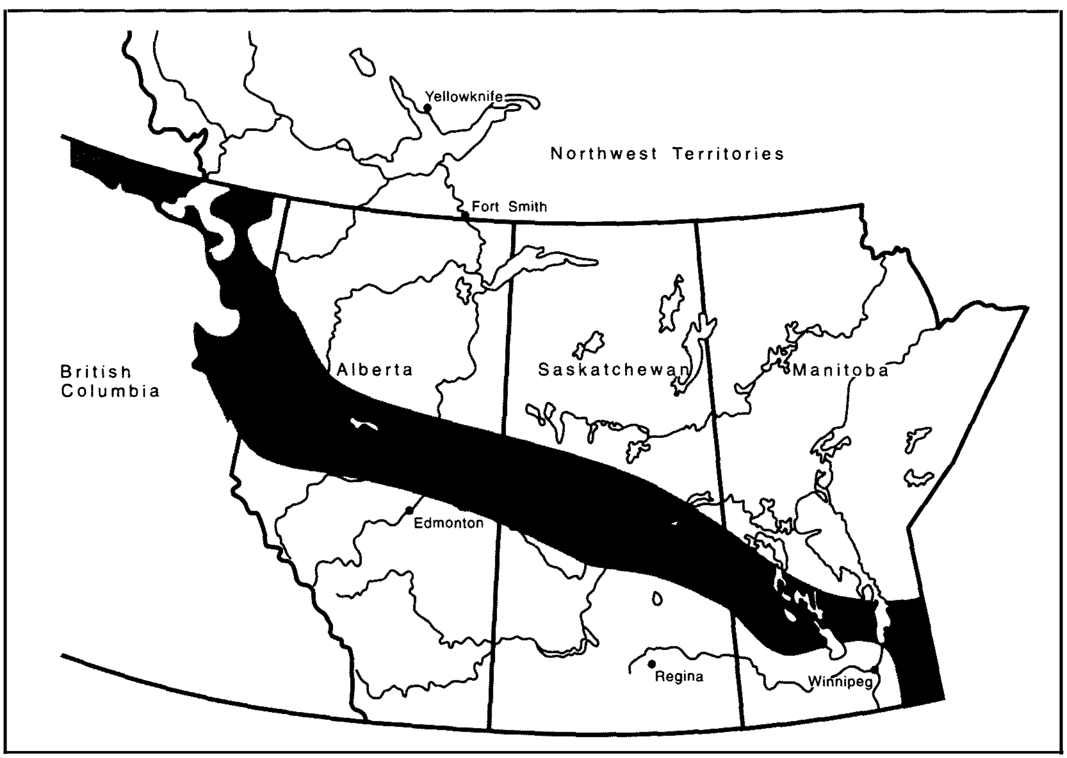

Figure 1. The geographic focus of this report is the main zone of commercially important aspen–balsam poplar in the prairie provinces and northeastern British Columbia as mapped by Fitzpatrick and Stewart (1968).

which dealt with ecology and management of the species in the mountains and plateaus of the western United States. Information from aspen studies in boreal and mixedwood regions is considered only incidentally in that source. Information about aspen in the Lake States and eastern Canada was reviewed by DeByle and Winokur only if the details were considered to be applicable to Rocky Mountain aspen ecosystems. Another up-to-date source of information on aspen in the United States and Canada is the Aspen Symposium '89 Proceedings edited by Adams (1990). The most recent comprehensive synthesis of available information on aspen in Canada is the growth and utilization report by Maini and Cayford (1968).

The Poplar Council of Canada is a central source of information on management and use of naturally-occurring aspen and balsam poplar stands, beginning with the Council's 1985 annual meeting and followed by the proceedings of the Council's 1988 meeting, which focused on management and utilization of Alberta's aspen and balsam poplar resource (Gambles 1988). Other recently released publications include the proceedings of the symposium entitled *Northern Mixedwood '89* (Shortreid 1991) and the proceedings of the Aspen Management for the 21st Century symposium (Navratil and Chapman 1991). An additional report by Massie et al. (1990) suggests an economic strategy for managing aspen on private lands in northeastern British Columbia.

Table 1 lists key publications dating from 1955 to 1991 that complement this report. Balsam poplar is referred to in some of these reports, but the emphasis is mainly on aspen. Supplementing the reference sources of Table 1 are several older bibliographies that focus either on *Populus* generally or aspen specifically: Farmer and McKnight (1967); Lamb (1967); Pronin and Vaughan (1968); Shoup et al. (1968); Commonwealth Bureau of Soils (1971); Hart (1976); Hambly (1985). Some aspen information is also included in the monograph on culture of poplars in eastern North America (Dickmann and Stuart 1983). A recent *Populus* bibliography has been prepared by Ostry and Henderson (1990).

This report begins with a review of ecological information about aspen and balsam poplar. Two subsequent sections deal with management and use of these species. A final section summarizes knowledge gaps and information needs. The opening section on ecology of these two boreal hardwoods draws from a geographically broader range of information sources than is the case for management and use. Many taxonomic, morphologic, physiologic, and interspecific relationships were considered to be based on ecological principles that apply beyond the study sites from which the data or concepts were derived. The ecological section of this review benefits from the large amount of information generated by aspen researchers beyond the prairie provinces, notably Ontario, the Lake States, the Rocky Mountain states of the western United States, and Alaska.

Management objectives and uses are strongly influenced by regionally distinct political, economic, and social factors; therefore, there was a greater effort to base those sections of this report on information derived mainly from the prairie provinces. For completeness, this could not be done exclusively, but it was considered important to make the sections on management and use as specific to the prairie provinces as possible.

In this report, nomenclature for vascular plants is based on Scoggan (1978). Nomenclature for mosses is based on Bird (1969). Nomenclature for birds is based on Salt and Salt (1976). Nomenclature for mammals is based on Banfield (1974). A glossary of terms is provided in Appendix 1.

Table 1. Information sources for a basic library on aspen and balsam poplar for the forest manager

Title	Authors	Available from
Utilization of hardwoods in northern Alberta. Main report.	Woodbridge, Reed and Associates Ltd. 1985	Northern Alberta Development Council 9621 – 96 Avenue Postal Bag 900-14 Peace River, Alberta T0H 2X0
Aspen quality workshop, February 12, 1987	Canadian Forestry Service & Alberta Forest Service 1987	Northern Forestry Centre Forestry Canada 5320 – 122 Street Edmonton, Alberta T6H 3S5
Classification and measurement of aspen decay and stain in Alberta	Hiratsuka et al. 1990	As above
Decay of aspen and balsam poplar in Alberta	Hiratsuka & Loman 1984	As above
Review of silviculture research: white spruce and trembling aspen cover types. Mixedwood Forest Section, Boreal Forest Region, Alberta, Saskatchewan, Manitoba.	Jarvis et al. 1966	As above
Management and utilization of northern mixedwoods	Samoil 1988	As above
Utilization and marketing opportunities for Alberta aspen solid wood products	Wengert 1988	As above
Proceedings of the workshop on aspen pulp, paper and chemicals	Wong & Szabo 1987	As above
Utilization and market potential of poplars in Alberta	Ondro 1989	As above
Guide to the silvicultural management of trembling aspen in the prairie provinces	Steneker 1976b	As above
Northern mixedwood '89	Shortreid 1991	Pacific Forestry Centre Forestry Canada 506 West Burnside Road Victoria, British Columbia V8Z 1M5
Hardwood management problems in northeastern British Columbia: an information review	Peterson, Kabzems, & Peterson 1989	B.C. Ministry of Forests Research Branch 31 Bastion Square Victoria, British Columbia V8W 3E7

Table 1. Continued

Title	Authors	Available from
Growth and utilization of poplars in Canada	Maini & Cayford 1968	Information Directorate Forestry Canada Ottawa, Ontario K1A 1G5
Poplar utilization symposium	Neilson & McBride 1974	As above
Trembling aspen in Manitoba	Canada Department of Forestry and Rural Development 1967	As above
Present and future uses of Canadian poplars in fibre and wood products	Keays et al. 1974	As above
Utilization of western Canadian hardwoods	McIntosh & Carroll 1980	Forintek Canada Corp. Western Forest Products Laboratory 2665 East Mall University of British Columbia Vancouver, British Columbia V6T 1W5
Ecology of the aspen parkland of western Canada, in relation to land use	Bird 1961	Agriculture Canada Research Branch Ottawa, Ontario K1A 0C5
A silvicultural guide for the poplar working group in Ontario	Davison et al. 1988 (see also earlier version by Heeney et al. 1980)	Ontario Ministry of Natural Resources Public Information Centre Room 1640 99 Wellesley Street West Toronto, Ontario M7A 1W3
Boreal mixedwood symposium	Whitney & McClain 1981	Great Lakes Forestry Centre Forestry Canada P.O. Box 490 Sault Ste. Marie, Ontario P6A 5M7
Aspen: ecology and management in the western United States	DeByle & Winokur 1985	U.S. Department of Agriculture Rocky Mountain Forest and Range Experiment Station 240 West Prospect Street Fort Collins, Colorado 80526
Utilization and marketing as tools for aspen management in the Rocky Mountains	U.S.D.A. Forest Service 1976	As above
Silviculture of aspen forests in the Rocky Mountains and the Southwest	Shepperd 1986	As above

Table 1. Continued

Title	Authors	Available from
Aspen Symposium '89 Proceedings	Adams 1990	U.S. Department of Agriculture North Central Forest Experiment Station 1992 Folwell Avenue St. Paul, Minnesota 55108
Manager's handbook for aspen in the north central states	Perala 1977	As above
Quaking aspen: silvics and management in the Lake States	Brinkman & Roe 1975	As above
Silvical characteristics of quaking aspen *(Populus tremuloides)*	Strothmann & Zasada 1962	As above
A review of literature relating to quaking aspen sites	Heinselman & Zasada 1955	As above
Aspen: symposium proceedings	U.S.D.A. Forest Service 1972	As above
Aspens: phoenix trees of the Great Lakes Region	Graham et al. 1963	University of Michigan Press Ann Arbor, Michigan
Silvicultural systems for the major forest types of the United States	Burns 1983	U.S. Department of Agriculture Forest Service Washington, D.C. 20250
Silvics of North America, volume 2, hardwoods	Burns & Honkala 1990	As above

Ecological information is grouped under 17 subheadings in this section: taxonomy; geographic distribution; morphology; clonal structure of stands; reproduction; stand development and mortality; productivity and growth; nutrient relationships; meteorological influences; soil, soil moisture, and water relationships; physiological responses; diseases; insects; site and successional relationships; wildlife relationships; the role of fire; and aspen and balsam poplar in relation to climatic change. The rather large subject of tree breeding is omitted from this review because it deals mainly with poplar hybrids. As a result, there is no separate section dealing with the genetics of aspen and balsam poplar. The limited genetic information that is contained in this report is covered in several different sections. Few long-term genetic studies have been reported and most current knowledge of clonal variation comes from observations of natural clones rather than from genetic tests. Cooperative research between several forest companies and the University of Alberta is currently under way to assess variation in aspen genotypes and the sensitivity of genotypes to different environments (Bryson 1990).

Taxonomy of Aspen and Balsam Poplar within the Genus *Populus*

In the following sections, the taxonomy of aspen and balsam poplar is discussed in terms of the linguistic origin of the name, *Populus*, and the taxonomic relationships of these two species within the genus *Populus*. Leaf morphology is diagrammatically shown for species of *Populus* native to Canada because it is the diagnostic feature that is most useful for distinguishing one species from another in the summer. Dichotomous keys developed by Maini (1968) for summer and winter identification of Canada's aspen and poplars are reproduced in this section.

Origin of the Name *Populus*

The name *Populus* has ancient linguistic origins, as summarized by Dickmann and Stuart (1983):

> Clute (1943) and Collingwood and Brush (1964) relate that the generic name *Populus* is derived from the early Roman expression *arbor populi*, meaning "the people's tree", because poplars were frequently planted along the wayside. Edlin (1963) has a different story. According to him, the Latin *Populus* can be traced back to the Greek verb *papaillo*, meaning to "shake or tremble". This idea of constant motion, referring to the well-known tendency of poplar leaves to flutter in the slightest breeze, also is found in one Gaelic name for aspen, *crann critheach*, or the shaking tree, and in its Welsh folkname, *coed tafod merched*, tree of the woman's tongue. Apparently the Greeks also shared this simile for a poplar leaf.

For some North American native languages, too, the typical fluttering leaves became part of the species name. The Onondaga Indian name for aspen is Nut-Ki-e, meaning noisy leaf. The word poplar is one of the few tree names to be shared, in different forms, by several modern European languages. It is peuplier in French, populier in Dutch, Pappel in German, poppel in Danish, poppeli in Finnish, poplys in Welsh, and pioppo in Italian (Dickmann and Stuart 1983).

A large geographic range for a tree species encourages a variety of regionally distinct common names. It is not surprising, therefore, that aspen, as the most widely distributed tree in North America, has been referred to in different regions as abele poplar, aspen poplar, white poplar, smooth-barked poplar, popple, asp, quaking asp, quaking aspen, and trembling aspen. Aside from the variety of common names, there is marked variability in aspen's external appearance in different parts of its transcontinental range. This led early taxonomists to suggest taxonomic subdivisions (Harper et al. 1985). At one time, as many as four different species were proposed: *Populus cercidiphylla* Britton; *Populus aurea* Tidestr.; *Populus vancouveriana* Trel.; and the original *P. tremuloides* Michx.

Groups within the Genus *Populus*

The genus *Populus*, a member of the willow family (Salicaceae), is generally divided into five sections as listed in Table 2. A sixth section Abaso Ecken. was proposed by Eckenwalder (1977) for Mexican poplar (*Populus mexicana* Wesmael.). Sections Turanga and Leucoides are not represented in Canada.

Although the nomenclature differs somewhat from the species names listed in Table 2, representatives of the genus *Populus* that occur in Canada are listed in Table 3.

Maini (1968) listed lanceleaf cottonwood (*Populus* × *acuminata* Rydb.) as the eighth *Populus* species in Canada. This species is now, however, considered to be a hybrid complex between *Populus angustifolia* James

Table 2. Sections, subsections, and species in the genus *Populus* (Dickmann and Stuart [1983] based on Food and Agriculture Organization [1980] and Little [1979])

Section	Species	Common name
Turanga Bge.	*P. euphratica* Oliv.	Euphrates poplar
Leucoides Spach.	*P. ciliata* Wall.	Himalayan poplar
	P. heterophylla L.	Swamp cottonwood
	P. lasiocarpa Oliv.	No common name
	P. wilsonii Schneid.	Wilson poplar
Leuce Duby		
Subsection Albidae	*P. alba* L.	White poplar
		Silver-leaved poplar
	P. monticola T. Brand.	Mexican white poplar
Subsection Trepidae	*P. adenopoda* Maxim.	Chinese aspen
	P. davidiana Schneid.	Korean aspen
	P. grandidentata Michx.	Large-toothed aspen
	P. sieboldii Miq.	Japanese aspen
	P. tremula L.	European aspen
	P. tremuloides Michx.	Quaking aspen
Tacamahaca Spach.	*P. angustifolia* James	Narrow-leaf cottonwood
	P. balsamifera L.	Balsam poplar
	P. cathayana Rehd.	No common name
	P. koreana Rehd.	Korean poplar
	P. laurifolia Ledeb.	Laurel poplar
	P. maximowiczii Henry	Japanese poplar
	P. simonii Carr.	Simon poplar
	P. suaveolens Fisch.	No common name
	P. szechuanica Schneid.	No common name
	P. yunnanensis Dode	No common name
	P. trichocarpa Torr. and Gray	Black cottonwood
	P. tristis Fisch.	Himalayan balsam poplar
Aigeiros Duby	*P. deltoides* Bartr. ex. Marsh.	Eastern cottonwood
	P. fremontii Wats.	Fremont cottonwood
	P. nigra L.	Black poplar

and one or more of *Populus deltoides* Bartr. ex. Marsh., *Populus fremontii* Wats., or *Populus sargentii* Dode (Brayshaw 1965; Scoggan 1978). All *Populus* species native to Canada extend into the United States.

The aspens that make up subsection Trepidae of section Leuce, including not only the North American *P. tremuloides* and *Populus grandidentata* Michx. but also the Eurasian *Populus tremula* L. and several other Asian species (Table 2), are considered by some investigators to be single superspecies. Certainly, all species in subsection Trepidae are easily crossed (Einspahr and Winton 1977). In particular, natural hybrids of *P. tremuloides* and *P. grandidentata* are common where they overlap from southeastern Manitoba eastwards (Barnes 1961; Andrejak and Barnes 1969).

At least 12 different varieties or forms of North American aspen have been named at various times by taxonomic authorities (Barnes 1969; Taylor and MacBryde 1977; Scoggan 1978): *aurea, vancouveriana, cercidiphylla, intermedia, rhomboidea, magnifica, davidiana, reniformis, pendula, minor, nana,* and *tremuloides*. Taylor and MacBryde (1977) identified three varieties of aspen in British Columbia: var. *vancouveriana* in the coastal Douglas-fir and coastal western

Table 3. *Populus* species that occur in Canada

Most frequently used common names	Synonyms	Current botanical name[a]
1. Trembling aspen, Quaking aspen, Aspen	No synonym	*P. tremuloides* Michx.
2. Large-toothed aspen, Largetooth aspen, Bigtooth aspen	No synonym	*P. grandidentata* Michx.
3. Balsam poplar, Hackmatack, Taccamahac, Balm of Gilead	*P. candicans* Ait.	*P. balsamifera* L. ssp. *balsamifera* and *P. balsamifera* L. var. *subcordata* Hylander
4. Black cottonwood, Balsam cottonwood	*P. trichocarpa* Torr. & Gray ex Hook; *P. balsamifera* L. var. *californica* S. Watson; *P. hastata* (Dode)	*P. balsamifera* L. ssp. *trichocarpa* (Torr. & Gray) Brayshaw
5. Narrow-leaf cottonwood, Willow-leaved cottonwood	No synonym	*P. angustifolia* James
6. Eastern cottonwood, Necklace poplar	No synonym	*P. deltoides* Marsh.
7. Plains cottonwood	No synonym	*P. deltoides* Marsh. var. *occidentalis* Rydb.

[a] Based on nomenclature by Brayshaw (1965), Taylor and MacBryde (1977), and Scoggan (1978).

hemlock zones; var. *aurea* in the boreal, subboreal, Caribou, interior western hemlock, and interior Douglas-fir zones; and var. *tremuloides* in a broad area involving eight coastal and interior biogeoclimatic zones. The latter variety is the only one of the three that Taylor and MacBryde (1977) indicate to be present in the relatively dry ponderosa pine–bunchgrass zone. In the prairie provinces the transcontinental distribution of var. *tremuloides* was mapped by Maini (1968) to occupy the Canadian Shield area of Manitoba, northern Saskatchewan, and extreme northeastern Alberta. Southwest of the Interlake Region of Manitoba, and in most of Saskatchewan, Alberta, British Columbia, the Yukon, and Alaska, Maini (1968) indicated that the dominant aspen was var. *aurea*.

Aspen has been reported to hybridize in the following combinations: *Populus alba* L. × *P. tremuloides* (Masson, Quebec); *P. angustifolia* × *P. tremuloides* (Lethbridge, Alberta); *P. balsamifera* × *P. tremuloides* (Manitoba and southern Ontario); *P. balsamifera* var. *subcordata* × *P. tremuloides* (Kenogami River, Ontario); *Populus deltoides* var. *occidentalis* Rydb. × *P. tremuloides* (southern Manitoba and Estevan, Saskatchewan, Red Deer River and Bow River, Alberta); *P. grandidentata* × *P. tremuloides* (Michigan); *P. trichocarpa* (T. & G.) Brayshaw × *P. tremuloides* (location unspecified); and *P. tremula* × *P. tremuloides* (Maple, Ontario) (Barnes 1961; Brayshaw 1965; Boivin 1967; Benson 1972; Ronald et al. 1973; Scoggan 1978; Zsuffa 1979; Dickmann and Stuart 1983; Harper et al. 1985).

In southern Alberta, Brayshaw (1965) found that aspen showed little tendency to cross with other *Populus* species. There is evidence, in that region, that aspen will hybridize more readily with poplars of section Aigeiros than with those of section Tacamahaca. In southern Alberta, balsam poplar hybridizes with other *Populus* species much more frequently than aspen does. In British Columbia and western Alberta, balsam poplar merges with black cottonwood, creating many intermediate individuals between the two species. In fact, although Hosie (1979) treated them as two species, the more common practice is to recognize them as two subspecies, *balsamifera* and *trichocarpa* of the species *P.*

balsamifera (Scoggan 1978). In the prairie provinces, one of the many forms of balsam poplar has been singled out as a variety—*P. balsamifera* var. *subcordata*, known as heartleaf balsam poplar. The Balm-of-Gilead (*Populus candicans* Ait.) is thought to have been derived from cuttings of a female heartleaf balsam poplar or a hybrid of it (Hosie 1979). In addition to the taxonomic study by Brayshaw (1965), the article by Rood et al. (1986) provides additional information on poplar hybrids from southern Alberta.

In southern Manitoba, most of the variants described by Ronald et al. (1973) originated from hybridization of *P. balsamifera* and *P. deltoides* var. *occidentalis*. The hybrid species, *Populus* ×*jackii* Sarg., encompasses the collective group of individuals resulting from this hybrid cross. The hybrid individuals are widely distributed in southern Manitoba and in Saskatchewan; these hybrids should be expected to occur wherever the two parental species are growing together. A tree considered to be the largest cottonwood in Saskatchewan, located in the valley of the North Saskatchewan River near the town of Petrofka, is a *P.* ×*jackii.* It has a diameter at breast height (dbh) of 155 cm, a crown span of 31.8 m, and a height of 20.9 m (Wedgwood 1989). *Populus deltoides* occurs sporadically along the Saskatchewan River as far northeast as Cumberland House. There is, therefore, reason to expect that *P.* ×*jackii* also occurs that far into the Boreal Forest Region (J. Stan Rowe, pers. com., June 1990).

Distinguishing Leaf, Bud, and Twig Features

In summer, leaves are usually a reliable way to distinguish species of *Populus* in Canada, providing leaves are selected from short, lateral shoots instead of from vigorously growing terminal shoots, epicormic branches, stump sprouts, or root suckers (Maini 1968). Typical shapes of leaves borne on short lateral shoots of Canadian *Populus* species are shown in Figure 2.

Dichotomous keys developed by Maini (1968) for identification of Canadian species of *Populus*, based on leaves in summer and twigs and buds in winter, are reproduced with minor modifications in the following text. Foresters using these keys are cautioned that differences between species of *Populus* are often less distinct in the field than they appear to be in the keys.

Geographic Distribution of Aspen and Balsam Poplar

Both aspen and balsam poplar are characterized by a large transcontinental distribution. The most detailed distribution maps of aspen and balsam poplar in Canada

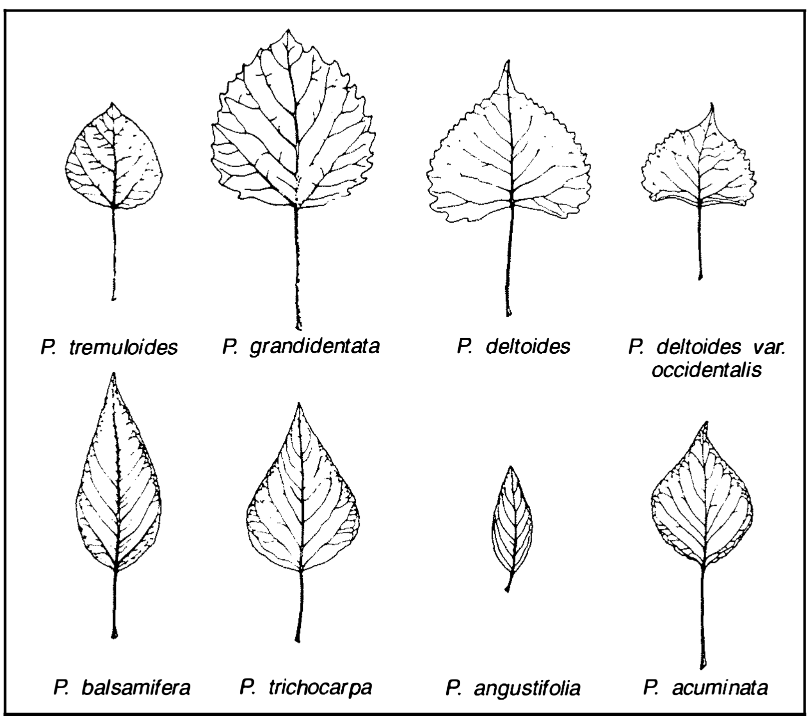

Figure 2. Outlines of leaves from short lateral shoots for Canadian species of *Populus*, scale 1/5 of natural size (Maini 1968).

KEYS TO THE GENUS *POPULUS* IN CANADA

Leafy Summer Condition

1. Leaf narrow, lanceolate, finely toothed. Petiole less than 1/3 length of leaf blade, flattened on top. Second year branchlets white or ivory-colored. Bud resinous. Range: western plains and foothills of the Rocky Mountains . . . . Narrowleaf cottonwood, *P. angustifolia*

   Leaf ovate or broader (may be lanceolate in seedlings of *P. balsamifera*). Second year branchlets usually greyish or yellowish 2

2. Petiole cylindrical, grooved on top, usually with glands at junction with blade, 1/3 to 1/2 length of blade. Leaf blade ovate to cordate, acuminate. Buds strongly resinous 3

   Petiole, at least in upper part, flattened in vertical plane, about 3/4 length of blade. Leaf blade or bicular, broadly ovate, elliptical, or deltoid. Buds not resinous or only mildly resinous 6

3. Capsule ovate, 2-valved, glabrous. Young shoots terete. Range: east, boreal forest, and Rocky Mountains . . . . Balsam poplar, *P. balsamifera* 4

   Capsule globose, 3-valved, young shoots commonly angled. Range: Pacific slope and southern Alberta . . . . Black cottonwood, *P. trichocarpa* 5

4. Buds, petioles, and leaves glabrous. Leaf base rounded. Range: transcontinental . . . . *P. balsamifera* var. *balsamifera*

   Buds, petioles, and lower leaf surfaces finely puberulent. Leaf base broadly rounded to cordate. Range: Saskatchewan to Newfoundland and Nova Scotia . . . . *P. balsamifera* var. *subcordata*

5. Capsule globose, and puberulent. Leaf broadly ovate, rounded to subcordate at base. Range: British Columbia, Yukon, and Alaska . . . . *P. trichocarpa* var. *trichocarpa*

   Capsule often broadly beaked, glabrous, or nearly so. Leaf cordate, acuminate. Range: southwestern Alberta, British Columbia, Yukon, and Alaska . . . . *P. trichocarpa* var. *hastata*

6. Leaf orbicular to broadly ovate or elliptical, glandless. Buds not resinous . . . . Aspens 7

   Leaf deltoid, often with glands at junction of blade and petiole. Buds mildly resinous . . . . . *P. deltoides* 9

7. Leaf coarsely sinuate-toothed; usually 10 or fewer teeth each side. Range: eastern North America . . . . Largetooth aspen, *P. grandidentata*

   Leaf finely serrate to crenate; usually 15 or more teeth each side. Range: transcontinental . . . . .Trembling aspen, *P. tremuloides* 8

8. Buds glabrous, brown. Young leaves not downy. Range: transcontinental . . . . . *P. tremuloides* var. *tremuloides*

   Buds finely grayish-downy. Young leaves downy. Range: Pacific coast . . . . . *P. tremuloides* var. *vancouveriana*

9. Buds glabrous. Leaves many-toothed. Range: southern Saskatchewan to Quebec . . . . Eastern cottonwood, *P. deltoides* var. *deltoides*

   Buds and young leaves minutely puberulent. Some leaves with 12 or fewer coarse, sinuate teeth on each side below the conspicuously entire apex. Range: southern Saskatchewan and Alberta . . . . Plains cottonwood, *P. deltoides* var. *occidentalis*

Leafless Winter Condition

1. Buds not resinous .... Aspens 2

   Buds resinous .... Poplars and cottonwoods 3

2. Buds glabrous, brown with the terminal bud longer than the subjacent lateral bud. Smooth bark white, gray, or pale green; roots pale brown. Range: transcontinental .... Trembling aspen, *P. tremuloides*

   Buds grayish-downy, with the terminal and subjacent lateral buds of almost equal length. Smooth bark greenish yellow; roots dark reddish brown. Range: eastern North America .... Largetooth aspen, *P. grandidentata*

3. Second year branchlets dull gray or gray-brown. Buds very resinous 4

   Second year branchlets pale yellowish to white. Buds moderately resinous 6

4. Young shoots terete. Terminal bud longer than subjacent lateral bud. Range: from continental height of land eastward .... Balsam poplar, *P. balsamifera* 5

   Young shoots commonly angled. Terminal bud not longer than subjacent lateral bud. Range: British Columbia, Yukon, and Alaska .... Black cottonwood, *P. trichocarpa*

5. Buds glabrous .... *P. balsamifera* var. *balsamifera*

   Buds not glabrous, minutely puberulent .... *P. balsamifera* var. *subcordata*

6. Second year branchlets white to ivory-colored, slender. Buds usually less than 10 mm long. Range: southern Alberta .... Narrowleaf cottonwood, *P. angustifolia*

   Second year branchlets pale yellowish gray, usually stout. Buds usually more than 10 mm long .... *P. deltoides* 7

7. Buds glabrous. Range: southern Saskatchewan to Quebec ...... Eastern cottonwood, *P. deltoides* var. *deltoides*

   Buds not glabrous, minutely puberulent. Range: southern Saskatchewan and Alberta .... Plains cottonwood, *P. deltoides* var. *occidentalis*

were published by Maini (1968) and in the United States by Little (1971). The most recent of these, by Little, are reproduced for aspen in Figure 3 and balsam poplar in Figure 4. The portion of the botanical range in which aspen grows to commercial size and is an important species in the forest types where it occurs is shown for the prairie provinces and northeastern British Columbia in Figure 1. Aspen of potential commercial importance also occurs in the Interior Plateau of British Columbia west of the Rocky Mountains. East of Manitoba the commercial range of aspen includes most of Minnesota, Wisconsin and Michigan, the northern parts of Vermont, New Hampshire and Maine, the upper Saint John River valley in New Brunswick, the eastern townships of Quebec, the northern clay belt of Quebec and Ontario, the Ottawa River valley, and the Great Lakes–Lake Nipigon–Lake of the Woods regions of Ontario (Strothmann and Zasada 1962; Maini 1968; Little 1971).

Aspen's exceptionally broad east-west distribution from the Atlantic coast in the Maritime provinces to the Pacific coast in southeastern Alaska (Fig. 3) is broken only by its absence in coastal British Columbia, except for its sporadic natural occurrence on southeastern Vancouver Island. Aspen's northern limit generally coincides with the 13°C July isotherm and is close to the forest–tundra ecotone (Maini 1968). Aspen's extreme northern limit in North America is in the Mackenzie River delta of the Northwest Territories.

In the prairie provinces, aspen's southern limit is formed by the Aspen Grove Section (Rowe 1972), which is a transition between boreal forest in the north and grassland or agricultural lands in the south. In the eastern United States, aspen's extreme southern limit is in Giles County, Virginia, and Dent County, Missouri. Farther west it occurs as far south as 21°N in Mexico, although

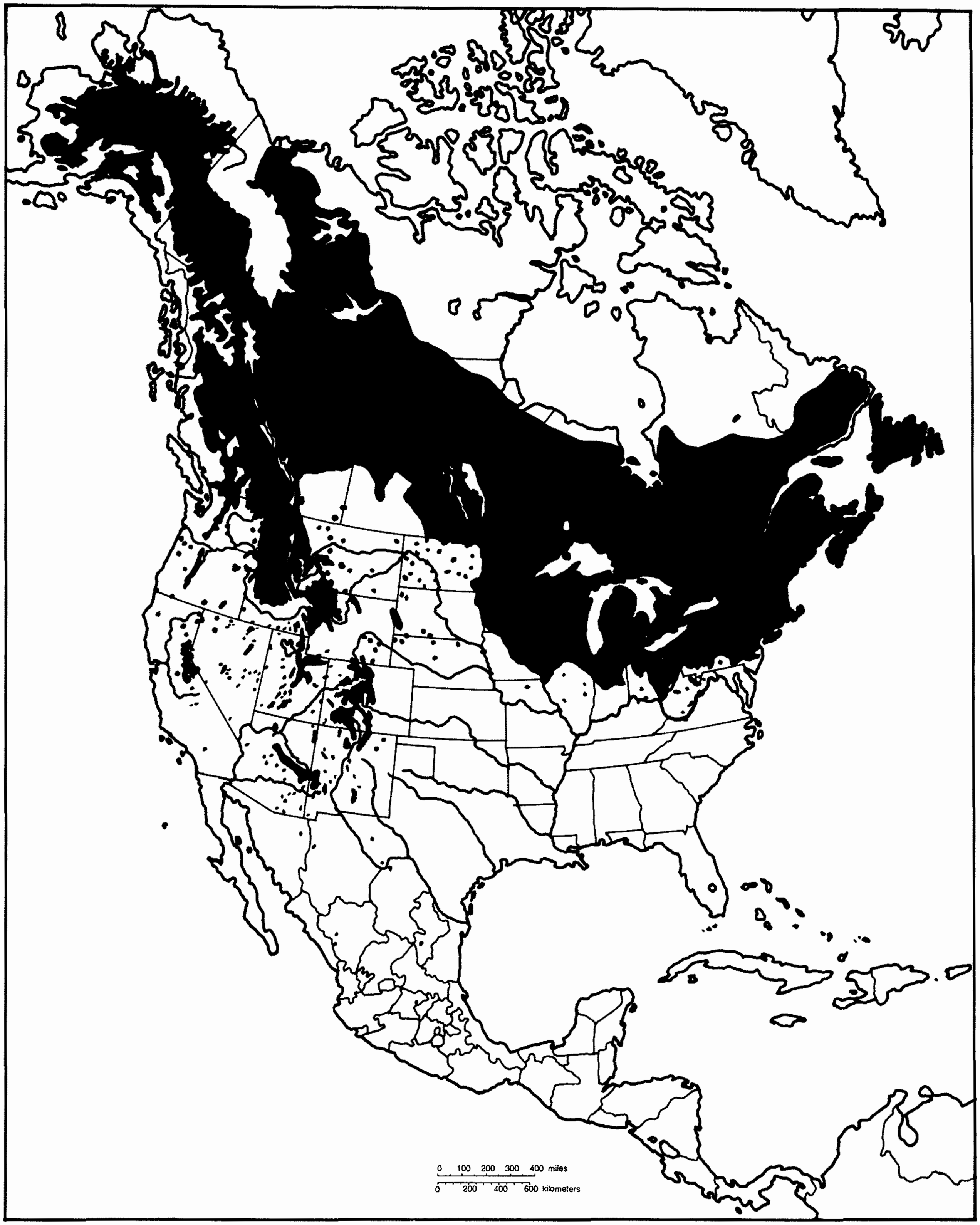

Figure 3. Current natural distribution of aspen in North America (adapted from Little 1971).

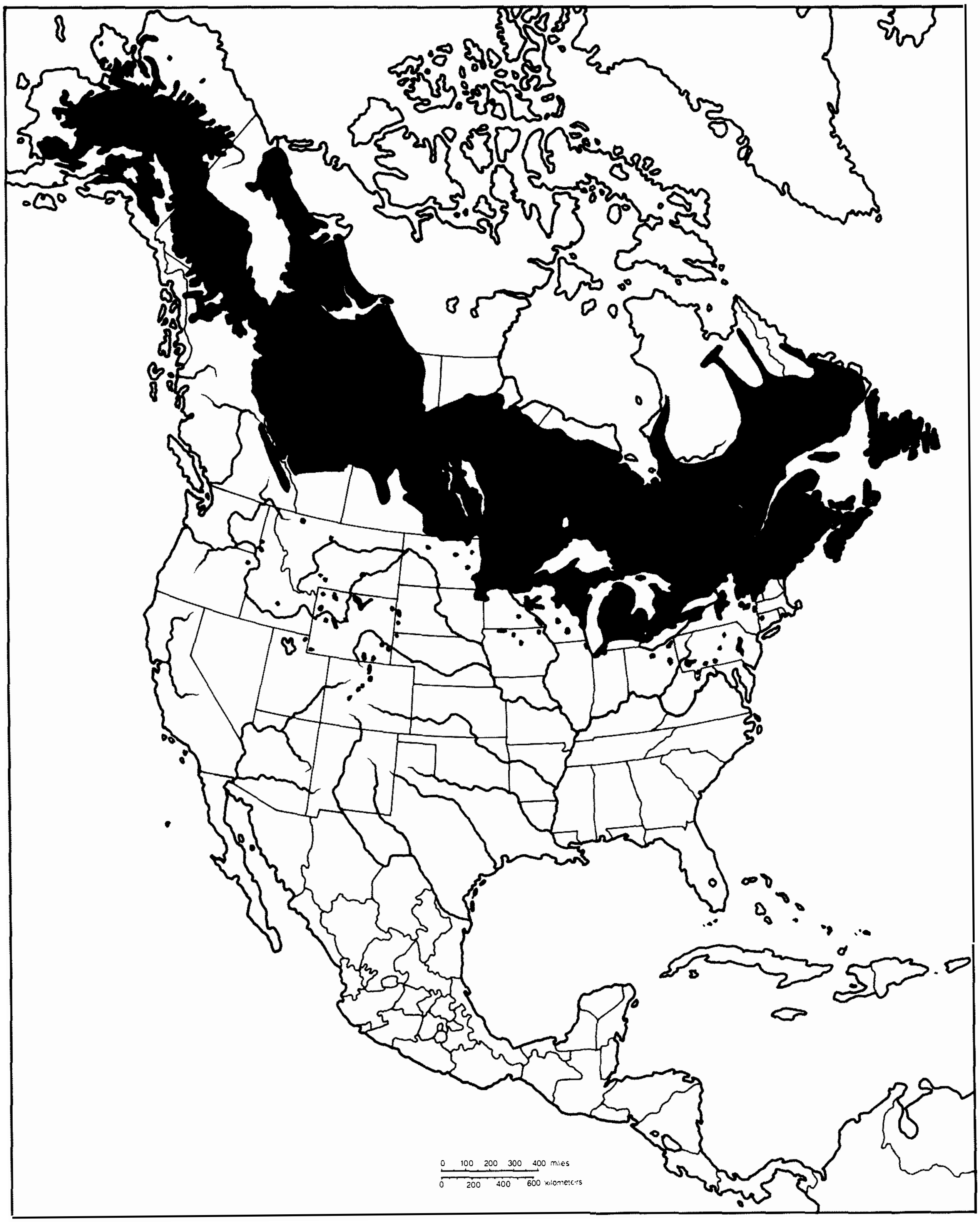

Figure 4. Current natural distribution of balsam poplar in North America (adapted from Little 1971).

the most southerly area of significant aspen stands is in Catron County, New Mexico (Little 1971).

As shown by comparison of Figures 3 and 4, balsam poplar generally does not extend as far northeast into the forest–tundra transition zone as aspen does. Exceptions are in Alaska, Labrador, and near James Bay in Quebec, where balsam poplar does occur farther north than aspen. Balsam poplar's occurrence is not as far south as that of aspen on the Atlantic coast and in the Lake States. Although balsam poplar occurs south to central Colorado, its distribution in the western United States is extremely sporadic compared to that of aspen. Balsam poplar is absent west of the Rocky Mountains in British Columbia, and it is replaced there by black cottonwood (*P. trichocarpa*).

Aspen's deciduous partners change from east to west within the prairie provinces. In northeastern British Columbia, Alberta, and much of Saskatchewan, balsam poplar is aspen's most common deciduous associate, followed by white birch (*Betula papyrifera* Marsh). In contrast, in eastern Saskatchewan and Manitoba other deciduous species may also be present, notably green ash (*Fraxinus pennsylvanica* var. *subintegerrima* [Vahl] Fern.), American elm (*Ulmus americana* L.), Manitoba maple (*Acer negundo* L.), and bur oak (*Quercus macrocarpa* Michx.). Basswood (*Tilia americana* L.) is an occasional associate in southeastern Manitoba (Looman 1987).

Morphology of Aspen and Balsam Poplar

The following sections describe the external appearance of aspen and balsam poplar, based on the typical form of shoots, buds, leaves, aments (catkins), branches, crowns, stems, and bark. Although not observable to the forester, root morphology is also included in this section because of the silvicultural importance of aspen's root system for sucker regeneration and clone management.

Shoots, Buds, Leaves, Aments, and Flowers

The following morphological description of aspen short shoots is a composite based on Strothmann and Zasada (1962), Maini (1968), and Jones and DeByle (1985b):

> twigs slender, glabrous, flexible, reddish brown, spreading or ascending; terminal bud 6–10 mm long; leaves 3–8 cm long with slender flattened petioles; blades of short shoots are orbicular to broadly ovate, glabrous, short acuminate, finely serrate–crenate to nearly entire, dark green above, yellowish-green below, as long as or longer than broad; aments soon pendulous; bracts of aments deeply divided into 3–5 attenuate long-bearded segments; stamens 6–12 in an obliquely prolonged entire-margined disc; ovary glabrous with short stout style, bicarpellate; capsules slenderly conic, 35 mm long, warty.

Although exceptions occur, the flowers of aspen are typically imperfect (unisexual) and the trees dioecious (with individual trees wholly female or wholly male). Strothmann and Zasada (1962) described exceptions from Massachusetts and Minnesota where aspen of seedling origin contained higher than usual percentages of trees with imperfect flowers of both sexes. There has been at least one report of uneven distribution of clones of the two sexes, with three or more male clones for each female clone (Pauley and Mennel 1957).

Aspen seed capsules mature when aments are 9–10 cm long. Each capsule is two-valved and about 0.6 cm long. The number of capsules per ament ranges from 70 to 100, with 6–8 seeds in each (Jones and DeByle 1985b). Each seed is surrounded by tufts of long, white, silky hairs attached to the basal end. There are from 1.1 to 1.4 million seeds per kilogram, including the weight of hairs, which make up about 38% of total seed weight (Maini 1968).

The western mountain variety of aspen, *Populus tremuloides* var. *aurea* (Tid.) Daniels, is distinguished from the typical eastern variety by its shorter calyces, larger anthers, and deep golden coloration of foliage in autumn. All varieties of aspen are characterized by leaves with flattened petioles that act as a pivot for the blade, which trembles in the slightest breeze. In contrast to the leaves on mature trees, the leaves of young suckers are much larger, often 18–20 cm long, very succulent, and typically twice as long as they are broad. Typical leaf shape from an aspen short shoot, in comparison with other species of Canadian *Populus*, is shown in Figure 2.

Short shoots of balsam poplar have morphological characteristics distinct from those of aspen. Maini (1968) described balsam poplar short shoots as follows:

> twigs lustrous, bright reddish-brown, terete; vegetative buds with 5–7 very resinous, pubescent and ciliate scales, fragrant; leaves 5–10 cm long, glabrous, dark green above, pale green, generally with rusty-brown resinous blotches below; broadly lanceolate to ovate, acuminate, rounded to subcordate at the base, margins

coarsely crenate–serrate; petioles terete; bracts of aments fringed at broad summit by many flexuous bristle-like segments; stamens many on an oblique entire disc; ovary and glabrous capsule subtended by a symmetrical, persistent, saucer-shaped disc; stigmas sessile with coarsely toothed rounded lobes; capsule thick-walled, ovoid.

The importance of distinguishing between short shoots and long shoots in aspen has been stressed by several researchers (Critchfield 1960; Kozlowski and Clausen 1966; Pollard 1970). Short shoots are preformed in the winter bud. Their growth is fixed because it is completed when the preformed stem units have elongated. In contrast, growth of long shoots involves not only the elongation of preformed stem units but also a period of free growth during which new stem units begin and elongate simultaneously. Short shoots complete their growth during a brief period in the spring, whereas long shoots may continue elongating until late summer. In an Ontario study, Pollard (1970) found that short shoots made up 87% of the leaf area; the 13% of leaf area represented by long shoots makes a relatively small contribution to primary production by the canopy in aspen stands.

The occurrence of both types of shoots in aspen, one characterized by fixed growth and the other by free growth, is accompanied by two types of leaves. The two basic leaf types are called early or late depending on their time of initiation and differentiation. Both leaf types may occur on long shoots, whereas short shoots have only early leaves. Early leaves are embryonic leaves in the winter bud, whereas the succeeding late leaves begin and develop during the period of free growth (Jones and Schier 1985).

The distribution of different shoot types changes as aspen crowns develop. The terminal and main lateral shoots of young aspen consist almost entirely of long shoots. As aspen tree crowns increase in size, short shoots soon outnumber long shoots, and most of the foliage consists of early leaves. At Petawawa, Ontario, Pollard (1970) found that long shoots made up 13% of the canopy in a 6-year-old stand, whereas they made up only 6% of the canopy in a 15-year-old stand. There were no long shoots at all in a 52-year-old stand. In the 6-, 15-, and 52-year-old stands, leaf biomass was 2600, 2600, and 1500 kg/ha, respectively, and leaf area index (surface area of foliage per unit area of ground surface) was 2.4, 2.9, and 1.6, respectively.

The Ontario leaf area index estimates were similar to those obtained for aspen and balsam poplar stands in Alberta where leaf area indexes of sampled *Populus* stands varied from 2.41 to 5.39 (Johnstone and Peterson 1980). The Alberta data show a slightly higher leaf area index for balsam poplar than for aspen stands. Leaf area index was not significantly correlated with mean height but was significantly correlated with the number of stems per hectare. This lack of correlation between mean stand height and leaf area index may occur because live crown length changes little after aspen trees reach 15–20 years of age. A young aspen stand has a large leaf system relative to the amount of respiring tissue present in the stem, branches, and leaves, and the net difference between photosynthesis and respiration is high, resulting in rapid growth.

These data on leaf area index indicate that very young aspen crowns may support as much or more foliage as older stands (Fig. 5). This suggestion appears

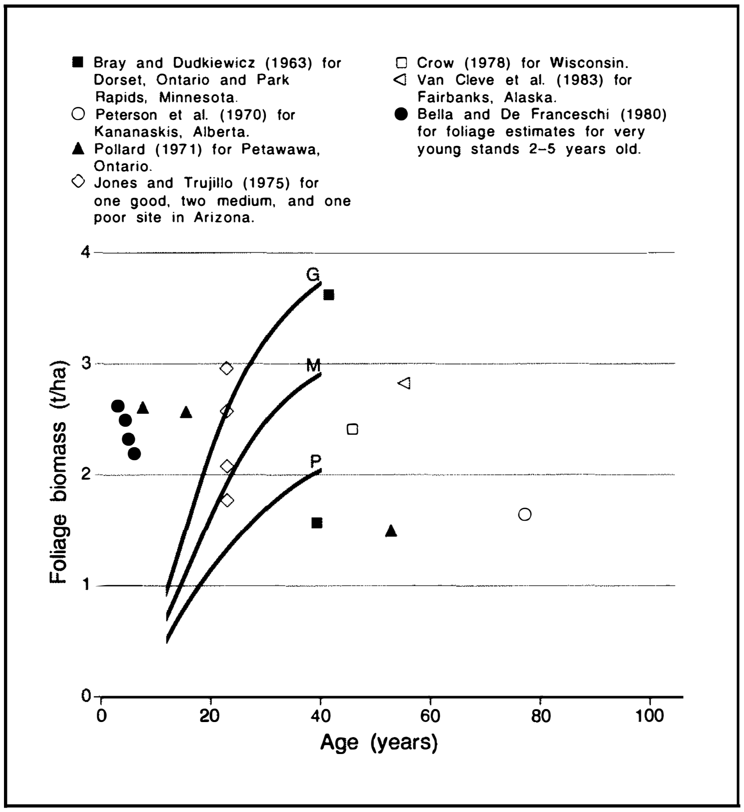

Figure 5. Aspen foliage biomass accumulation curves for good (G), medium (M), and poor (P) sites in north-central Alberta (Bella and De Franceschi 1980). For comparison, other estimates of foliage biomass are presented.

to be borne out by data presented by Bella and De Franceschi (1980), whose results indicate that there may actually be a decrease in foliage biomass following an early peak in the early stages of stand development. In the most dense stands sampled, these authors recorded a foliage dry weight standing crop of 2.785 t/ha in 2-year aspen stands, 2.631 t/ha in 3-year stands, 2.472 t/ha in 4-year stands, and 2.310 t/ha in 5-year stands. The relatively high leaf biomass at age 2 is likely a result of the predominance of long shoots, with the entire unbranched sucker being essentially one long shoot that supports exceptionally large individual leaves. As side branches and short shoots begin to develop on the young suckers after age 2, there is a higher proportion of biomass represented by woody material and not only a relative but an absolute decrease of foliage dry weight per hectare, at least up to age 5.

Branches and Crowns

Crown geometry has not been the subject of much study in aspen and balsam poplar, but there is considerable information on crown dimensions and branch weights as a result of biomass studies in the prairie provinces. Those biomass data, plus information on changes in the relative proportions of long and short shoots as crowns develop, are summarized here.

In general, aspen and balsam poplar in closed stands have shallow crown systems and relatively low branch biomass. Balsam poplar typically has a more columnar, open crown than aspen, formed by a few stout ascending branches (Fig. 6). Both balsam poplar and aspen growing in closed stands are characterized by a sparse branch and crown system relative to total tree size. This is particularly evident when an aspen canopy is viewed vertically from the ground (Fig. 7). It is because of its relatively inconspicuous crown, in contrast to that of conifers, that aspen's gradually tapering stem appears to extend almost to the top of the tree.

Throughout its geographic range, aspen is rated as very intolerant to shade, a characteristic that it retains throughout its life. Only in open-grown aspen is there some opportunity to develop relatively deep crowns (Fig. 8). Its intolerance of shade results in excellent natural pruning, as shown by the aspen in Figure 9.

From Alberta sample locations shown in Figure 10, Johnstone and Peterson (1980) recorded crown dimensions for aspen and balsam poplar (Table 4).

The notable feature of these data is that crown depth as a percent of total tree height drops greatly as aspen and

Figure 6. Balsam poplar has more sharply ascending branches and rougher stem bark than aspen (photo courtesy of A. Kabzems).

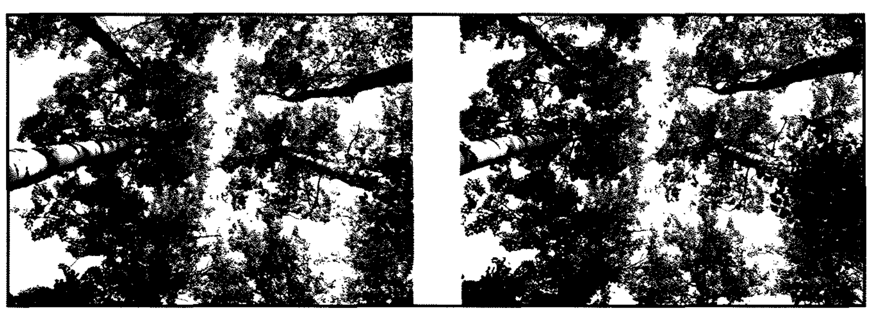

Figure 7. Aspen stands are characterized by a relatively open canopy, shallow tree crowns, and stems that appear to extend, with little taper, to almost the tops of the crowns. For best results use a stereoscope to view this set of photos.

Figure 8. Deep crowns can develop only where aspen grows in the open (photo courtesy of Sask. Govt. Photo by Alan Hill).

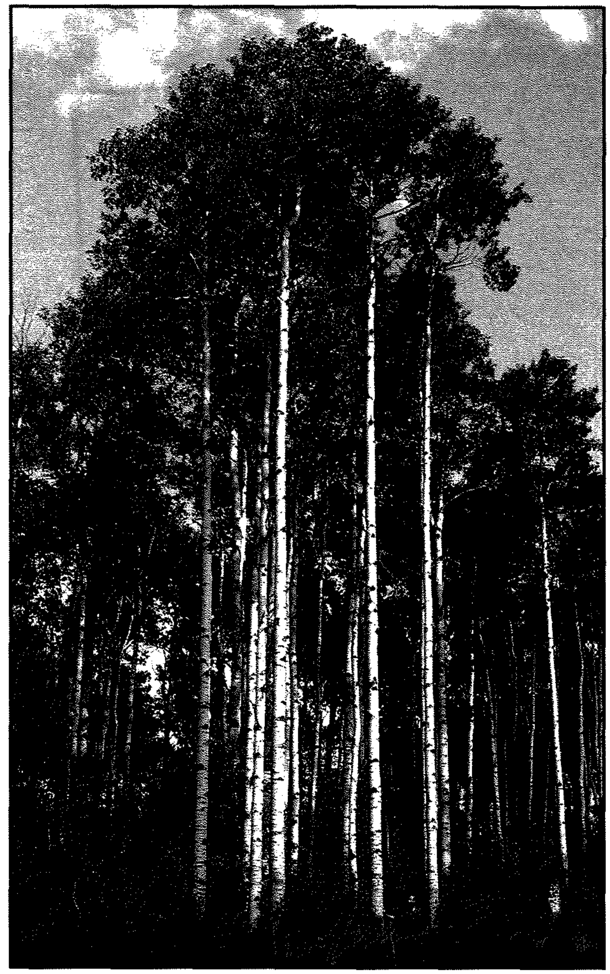

Figure 9. Excellent natural pruning and short crowns typical of mature aspen stands, Swan Hills, Alberta.

Table 4. Crown dimensions for aspen and balsam poplar in Alberta

Variables	Aspen (n[a] = 254)			Balsam poplar (n = 60)		
	Min.	Max.	Mean	Min.	Max.	Mean
Ages sampled (yr)	8	83	45 ± 21	16	65	32 ± 13
Dbhob[b] (cm)	2.0	31.5	12.7 ± 6.3	2.3	27.4	11.7 ± 6.0
Total height (m)	4.1	27.7	13.1 ± 5.4	3.9	23.2	13.5 ± 5.1
Crown depth (m)	2.8	9.1	5.1 ± 1.8	2.1	7.5	5.6 ± 0.9
Crown width (m)	0.6	7.2	2.4 ± 1.1	0.4	5.1	2.6 ± 1.2
Crown depth as % of total height	67.2	32.9	39.0	54.4	32.3	41.4
Crown width as % of crown depth	21.5	78.7	46.0	18.9	67.9	46.0

[a] n = sample population.

[b] Dbhob = diameter breast height outside bark.

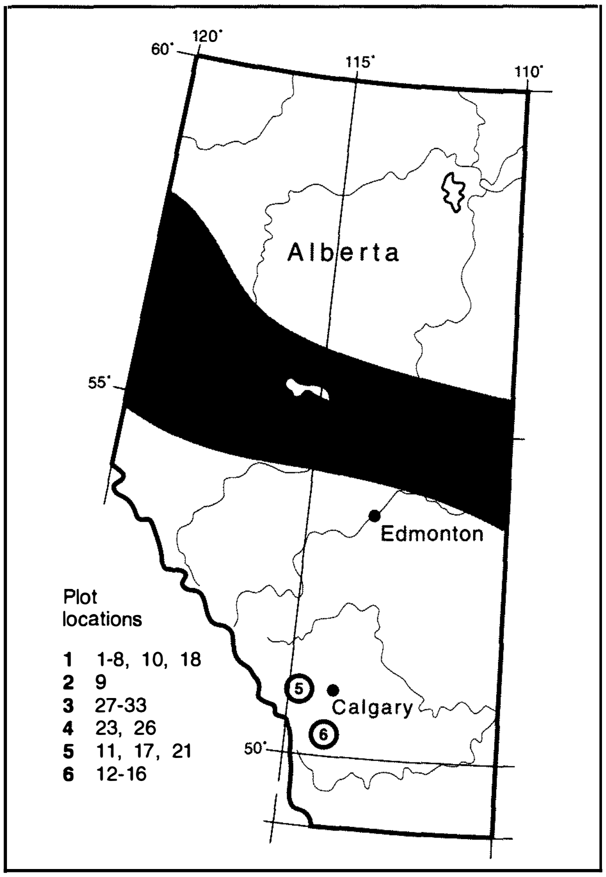

Figure 10. Alberta sample locations for aspen and balsam poplar crown dimension and aboveground biomass data (Johnstone and Peterson 1980).

balsam poplar mature. For example, balsam poplar at maximum age (65) has a crown depth–total tree height ratio of only 32.3%, whereas at minimum age (16), it is 54.4%. This is a reflection of the shade intolerance that prevents retention of a deep crown as stand height increases; live crowns simply move upwards as the stand develops so that even at mean age (45 years), in the 254 aspen sampled, crown depth was only 5.1 m compared to 2.8 m at age 8. The same holds true for balsam poplar. Crown width as a percent of crown depth increases greatly in the progression from young to mature stands because the canopy is limited in the extent to which it can deepen in these shade intolerant species.

Dry branch weight as a percent of total dry weight of the aboveground tree is another index of crown geometry. For the same Alberta sample population of 254 aspen and 60 balsam poplar, Johnstone and Peterson (1980) recorded a branch dry weight that was 10.5% of total aboveground dry weight for aspen with a mean age of 45 years and 8.7% for balsam poplar with a mean age of 32 years. Similar results can be derived from the Alberta and Saskatchewan biomass yield tables prepared by Bella and De Franceschi (1980). For example, at age 40 on a poor site in Saskatchewan (site index 16 m at age 50) branch dry weight was 11.0% of total aboveground dry weight in aspen; on a medium site at the same age, branches made up 10.4%; on a good site (24 m at 50 years) branches represented 9.9% of total aboveground dry weight. At the maximum age sampled by Johnstone and Peterson (1980) in Alberta aspen (83 years), branch dry weight reached 18.8% of aboveground weight. Johnstone and Peterson found that branch bark dry weight is about 33% of total branch weight in aspen at age 8 and about 28% at ages 45 and 83; in balsam poplar it is about 40% at age 16, 31% at age 32, and 28% at age 65.

The relatively sparse crowns of aspen and balsam poplar, compared to those in conifers, are economically important because the relatively small number of branches reduces delimbing time.

Stems and Bark

In contrast to its common associate, white spruce (*Picea glauca* [Moench] Voss), aspen has a slender stem relative to its height. Taper is also relatively gradual in aspen stems.

Aspen bark is relatively smooth and in many stands is sufficiently white-colored to lead the uninformed observer to confuse the tree with white birch. The smooth bark of aspen is a result of a persistent periderm, the outer tissue of bark that consists of cork and cork cambium (Kaufert 1937). The bark is described as white, greenish-white, yellowish-white, yellowish-gray, yellowish-brown, gray, or green (Jones and DeByle 1985b). The white and yellow-brown colors result from a coating of dead cork cells that rub off easily. Chlorophyll in the bark gives it the green hue evident in many clones. Figure 11 illustrates bark color differences in two adjacent clones in the Kananaskis River valley, Alberta. At maturity, some aspen develop roughened and fissured bark, but less strongly than balsam poplar. Dark and rough patches of aspen bark are commonly associated with some surface injury from a variety of insects and diseases, and by gnawing, rubbing, or climbing animals. Mature aspen bark is also roughened naturally by numerous dark-colored markings and by callus formation in the form of black gall. Juvenile balsam poplar has smooth, greenish to reddish-brown bark, but with maturity it becomes grey to greyish-black and is divided into flat, scaley, or shaggy ridges separated by narrow fissures.

Figure 11. Adjacent clones are often distinguishable by differences in branch scars, surface texture, and color of bark.

The natural surface features and color of aspen and balsam poplar bark are modified to some extent by resident lichens, mosses, and liverworts. For the reader interested in the identity of epiphytes that grow on aspen and balsam poplar bark in the prairie provinces, details are provided by Case (1977) for lichens, by Bird (1969) and Vitt (1973) for mosses, and by Bird and Hong (1975) for liverworts.

Proportion of Stem Made Up of Bark

In 254 aspen trees sampled in Alberta, Johnstone and Peterson (1980) estimated stem bark dry weight to be about 30% of total stem weight in 8-year-old aspen, about 20% in trees with a mean age of 45 years, and about 18% in the oldest tree sampled (83 years). In 60 balsam poplars sampled, bark made up about 35% of total stem weight at age 32 and 19% at age 65. From a sample of 152 aspen trees in Saskatchewan, data from Bella and De Franceschi (1980) indicated that bark represented 20.5% of total stem dry weight at age 40 on a good site (site index 24 m at 50 years), 21.3% at the same age on a medium site (20 m at age 50), and 22.3% at age 40 on a poor site (16 m at age 50).

Photosynthesis in Aspen Bark

The well-known occurrence of green cells (chloroplasts) in aspen bark, as shown in the left-hand stem of Figure 11, enables stems and branches to carry on photosynthesis in the absence of leaves (Barr and Potter 1974). Photosynthesis in aspen bark is, however, thought to make a negligible contribution to tree growth. For example, Foote and Schaedle (1976) reported that in 5- to 7-year-old aspen the stem was not capable of net production of organic matter from photosynthesis, but there was enough stem photosynthesis to offset the respiratory loss of carbon dioxide (CO_2) from the stem. Photosynthate produced in the bark is transported laterally in ray cells to xylem, phloem, and cambium (Shepard 1975). The annual contribution of bark photosynthesis to the carbohydrate supply of a tree has been estimated to be only 1–2% (Foote and Schaedle 1978). Although this is a small contribution, the fact that bark photosynthesis can equal stem respiration is thought to increase the chances of recovery of stressed trees after insect defoliation or after a severe late spring freeze (Jones and Schier 1985).

Root Systems

The most detailed Canadian studies of aspen root systems were carried out by Maini (1965a, b, c; 1968) and by Strong and La Roi (1983a, b; 1985). Their information is summarized here. For the area in which this report focuses, the studies by Strong and La Roi near Lesser Slave Lake, Alberta, provide the best information on aspen root-system morphology in northern mixedwood ecosystems.

The root system of aspen is unique among forest tree species in several ways: parent roots are usually much older than the sucker-origin stems that they support; stems are interconnected to a common parent root system; typical swelling of the parent root occurs on the distal side of each sucker, that is away from the older stem to which the parent root is attached; and roots are widely spreading in a lateral network. The limited information on root system biomass and changes of root biomass as aspen stands develop is also summarized in the following text.

General Form of Aspen Root Systems

The typical widely spreading aspen root system is supported by strong, vertically penetrating roots, originating near the tree base, and "sinkers" that arise from the lateral root system. Usually four or five strongly developed lateral roots originate from the tree base and then send out branch roots within 0.6 m of the stem base. Some of the cord-like branch roots, which extend a long distance without branching or reduction in thickness, are particularly suitable for sucker production (Maini 1960). These cord-like roots grow faster than the rapidly tapering laterals (Maini 1968).

The lateral roots of aspen undulate within the upper 1 m of soil and show only occasional branching. Lateral roots may extend for more than 30 m into adjacent open areas. Shallow laterals tend to follow minor soil surface irregularities, sometimes growing upward into decaying conifer stumps, where they can produce suckers (Jones and DeByle 1985b). Examples of aspen roots growing along the soil surface beneath fallen logs as well as into the logs themselves have been cited by Jones and DeByle. These observations are from the Rocky Mountain region of the United States and the degree to which they are applicable to aspen in the boreal forest region has not been documented.

"Sinker" roots may descend from points anywhere along a lateral root. In two Utah clones, Gifford (1966) observed that only 30% of the "sinker" roots originated from the base of stems. They reached depths of more than 2.7 m, often following old root channels. At their low extremities, "sinker" roots branch profusely into a dense fan-shaped mat. Dense mats of fine roots often occur when the tree roots encounter an impeding layer, such as rock, dense clay, or saturated soil (Jones and DeByle 1985b).

Vertical Distribution of Aspen Roots

Strong and La Roi (1983a, b; 1985) included aspen in their detailed root morphology studies about 55 km southeast of Lesser Slave Lake, Alberta. On all four sites examined, two on fine-textured and two on coarse-textured soils, aspen stems were connected by lateral roots near ground level. Lateral root connections were still evident in aspen as old as 79 years and 24 m tall. Peridermal scar tissue on the lateral roots marked the positions of former suckers that formed a denser stand earlier in its development.

Strong and La Roi (1983b) found that, in contrast with white spruce, aspen root morphology was distinctly different in sand compared with clay–loam substrates. With increasing age on both substrates, however, aspen developed a secondary root system, which supplemented the primary lateral roots that propagated the clone. On sandy substrates secondary lateral and sinker roots developed. The secondary laterals grew outward from the tree and then descended sharply, with few branches except in the distal portions, to a maximum depth of 2 m. A few "sinker" roots usually occurred near the stump. Heart-like roots were present on the undersides of some horizontal lateral roots, just outside the stump margin; these roots descended vertically to depths of 1 m, were stout, and very branched. In addition to lateral and heart-like roots, numerous stout and relatively short roots developed beneath the stumps of some trees. In contrast, on fine-textured substrates aspen had spreading-horizontal to slightly oblique lateral roots and a sphere of short stout roots below the stump. These roots were secondary to the primary lateral root system responsible for sucker production.

In the Lesser Slave Lake study area, jack pine (*Pinus banksiana* Lamb.) and aspen lateral roots were confined to mineral soil horizons, whereas the lateral roots of black spruce (*Picea mariana* [Mill.] B.S.P.), balsam fir (*Abies balsamea* [L.] Mill), white spruce, and tamarack (*Larix laricina* [Du Roi] K. Koch) were concentrated in organic soil horizons (Strong and La Roi 1983b). Based on a broader review of 19 published papers that provided information on vertical root distribution in northern tree species, Gale and Grigal (1987) found that early successional or intolerant tree species had a significantly greater proportion of roots occurring deeper than did late successional or tolerant species.

Despite the potentially deeper rooting of aspen, compared to other tree species in the Lesser Slave Lake study area, roots of aspen are still concentrated in a zone between 5 and 20 cm below ground surface (Strong and La Roi 1983a). It is for this reason that the upper 20–25 cm of the soil surface is of such importance to boreal mixedwood silvicultural treatments.

Root Dynamics within Aspen Clones

Although root grafting is rare in natural stands of aspen, the root system of this species is characterized by parent roots that have interconnecting links between the stems of a clone. In the Rocky Mountain region of the United States, few suckers 2 years old or less have well developed independent root systems (Schier and Campbell 1978), and in two Utah aspen clones, Gifford (1966) found that 30% of the stems that ranged from 18 to 26 years of age had no independent roots or only one root in addition to the parent root. Gifford reported that the longest distance observed along a connecting root without a living stem was 7.9 m and the shortest was 0.15 m. DeByle (1961), working in Michigan, found that small roots that developed at the base of an aspen sucker during the first 25 years were of greater physiological importance to the growth and survival of the sucker than either end of the parent root alone, but of lesser importance than the parent root as a whole.

Suckers that originate on a root system of a parent tree remain connected by parent roots, even after they have developed their own root systems. Radial growth of the root connection is negligible and the connection between the two trees remains alive until one of the two trees dies (Maini 1960). While Maini was excavating the root systems of aspens, live connections between trees as old as 65 years were observed. Translocation of water-soluble dye was recorded through these old root connections that still had a capacity to form suckers. It is evident that such groups of stems may remain functionally interconnected throughout much of the life of the aspen stand (Maini 1968; Tew et al. 1969). There is also evidence that the variability in longevity of functional connections is influenced by site (Cottam 1954; DeByle 1964) and that some connections will likely decay and break (Barnes 1959; Gifford 1966).

The information summarized above indicates that although root systems of aspen clones are long-lived, they are very dynamic. A newly formed aspen sucker depends upon the parent root for nutrients and water. This ready-made root system gives aspen suckers a growth and survival advantage over seedlings of aspen and other species (Graham et al. 1963). In the words of Jones and DeByle (1985b), suckers literally adopt a portion of the parent root as their own. The degree of dependence suckers have on their parent roots diminishes as the suckers develop their own root systems.

There is evidence that most adventitious roots formed below suckers die the same year they are initiated. The absence of a correlation between numbers of roots and sucker age is thought to be due to root mortality and the large numbers of roots initiated during the current year (Schier 1982). Small suckers without their own root system can be dependent on either end of the parent root, that towards the point of attachment with a main stem (proximal end), or that on the side opposite from the point of attachment (distal end). Excavations of small rootless stems ranging in age from 3 to 15 years revealed cases of either distal or proximal ends of the parent root rotted away. This suggests that translocation can take place in either direction along the parent root. There are also records of rotting along a parent root that had resulted in segregation of a large clone into several smaller clone groups (Gifford 1966).

If a forest manager wishes to base silvicultural decisions on an understanding of aspen root dynamics, several points are important. The first is that death of an aspen stem does not necessarily mean death of the underlying roots. For example, there are records of aspen stems that have died and rotted away from parent roots that remained alive, still serving the clonal group (Gifford 1966). It is also important to recognize that sometimes inconspicuous aspen suckers are the only indicators that a functional aspen root system exists in what is considered, silviculturally, to be a coniferous stand. A substantial root system may persist even when successional or other factors severely limit the aboveground standing crop of aspen. In the lower foothills of Alberta, the tenacity and longevity of the root systems of aspen clones were revealed by Horton (1956), who found aspen suckers in almost every stand regardless of age, density, or amount of conifers present. Even under very dense canopies of conifers there were weak, inconspicuous suckers, most of which probably would live only a few years. It is now known that aspen roots may persist in the absence of canopy aspen, nurtured only by transient suckers beneath the coniferous canopy (Schier et al. 1985). The aspen manager should not, however, rely on such root systems to produce a dense new crop of suckers immediately if the coniferous overstory is removed because poorly stocked aspen stands tend to produce few suckers.

The longevity of aspen root systems in the absence of aspen in the canopy has been known for a long time, but there is little or no experience with silvicultural manipulation of this reproductive resource. A recent review of suckering in *P. tremula* (Bärring 1988) referred to an old German textbook for professional foresters (Hartig 1851) in which it was noted that even if aspen trees have long since disappeared the roots may survive in closed stands by scarcely noticeable suckers that emerge annually in the shade. Russian researchers (Turskij 1904; Petrov 1967), and others in Sweden (Tiren 1949), have reported the same phenomenon in *P. tremula*, as have Marr (1961) and Peet (1981) in the western United States aspen.

The detailed documentation of this phenomenon in European aspen by Bärring (1988) revealed that, in shade, aspen roots are capable of producing only small, weak, and short-lived suckers. Few suckers survived more than 2 years, but replacements regularly emerged.

This continuous process is enough to maintain the root system for a very long time. Bärring cautioned that small suckers that develop in shade are easily overlooked because they have a different leaf shape than normal, often resembling the leaves of sterile wintergreen (*Pyrola secunda* L.).

It is not well understood where aspen suckers are most likely to develop relative to the underlying root system. For example, cuttings from an aspen root do not show a significant change in suckering capacity with increasing distance from the stem, which indicates that distance from the parent tree or root age are not factors that regulate suckering within lateral roots (Schier 1981a, b). There are, however, indications that the regeneration strategy, at least in deteriorating aspen clones in Utah, is to expand the parental root system rather than to form new roots.

Most aspen suckers arise from lateral roots less than 2 cm in diameter or on points along a lateral root where it has tapered to less than 2 cm. This establishes a large number of suckers on relatively young roots, and suggests that suckers would be more likely to be concentrated near the outer parts of parental root systems. Furthermore, expansion of the clonal root system is encouraged by the manner in which a sucker is attached to the parental root. The base of the sucker is bowed toward the root tips. Thus, the vascular tissue is oriented so that photosynthates and growth regulators from the sucker are translocated toward these growing tips (Schier 1982).

In contrast to the suggestion that sucker formation is favored near the outer parts of a root system, Schier (1975) noted that suckers tend to occur in the vicinity of residual stems where root density is high. Excavations described by Schier revealed that living surface roots did not extend far into the open spaces between parent stems but this observation, too, was in a deteriorating aspen clone, which may not be representative of vigorous aspen stands in boreal forest types of the prairie provinces and northeastern British Columbia.

Root Development of Aspen and Balsam Poplar Seedlings

Little information is available on initial development of roots on *Populus* seedlings. The primary root, when only a few days old, is very sensitive to high temperatures and to drought (Maini 1960). During the first year, the primary root tends to extend vertically into the soil. Subsequently, adventitious roots develop near the root collar and extend laterally (Maini 1968). Jones and DeByle (1985b) noted that aspen seedlings during their first year have fibrous, branching, lateral root systems with few taproots. In moist, sandy soil, Day (1944) found at the end of the first year that lateral roots were about 40 cm long and taproots about 15 cm deep. In the second year, lateral roots had grown to 1.8 m and suckers appeared on them. Day found an 18-year-old tree, presumably of seedling origin, that was 7.6 m tall with a main lateral root 14 m long and with branch "sinker" roots to a depth of 2.3 m.

The Clonal Structure of Aspen and Balsam Poplar Stands

Although aspen and balsam poplar do regenerate from seeds, stands of clonal origin predominate. An example of six adjacent clones, ranging in size from 35 to 1002 stems per clone in a study site near Smith, Alberta, is reproduced in Figure 12, based on unpublished Forestry Canada data assembled by A.K. Hellum. Figure 13 portrays adjacent small clones, as shown by differences in autumn leaf colors, in the Kananaskis River valley, Alberta. There is abundant literature on aspen's clone-to-clone variation in features such as leaf size and shape (Fig. 14); times of leaf flushing and leaf fall (Barnes 1969); stem form (van Buijtenen et al. 1959); growth rate (Zahner and Crawford 1965); fiber length (Einspahr and Benson 1967); percentage decay, volume of decay, gross volume, and net volume (Wall 1969, 1971; Kemperman et al. 1978; Hiratsuka and Loman 1984); mean annual shoot growth and mean size of parent roots that give rise to suckers (Schier 1982); and levels of carbohydrate reserves in aspen roots (Tew 1970a, b; Schier and Johnston 1971). Time of leaf flushing in a given clone can be as much as 3 weeks earlier than in adjacent clones on the same site. Clones that flush earliest are not necessarily the first to change color in autumn (Morgan 1969; Greene 1971).

In Manitoba, Wall et al. (1971) noted that some clones became chlorotic on nutrient-deficient sites whereas others did not. Other authors have documented clone-to-clone variations in morphology, tree quality, and physiological responses (Garrett and Zahner 1964; Horton and Maini 1964; Barnes 1966, 1969, 1975; Steneker and Wall 1970; Schier 1973a, b; Copony and Barnes 1974; Jones and Trujillo 1975; Kemperman 1977; Lehn 1979; Lehn and Higginbotham 1982; Heidt 1983). Genetic studies involving electrophoretic analysis of isoenzymes offer the most precise techniques for clonal differentiation (Cheliak 1980; Cheliak and Dancik 1982; Cheliak and Pitel 1983).

Features singled out by Steneker and Wall (1970) for aspen clone recognition in the prairie provinces included: time of flowering; times of leaf flushing, and times that leaves fall; leaf shape; bark color and bark texture; and tree form. Generally, the ideal times to identify clones are

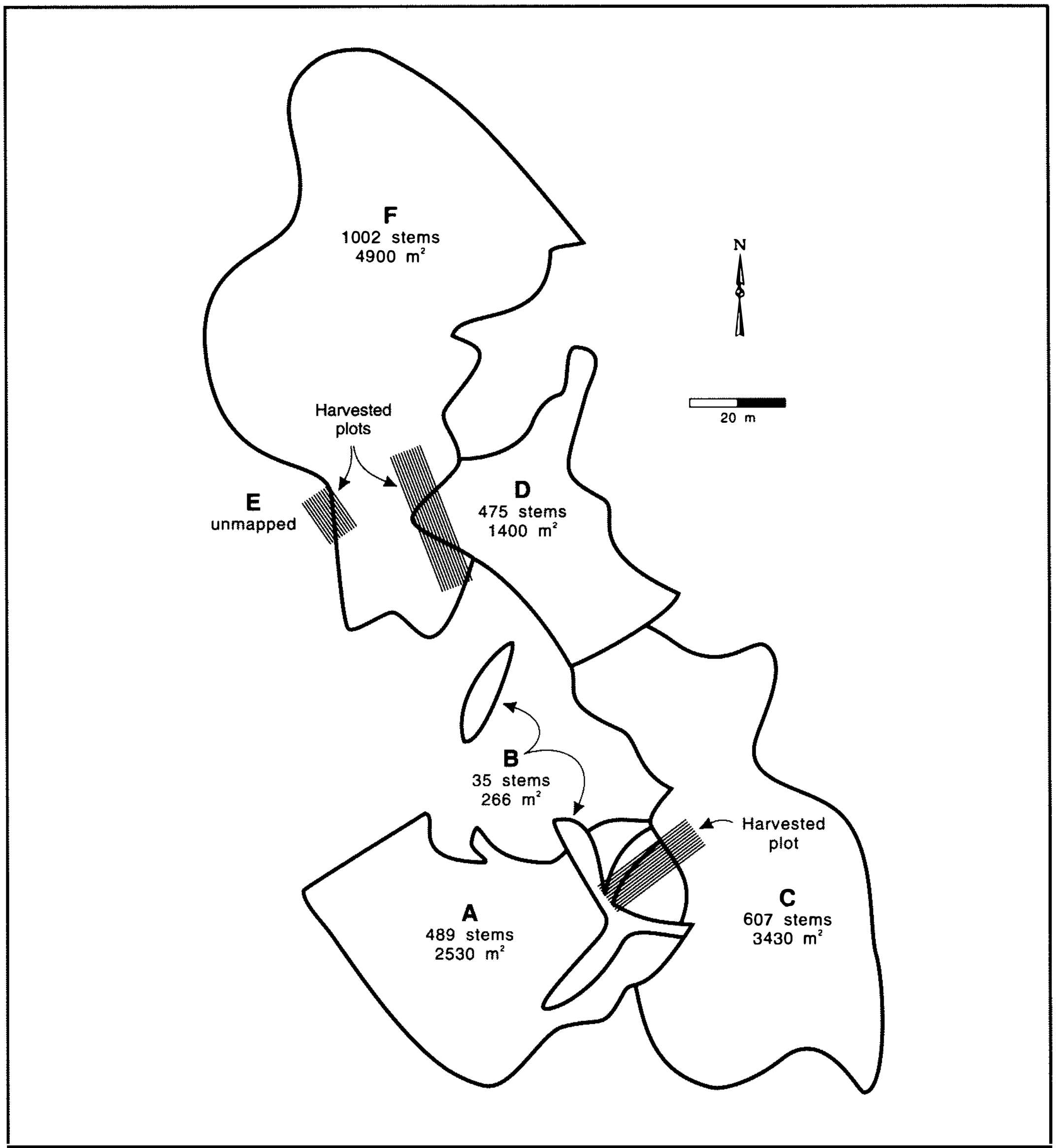

Figure 12. Example of clone distribution, ranging from 35 to 1002 stems per clone, in a study area near Smith, Alberta.

the period of leafing out in late spring and the period of color change and leaf fall in early autumn (Fig. 13). Many clones that look much alike in midsummer contrast sharply in early autumn or late spring (Jones and DeByle 1985a). For the field forester, the morphological features most helpful for differentiating aspen clones have been defined by Barnes (1966), Steneker and Wall (1970), Kemperman (1977), Horton (1984) and Jones and DeByle (1985a). Table 5 lists criteria, in decreasing order of usefulness, for distinguishing aspen clones in different seasons, based on information from Barnes (1969) and Jones and DeByle (1985a).

Despite the well-documented clonal distribution of aspen, there is not yet a widespread understanding of how to incorporate clonal variation into silvicultural operations. There has been little opportunity to date for boreal mixedwood forest managers to consider clone-to-clone differences within aspen stands. For example, it is known that the degree of overstory disturbance necessary to stimulate suckering is not the same in each clone (Shepperd 1986). The challenge for the field forester is how to recognize different clones in a stand and how to vary treatments at a scale that matches clone distribution within a stand. The ability to differentiate aspen clones

Figure 13. Closed stands are commonly made up of many adjacent small clones, as shown by differences in autumn leaf colors, Kananaskis River valley, Alberta.

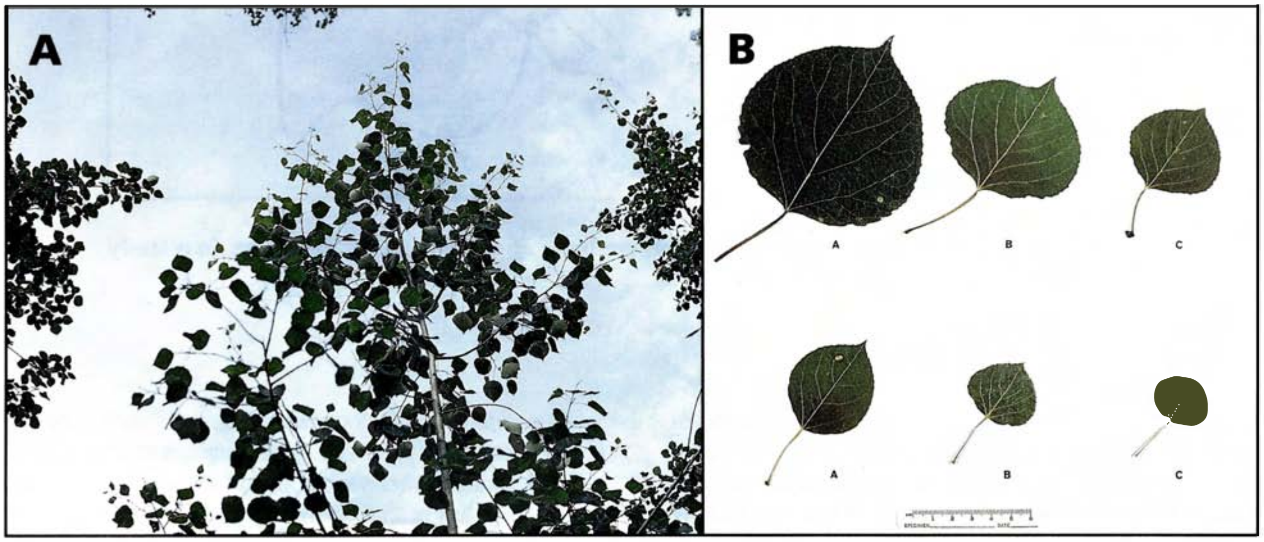

Figure 14. In summer, adjacent clones can often be distinguished by shape and sizes of leaves. A. Large-leaved clone in center, flanked by two small-leaved aspen, near Lesser Slave Lake, Alberta. **B.** Comparative sizes of large, medium, and small leaves from two clones shown in photograph A. Scale at bottom is 15.2 cm (6 inches).

Table 5. Criteria for distinguishing clones, by season and in order of usefulness. Adapted from Barnes (1969) and Jones and DeByle 1985c.

All seasons

Bark
1. Texture
2. Color

Stem characteristics
3. Form
4. Branching habit (angle, length, and internode length)

Susceptibility to injury and disease
5. Sunscald
6. Frost crack
7. Insect and disease injury

Miscellaneous
8. Self-pruning
9. Galls

Spring
1. Sex
2. Time of flowering, and flower characteristics
3. Time, color, and rate of leaf flushing

Summer
1. Leaf shape (width/length ratio), color, and size
2. Shape of leaf blade base
3. Leaf margin; number, size, and shape of teeth
4. Shape of leaf tip
5. Leaf rust infection

Autumn
1. Leaf color
2. Time and rate of leaf fall

is of practical importance because superior clones can be several times more productive than inferior ones. There are also marked clonal differences in suckering ability and disease resistance.

Significance of Clones for Silvicultural Decisions

Although Navratil (1987) expressed reservations about the concept of silvicultural manipulation of clones to encourage those that possess superior qualities, aspen management will in the forseeable future need to be based on an understanding of clonal silviculture. One reason for this prediction is the widespread occurrence of aspen stands that have regenerated from root suckers. Furthermore, even if aspen trees of seedling origin are more common in the boreal and mixedwood zones than previously thought, there is reason to expect that each surviving seedling-origin stem will eventually develop into a clone of stems interconnected by a common root system.

If a forester does wish to carry out silviculture based on the clonal nature of aspen stands, it is important to note that clones in the northern mixedwood region are generally very small, normally a fraction of one hectare. Steneker (1973) observed an estimated 1000 clones per hectare in a study site in Manitoba. At the other extreme, outside of the northern mixedwood region, individual clones of up to 40 ha have been recorded in the United States (Kemperman and Barnes 1976). As outlined in the following text, aspen management on an individual clone basis is likely to find its first silvicultural application in the context of decay management (Hiratsuka and Loman 1984). There is evidence that each aspen clone has a unique pattern with respect to rot columns within the stem (Wall 1971). Adjacent or intermingled clones on the same site have been noted to differ markedly in percentage decay. Wall also noted that one clone that occupied two distinguishable sites did not differ significantly in percent decay on the two sites that it occupied. Researchers in Alberta suggested that for expression of decay the genetic origin of aspen is more important than site quality (Hiratsuka and Loman 1984). These authors also noted that all species that regenerate vegetatively grow rapidly, but such species also tend to have short pathological rotation ages.

Recognition and encouragement of clones that have superior growth rates or preferred wood properties, which may involve triploid clones (Einspahr et al. 1963), will likely be a later development than clone differentiation for purposes of decay prediction. Although not confirmed for the boreal portions of aspen's geographic range, there is evidence from the Rocky Mountain states that bark color is an indicator of a clone's growth rate and productivity. Shepperd (1981, 1987) noted that green-barked stands had higher average site indexes and higher mean annual increments than yellow-barked stands; yellowish bark color may be indicative of stress.

Importance of Clone Recognition during Sampling

Twenty-five years have passed since Zahner and Crawford (1965) lamented that site productivity studies, insect and disease studies, and silvicultural practices ignored the clonal structure of aspen stands. This criticism was based on the observation that sampling methods conventionally applied to even-aged forest stands composed of genetically diverse species were also applied to aspen stands. To a large extent, the same holds true today. Why is this a problem? Zahner and Crawford described the dilemma as follows. A common mensurational approach is to sample several dominant or codominant trees on a small sample plot as a measure of site productivity. In a stand of seedling origin, these measured individuals represent different individual genotypes. In contrast, in aspen stands of sucker origin areas of 1 ha or more may be occupied by one clone, which is a single genotype. A sample of several dominant or codominant aspen stems, therefore, may be simply several measurements of one genetic individual. Furthermore, in a stand of seedling origin the genetically slower growing individuals are suppressed by the dominant individuals. In contrast, in aspen stands, especially those characterized by separate clones that do not overlap, the slower growing or less competitive genotypes are not eliminated; successful stems of the poorest genotypes still emerge as dominants within their particular clone, sometimes over relatively large areas (Zahner and Crawford 1965).

The only way to sample the species population of an aspen-dominated area is to ensure that separate measurements are made in several genetically different clones. Failure to do so is equivalent to sampling the productivity of a seedling-origin stand of white spruce by measuring one tree, and not necessarily a dominant tree.

Male and Female Clone Differences

Relative to male clones, female aspen clones tend to have larger numbers of stems per clone and greater basal area. Female clones also reveal a larger increase in areal spread over a 25-year growth period, and have a different size-class distribution than male clones. Such data do not support the hypothesis that greater female investment in sexual reproduction associated with fruit production is at the expense of vegetative growth. As a result of these observations, it is evident that measures of clonal growth as well as individual stem growth are necessary to clarify the relationship of sexual reproduction and vegetative growth in long-lived clonal plants such as aspen (Sakai and Burris 1985).

Further data are necessary to explain why female aspens should exhibit greater clonal growth than males. One untested hypothesis is that stored and current photosynthate may be utilized differently by male and female aspen trees in reproduction. There could also be indirect selection for larger clones in females, with more small stems that bear flowers, as opposed to male clones where selection might favor fewer, but taller, stems to increase effectiveness of pollen dispersal (Sakai and Burris 1985).

Natural Occurrence of Triploid Clones

Chromosome numbers reported in aspen are mainly diploid *($2n = 38$)*, but a few naturally occurring triploids were recorded by van Buijtenen et al. (1957), one from Minnesota, two from Michigan, and one from Colorado. Every and Wiens (1971) studied 18 aspen populations in the Wasatch Mountains, Utah, and confirmed that three were triploid and one was tetraploid. Chromosome numbers were determined primarily from meiotic materials from pollen mother cells, although it is also possible to obtain mitotic chromosome counts from young leaves just emerging from the bud.

Morphological differences between polyploid and diploid trees are often subtle. It was reported by van Buijtenen et al. (1957) that triploid aspen are generally larger than comparable diploids, especially the leaves. No such distinction could be made by Every and Wiens (1971) in Utah because of the extreme leaf variation in adjoining diploid aspen clones, in which leaves of some clones were twice the size of leaves in other clones. The giant *P. tremula* described by Müntzing (1936) was a triploid. The largest recorded aspen in Wisconsin was also a triploid (Einspahr et al. 1963), and the same is true for Riding Mountain National Park in Manitoba (W. Jim Ball, pers. com., February 1988).

Aspen and Balsam Poplar Reproduction

The possession of both sexual (seedling) and asexual (sucker) methods of reproduction gives aspen and balsam poplar an advantage over their companion boreal conifers. Seedling and sucker reproduction are described in the following sections as though they are phenomena that occur at different places, different times, or under different circumstances. In reality many aspen stands are probably a result of concurrent development of seedling-origin and sucker-origin stems. Most of the literature focuses on sucker reproduction but recent research in the prairie provinces reveals the importance of seedling reproduction of aspen in that region. It is known from recent Alberta Forest Service and Forestry Canada surveys in Alberta that there can be significant ingress of aspen seedlings and suckers into areas of previous softwood stands. This tends to shift such areas to mixedwood cover types. Although research on this phenomenon is underway, more information is needed about development, competition, and variability of such mixedwood stands.

Reproduction by Seedlings

Differences in root morphology can be used to distinguish aspen of seedling and sucker origin (Fig. 15). Natural seedlings of aspen were reported in the early literature (Moss 1938), and in some regions and sites, stands of seedling origin may be more abundant than previously thought (McDonough 1979). Certainly aspen is a prolific seed producer. Aspen can flower as early as 10 years of age, although 15 years is more common (Maini 1968). This species produces good seed crops every 4 or 5 years after age 10–20 (Perala and Russell 1983). The seeds are light, averaging 6.6 million/kg. They are buoyed by long silky hairs and may be carried by wind for several kilometres. A single tree may produce a million or more seeds, and germinative capacity at seedfall usually exceeds 95% (Schopmeyer 1974). Seedbed and microenvironment requirements for seedling establishment, however, are stringent. Aspen's tiny seeds lack endosperm, so seedling establishment requires that they come into immediate contact with moist soil to absorb water and nutrients; even a few hours of drought can cause seedlings to wilt. Ironically, aspen seedlings are easily washed away by heavy rain (Borset 1960). Aspen seedling establishment is most likely to occur on moist or wet sites (Maini 1968). Mineral soil seedbeds are best but they must be continually moist during the short period of seed viability and during early root growth. It appears that extended periods of adequate surface moisture, low evapotranspiration, and lack of competition from other plant species are important prerequisites for aspen seedling establishment.

To date, few aspen seedlings have been planted in the prairie provinces; one recorded example is the inclusion of aspen seedlings in the Manitoba poplar clone trials described by Steneker (1976a). These seedlings were planted between 1965 and 1969, and when assessed in 1973 they were particularly free of stem and branch defects.

Most of the aspen literature emphasizes that conditions for natural seedling establishment are so critical that stands of seedling origin are relatively infrequent. Such stands, however, have been documented on various surfaces: drained sedimentary peat in Minnesota (Nielsen and Moyle 1941); ashes of burned-out peat, following drainage in Wisconsin (Strothmann and Zasada 1962);

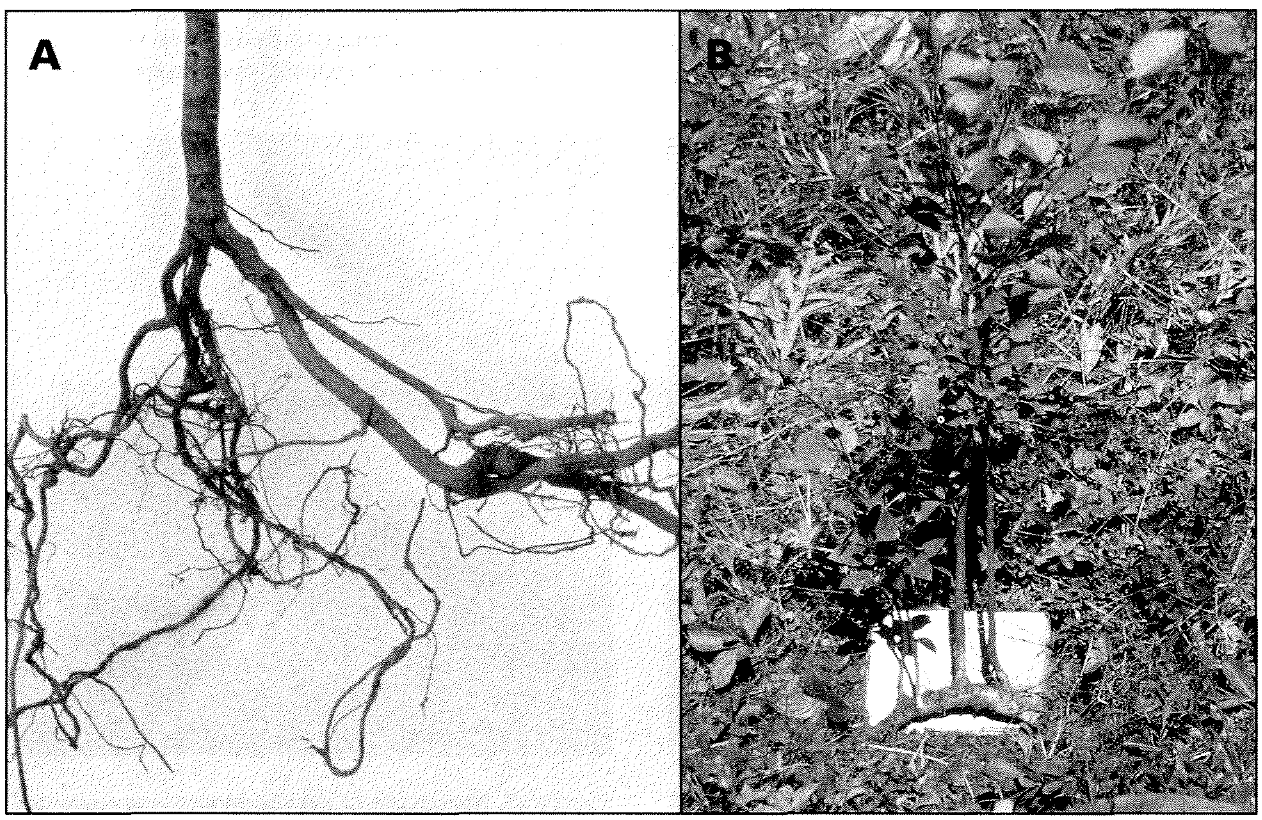

Figure 15. Differences in root morphology in young aspen of seedling (A) and sucker (B) origin (photos courtesy of S. Navratil).

volcanic cinder cones in Idaho (Eggler 1941); landslides in New England (Flaccus 1959); nursery beds intended for other species (Graham et al. 1963); mine tailings (Williams and Johnston 1984); in small, moist mossy depressions of Precambrian rocks (J. Stan Rowe, pers. com., June 1990); and in a variety of harvested or burned-over lands that were formerly occupied by other forest types in the Lake States (Kittredge and Gevorkiantz 1929). The best chance for aspen seed germination and survival is on an alluvial or humus seedbed with moderate temperatures, a reliable and continuous moisture supply during seed germination, good drainage, and little competition from other vegetation (Steneker 1976b). Zasada et al. (1977) were of the opinion that seed regeneration of aspen is potentially more important in northerly parts of its range, as in Alaska, because the relatively cold soil conditions are not conducive to suckering. There is not much experience with planting of aspen and balsam poplar, although Zasada et al. (1983, 1987) provide some information on survival and growth of planted seedlings of these species in experimentally burned upland black spruce sites in Alaska.

Recent research by the Northern Forestry Centre has revealed an abundance of aspen seedlings in the Edson, Whitecourt, Rocky/Clearwater, and Grande Prairie forests in Alberta. Seedlings have been most commonly observed on lodgepole pine cutovers on mesic and subhygric sites. The latter observation is particularly important because it is known that aspen seeds will germinate over a broad range of temperatures but have a stringent requirement for mineral soil that is moist at the correct time. Observations to date indicate highly variable densities of aspen seedlings, commonly ranging from 1000 to 16 000 seedlings per hectare. This variability results in a wide range of seedling–sucker mixtures and, where this occurs, aspen of seedling origin can become an important component of future stands. Site preparation increases aspen seedling establishment because even more soil is exposed than there is from harvesting alone. Soil exposure and site preparation encourage seedling establishment; aspen seedlings are typically established 1–5 years after soil exposure. Although height growth of aspen seedlings is slower than suckers, they are comparable to growth of lodgepole pine seedlings (Navratil, Bella, and Peterson 1990).

Vegetative Reproduction

Most aspen regeneration is by root suckers (Fig. 16), although stump sprouts and root collar sprouts (Fig. 17) occur if the harvested trees are relatively young (Heeney et al. 1980). The requirements for stimulation of aspen suckers are well known. For the forest manager, the two most important factors for stimulation of aspen suckers are disruption of apical dominance and increased soil temperature. As documented by Hambly (1985) there are, however, several controls over aspen suckering:

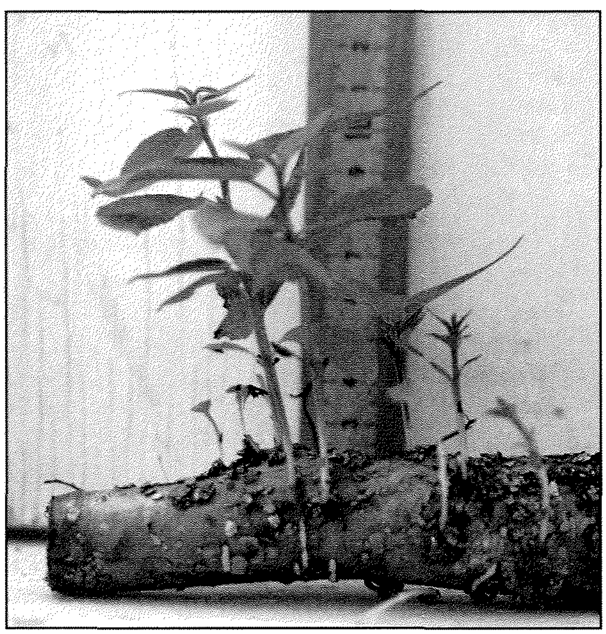

Figure 16. Aspen suckers developing on segments of lateral roots (photo courtesy of S. Navratil).

Figure 17. Sprouts from the stump and root collar are common when young aspen stands, under 25 years, are harvested. In older stands, root suckers predominate.

growth regulators, particularly auxins and cytokinins (Farmer 1962; Steneker 1972; Schier 1976); root carbohydrate reserves (Schier and Zasada 1973; Schier 1976); root size (Kemperman 1978); the inherent ability of each individual clone to sucker (Maini 1967); soil temperature (Horton and Maini 1964; Maini and Horton 1966; Gifford 1967; Perala 1974a; Steneker 1974a; Schier 1976); root depth (Horton and Maini 1964); and soil moisture levels (Maini and Horton 1964, 1966). The amount of suckering also depends on the degree of stand disturbance.

Stand age does not affect suckering ability, provided the stand is not breaking up because of decay (Steneker 1976b). Some overmature stands may have reduced suckering ability because the growth potential of aspen sucker stands is dependent on an intact parent root system (Schier 1973a; Perala 1978). Suckers that develop early in the growing season grow taller than those that develop later. Under favorable conditions, suckers may grow as much as 2.5 m the first year, but in the second and subsequent years leader growth is normally about 1.8 m. Suckers are initially sustained by the root system of the parent tree. Sandberg (1951) noted that suckers were able to incorporate into their permanent root system the entire terminal portion of the parent root system. A distinct thickening of the parent root usually occurs at the point of sucker origin, but only on the side away from the parent tree. This indicates that translocation of nutrients produced in the sucker is towards the growing tip of the parental root system; in other words, the sucker takes over the distal portion of the root system. Interestingly, Sandberg (1951) also recorded new root systems of 1-year-old aspen that extended for 4.7 m.

Most aspen suckers originate along horizontal lateral roots that have diameters between 0.5 and 2.5 cm. It is not clear if larger diameter roots are poor sucker producers or if they are simply less abundant than roots under 2.5-cm diameter (Perala 1978). These roots occur predominantly in the upper 60 cm of soil, and most suckering occurs where the roots are from 4 to 12 cm below the surface (Horton and Maini 1964). Most suckers are formed during the first growing season after a major disturbance such as fire or harvesting, although others do originate during the second or third growing seasons (Sandberg and Schneider 1953; Heeney et al. 1980). Suckering ability may be as much as 20 times greater in some aspen clones than in others (Farmer 1962; Boekhoven 1964; Garrett and Zahner 1964). The main control over suckering, however, is insolation-induced temperature increase. Maini and Horton (1964) concluded that the soil temperature increase that results from logging—rather than the actual cutting of aspen trees—is the most critical requirement for sucker stimulation. It cannot be assumed that sucker production is guaranteed on all sites after harvesting. For example, there are sites in Saskatchewan with heavy soils and thick duff that do not regenerate readily with aspen.

Human Influences on Aspen Vegetative Reproduction

The main factor that the forest manager can manipulate to regenerate harvested aspen stands is the degree of overstory and understory competition remaining. The other factors affecting sucker regeneration—aspen stocking, stand age, clonal variability, and site—are fixed for a given mature stand. To ensure that the next stand is well stocked with aspen, the basic requirement is to control competition from the remaining vegetation (Perala 1972).

Harvesting aspen during the dormant season generally results in maximum aspen suckering during the next growing season, but after 2 or 3 years the effect of the cutting season is negligible. As long as the present stand is healthy and well stocked, clear-cutting can be carried out at any time with reasonable assurance that a sucker stand will follow (Steneker 1976b). This provides considerable flexibility in harvest scheduling for aspen stands. Choice of the best season for harvest may, however, be based on other criteria. For example, winter logging produces more uniform and less dense regeneration, facilitates harvest, and prevents soil compaction on wetter soils with clay components. In contrast, summer logging may be more destructive to shrub cover than winter logging, thereby lessening competition for aspen suckers (Bella 1986). In the Lake States, subsequent survival and growth of suckers can be seriously reduced if there is residual shading because aspen requires full sunlight to develop (Perala 1972).

A complete clear-cut without burning is still the best way to regenerate aspen stands. If burning is used to reduce overstory shading or to increase soil temperatures, however, then the stands should be burned during the first dormant season following harvest, and preferably before substantial suckering takes place. This procedure would minimize growth loss caused by the reinitiation of suckering. Assuming there is good drying weather, aspen slash from summer harvesting can be ready to burn in the fall of that year or during the following spring (Perala 1974a).

Encouragement of Balsam Poplar Regeneration

It is well known that balsam poplar has more ways of regenerating than aspen does. Regeneration of balsam poplar following harvesting, however, is not as well documented as aspen. Some of the most detailed information is from work by Zasada et al. (1981) in the Susitna valley of Alaska, where regeneration after clear-cut logging with both chain saws and tractor-mounted shears was compared for summer, fall, and winter operations. Logging with shears in both summer and fall resulted in the most surface disturbance and the greatest rate of poplar regeneration. Regeneration was from seeds, stump sprouts, root suckers, and buried branches. Regeneration in summer- and winter-logged sites was primarily from root suckers, but logging in the fall resulted in regeneration from buried branches. More than 50% of the stumps produced sprouts the first and second years; but after 4 years only 15% of the stumps in the areas logged in summer still had live sprouts. Limiting clear-cutting to summer and encouraging disturbance of the surface was recommended by the Alaska researchers as the best way to ensure balsam poplar regeneration.

There are several management implications of the research results outlined above. First, in terms of methods available for regeneration, balsam poplar is more versatile than aspen. For balsam poplar, seed regeneration is best on mineral soil, and root sucker production benefits from removal of the forest floor. Broken branch segments must be buried during harvesting to produce new trees. Thus, the probability of regeneration by these means appears to be increased by surface disturbances. Increased surface disturbance could be accomplished by concentrating logging during snow-free periods or by postharvest site preparation. The fourth means of regeneration, stump sprouting, does not appear to result in tree for tree replacement. Dormant season harvesting is most desirable if maximum sprout production is desired (Zasada et al. 1981).

Tissue Culture for Propagation of High-value Aspen

Unlike poplars, aspens are not easily propagated from stem or shoot cuttings. There is, therefore, an interest in other ways to propagate aspen that have superior qualities for the pulp and paper industry. An example is Ta-10 (*P. tremula* L.), a tetraploid European aspen that has a superior growth rate, greater specific gravity and greater fiber length than aspen normally has. This hybrid originated in southern Sweden and was first crossed with *P. tremuloides* at the Institute of Paper Chemistry, Wisconsin, in 1958. Since then it has been crossed with many other aspens in the United States, and up to 1 million triploid hybrid seeds have been produced annually for the past 20 years. Although Ta-10 can be readily grafted onto diploid or triploid rootstock, vegetative propagation has been hampered first because hardwood cuttings do not root and second because only minimum root development occurred with this particular clone when root stimulation was attempted below the graft union. In these circumstances, tissue culture is a compelling alternative (Wann et al. 1988). Ostry et al. (1990) are also recent proponents of the role of tissue culture for aspen propagation.

The method reported by Wann and co-workers is based on production of multiple shoots from dormant buds collected in January and February. Apical meristems and several layers of intact leaf primordia were cultured on woody plant medium containing naphthaleneacetic acid (NAA) and benzyladenine. After 6–8 weeks bud break occurred and shoots formed and multiplied. After 4 months, stable shoot cultures could be obtained on the culture medium without NAA. These cultures provided a continuous source of shoots suitable for rooting. Root formation was accomplished *in vitro* or by transfer of shoots from tissue culture to a mist bed. Once established in soil, plants assumed growth rates and characteristics similar to plants from natural root sprouts. The recent work by Ahuja (1984a, b), Wann and Einspahr (1986), and Wann et al. (1988) indicates that, aside from grafting, tissue culture is an attractive method of vegetative propagation for difficult-to-root species such as aspen.

Stand Development and Mortality

Early development of stands of sucker origin is well understood for aspen because several biomass studies focused on young stands (Pollard 1971; Bella and De Franceschi 1980). Aspen stands of sucker origin may begin, in extreme cases, with several million suckers per hectare, but even where there are more modest densities, in the range of 20 000 suckers per hectare, there is a very rapid reduction in density in the first 5 years. A reduction of 80% in number of suckers per hectare is not uncommon from year 1 to year 5; in the prairie provinces, Northern Forestry Centre data revealed a 45% decrease in sucker density in just 1 year (from year 2 to year 3). These rapid changes emphasize the importance of making interpretations in relation to a specified time after logging (Navratil and Bella 1988).

Aside from aspen's characteristic rapid sucker growth and rapid natural thinning, this species is also typified by relatively quick definition of crown classes. Early crown closure results from a combination of leader growth and rapid extension of lateral shoots on suckers more than 1 year old. After the canopy closes, trees stratify into crown classes quickly, despite genetic uniformity within clones (Heeney et al. 1980). It is the lower crown classes that experience the greatest mortality. Typical stages in aspen stand development are portrayed in Figure 18.

Figure 18. Typical stages in aspen stand development. A) New suckers near the end of the 1968 growing season following the May 1968 burn near Lesser Slave Lake, Alberta. B) Suckers over 2 m tall on 1 August 1970 following the same 1968 burn. C) Typical stand approximately 18 years old with significant number of small dead standing stems in the stand, following a period of natural mortality around 15 years of age. D) Mature, 80-year-old stand, which has thinned itself naturally, near Lesser Slave Lake, Alberta.

Stem Density Changes during Early Stand Development

This literature review did not reveal any data on changes in stem density during the first few years of seedling-origin aspen stands. The several Michigan aspen stands reported by Graham et al. (1963) to be of seedling origin have not been described in the literature in terms of mortality and natural thinning during early stand development. Zackrisson (1985) estimated seedling mortality for *P. tremula* in southern Sweden, where a recently burned 1000-ha area was estimated to have 9 million aspen seedlings per hectare 1 year after the fire, out of which an estimated 90 trees per hectare were expected to remain by the time they were of seed-bearing age.

If all clones on an area were initially established at about the same time, then the number of clones per unit area would be an indicator of the number of seedlings that survived to serve as the original stem of each clone in that area. In a Manitoba study by Steneker (1973), the largest clone mapped was 1.54 ha, but clone sizes averaged only 0.08 ha in a 40-year-old aspen stand in Riding Mountain National Park and 0.006 ha in a 25- to 50-year-old stand in Agassiz Forest Reserve. The maximum number of clones recorded in a 0.04-ha plot was 40. This translates into 1000 clones per hectare, which, if the clones were all established at about the same time, would have required 1000 surviving seedlings per hectare. At least one investigator (Bertenshaw 1965) did conclude that clone size is influenced by the pattern of initial seedling establishment more than it is by site. If new seedlings are periodically introduced into clone-covered areas, however, then present clone size may be a poor index of the number of seedling-origin stems that originally occurred on any given hectare of land now dominated by distinctly recognizable clones.

For stands of sucker origin, the naturally decreasing stem density that occurs in the first few years of stand development is supported by abundant published data (Pollard 1971; Bella and De Franceschi 1980; Perala 1984; Bella 1986). Age density relationships from these and other references are summarized in Table 6 and graphically in Figure 19. In general, sucker density rapidly declines in new stands established after clearcutting. Typically, the least vigorous suckers die during the first 1 or 2 years, leaving one or two dominant suckers in each clump. Competition reduces most clumps to a single stem by the fifth year after cutting, and almost all to a single stem by the tenth year (Sandberg 1951; Turlo 1963).

Pollard (1971) documented the distribution of biomass by diameter classes as a young aspen stand in

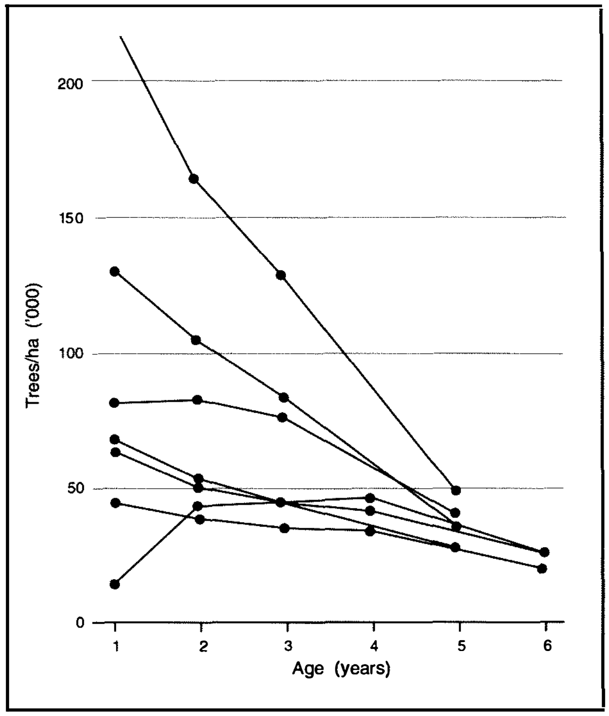

Figure 19. There is a rapid reduction in number of aspen stems per hectare as a result of natural mortality in the first few years of stand development (Steneker 1976b).

Ontario progressed through natural thinning from age 4 to age 7. In each of these 4 years, most of the biomass occurred in the upper and middle dbh classes. Biomass in the form of small shoots (low dbh classes) decreased with each successive year. Pollard concluded that the increase in biomass of the stand as a whole depended entirely on the development of the upper dbh classes. Annual reductions in stand density were largely a result of the mortality of stems under 1 cm dbh. The significance of this observation is that, in short rotation management, the proportion of very small stems (which could downgrade the quality of a final product) rapidly diminishes each year. For example, Pollard's data revealed that at 4 years, 16% of the biomass occurred in shoots under 2 cm dbh; at 7 years, shoots of this size formed only 4% of the biomass.

What are the maximum stem densities that might be encountered in young aspen stands? From sampling sites in Alberta and Saskatchewan, the highest density class recorded by Bella and De Franceschi (1980) showed the following progression of density with age: 280 000 stems/ha at age 2; 190 000 stems/ha at age 3; 125 000 stems/ha at age 4; and 80 000 stems/ha at age 5. In approximately the same sampling region, within the

Table 6. Number of aspen suckers per hectare in relation to age. (Various sources as summarized by Peterson, Kabzems, and Peterson 1989.)

Reference (location)	Age (years)										
	1	2	3	4	5	6	7	8	9	10	17
Crouch 1983 (Colorado)	76 758	74 198	55 285	36 176	24 513	20 707	17 816	–[a]	–	–	–
Crouch 1981 (Colorado)	–	–	–	–	–	18 021	13 135	10 959	7 455	6 417	–
Perala 1984 (Minnesota)	128 045	91 095	63 765	43 510	29 790	22 005	16 190	–	–	–	–
Weingartner 1980 (Ontario)	46 800	41 400	31 400	–	–	–	–	–	–	–	–
Pollard 1971 (Ontario)	–	–	–	31 000	29 000	26 000	22 000	–	–	–	–
Bella 1986 (Saskatchewan)	74 000	59 000	48 000	47 000	38 000	27 000	–	–	–	–	9 000
Steneker 1976b (prairie prov.)	225 000	162 000	130 000	85 000	50 000	–	–	–	–	–	–
Steneker 1976b (prairie prov.)	44 000	40 000	35 000	33 000	29 000	21 000	–	–	–	–	–
Bella and De Franceschi 1980 (highest density class, Alta./Sask.)	–	280 000	190 000	125 000	80 000	–	–	–	–	–	–
Bella and De Franceschi 1980 (lowest density class, Alta./Sask.)	–	160 000	110 000	75 000	50 000	–	–	–	–	–	–

[a] Data not available.

Mixedwood and Lower Foothills sections of the Boreal Forest Region from the Manitoba–Saskatchewan boundary to the Alberta–British Columbia boundary, Peterson et al. (1982) recorded aspen stands with sucker densities as high as 433 000 stems/ha at age 2, and 201 000 stems/ha at age 3 (Table 7). These latter examples, however, are from a study that deliberately searched for upper limits of standing crop and stand density in young stands.

There appears to be a wide range of acceptable early stand densities for sucker-origin aspen. One reason may be the tendency for stands to end up with a relatively similar density, in the range of 20 000 to 25 000 stems/ha by approximately age 6, whether sucker density the first year after harvesting is as low as 44 000 or as high as 225 000 stems/ha (Table 6).

Sucker production is influenced by stocking of the parent stand before cutting. Poorly stocked aspen stands produce few suckers after logging. In Michigan, Graham et al. (1963) found the following relationship between the basal area of parent stands and mean sucker production 1 year after clear-cutting; basal area less than 11.48 m^2/ha, 12 850 suckers/ha; 11.49–22.96 m^2/ha, 17 300 suckers/ha; and more than 22.96 m^2/ha, 24 450 suckers/ha.

Rapid Canopy Closure in Aspen Stands

Compared to conifers, canopy closure is achieved at a very young age in aspen stands. For example, a notable feature of the data reproduced in Table 7 is the rapid development of a foliage standing crop comparable to that in older stands. The foliage standing crop in excess of 7.5 t/ha at ages 12 and 14 is greater than that in some

Table 7. Height of tallest stem, stand density, foliage/wood ratio, aboveground standing crop, and foliage dry weight for Alberta and Saskatchewan aspen stands, listed by increasing stand age (adapted from Peterson et al. 1982)

Plot no.	Age (years)	Height of dominant stem (cm)	Stems/ha ('000)	% foliage[a]	% wood[a]	Fresh standing crop (kg/m^2)	Dry standing crop (kg/m^2)	Foliage dry weight (t/ha)
330	2	167	432.9	32.5	67.5	1.73	0.70	2.27
317	3	258	95.5	23.0	77.0	1.73	0.76	1.75
327	3	293	108.3	17.0	83.0	3.41	1.49	2.53
363	3	283	201.4	20.1	79.9	2.36	1.13	2.27
1	4	462	44.6	25.0	75.0	3.03	1.25	3.12
97	5	412	101.1	14.3	85.7	6.40	2.96	4.23
308	11	735	69.2	11.0	89.0	7.96	3.72	4.09
311	11	527	95.5	11.7	88.3	5.17	2.31	2.70
27	12	643	38.2	10.0	90.0	6.86	2.84	2.84
30	12	621	67.6	8.5	91.5	11.86	5.83	4.95
31	12	701	52.5	12.5	87.5	12.07	6.02	7.52
32	12	541	66.8	9.2	90.8	9.71	4.87	4.48
53	12	410	75.6	10.8	89.2	4.96	2.27	2.45
54	12	551	36.6	7.9	92.1	6.54	3.28	2.59
300	12	464	67.7	18.4	81.6	4.68	2.05	3.77
2	13	670	38.2	19.4	80.6	7.95	3.26	6.32
7	13	695	39.0	10.6	89.4	6.53	3.08	3.26
90	13	628	100.3	10.4	89.6	8.75	4.28	4.45
10	13	761	70.8	8.0	92.0	13.63	6.63	5.30
57	13	530	152.8	9.1	90.9	8.78	4.21	3.83
91	14	748	79.6	10.5	89.5	15.57	7.33	7.69
359	14	610	105.9	11.9	88.1	10.59	5.20	6.19
20	18	968	25.5	9.7	90.3	15.02	7.04	6.80
36	29	628	21.5	14.5	85.5	14.74	6.40	9.28

[a] Percentages based on fresh weight.

stands several years older, and is not much less than the foliage dry weight of 9.3 t/ha in a 29-year-old stand. There is other evidence from the literature that canopy closure and development of foliage standing crop comparable to that in mature stands can occur relatively early in aspen. Perala (1984) followed the first 7 years of development of aspen sucker stands on a good and an excellent site in Minnesota. He noted that, according to the 3/2 power law of self-thinning (Drew and Flewelling 1977), the good site was fully occupied at age 2 and the excellent site by age 3. Similarly, Pollard (1970, 1971) described an Ontario stand in which the canopy had apparently closed and was rapidly approaching maximum development at age 4. The sampled stand had a leaf area index of 2.4 in the fifth year, almost as much foliage per unit area of soil surface as in a 15-year-old stand where leaf area index was 2.9. In fact, a mature 52-year-old stand at the Petawawa study site, with a leaf area index of only 1.6, supported less foliage per unit area than did the 5-year-old stand. The rapid development of the "photosynthetic factory" in young sucker stands is of importance to aspen silviculturists. It gives young aspen stands a major competitive advantage over any boreal conifers that may be present. Early development of essentially a full canopy is also necessary for short rotation aspen management.

Mortality Patterns in Young Aspen Stands

Aspen does not stagnate from overstocking as many conifer species do. There are periods of accelerated mortality that result in waves of natural thinning in young aspen stands. The first period of accelerated mortality commonly occurs at about age 5, according to observations on Lake States aspen (Graham et al. 1963). These authors attributed this first wave of thinning to the combined effects of insects and fungi, including leaf hoppers, aphids, leaf-spot diseases, oyster shell scale, scurfy scale, gall-forming *Saperda*, the root-girdling *Agrilus*, *Cytospora*, and *Hypoxylon*. The combination of these interacting organisms results in the death of many aspen suckers. Detailed studies at Petawawa, Ontario, revealed that the smallest stems are most likely to succumb (Pollard 1971), leaving the largest diameter suckers to take advantage of the more favorable conditions created by the process of natural thinning. Similar findings have been reported by Perala (1973) for Lake States aspen.

In the Lake States, the next period of accelerated attack by insects and fungi occurs when aspen are 12–15 years old. The same complement of insects and disease as in the 5-year mortality are present except that they occur higher on the tree in the branch-foliage system. At this stage, the trunk experiences attacks by various borers, initiating interactions between these insects, *Agrilus* beetles, *Hypoxylon*, and other cankers. Following the second period of thinning the stand grows rapidly until 21–25 years of age, when the last period of accelerated natural thinning occurs (Graham et al. 1963).

Aspen Stand Breakup

Aspen stand breakup is not yet well understood in the boreal region of the prairie provinces; most of the available information is from the Lake States (Graham et al. 1963) or from the western United States (Fralish 1972; Shepperd and Engelby 1983). The relative lack of stand breakup data from the prairie provinces is likely because it is not as common a feature as it is in more southerly parts of aspen's geographic range. Fralish (1972) suggested that natural stand breakup does not occur with the same frequency or at the same stand age throughout the geographic range of aspen. Although there is evidence that natural breakup varies with climatic conditions, it does tend to follow a definite pattern in each stand. With the slowing of growth at maturity, holes occur in the canopy, thereby subjecting the stand to increased exposure to wind, sunlight, and evaporation. Aspen appears to be intolerant to such sudden stresses, and the result is loss of vigor, and increased susceptibility to disease and insect attack, all of which increase the frequency of breakage and death of individual trees. The process of deterioration may take only 3–4 years. Deterioration in Rocky Mountain aspen stands (Shepperd and Engelby 1983) is marked by slow death of the overstory and concurrent root system deterioration. Such deteriorating clones generally display poor suckering in response to cutting.

When breakup does occur in aspen stands there is an increase in the rate at which coarse woody debris is added to the forest floor (Fig. 20). The simplest way to estimate accumulation rates for coarse woody debris is to determine tree mortality within permanently marked plots. This method by itself, however, underestimates input of coarse woody debris because large branches and broken tops of boles are missed. In North American coniferous and deciduous forest ecosystems, measured input rates for coarse woody debris range from 0.1 to 30.0 t ha^{-1} yr^{-1} (Harmon et al. 1986). Few data are available for aspen, but Gosz (1980) recorded that coarse woody debris contributed 0.45 t ha^{-1} yr^{-1} to the forest floor in a New Mexico aspen stand.

Productivity and Growth

To model aspen growth, several approaches have been described: Bella (1970, 1972); Grabowski (1981); Grabowski et al. (1981); Holdaway and Brand (1983); Gale and Grigal (1988, 1990); Burk et al. (1990); and Walters and Ek (1990). Among the researchers cited above, Bella developed a yield forecasting model that

Figure 20. Stand breakup is normally associated with overmature stands but other factors, in this case slow mortality after fire, can lead to breakup of younger stands (photo courtesy of A. Kabzems).

used periodic height and dbh increment to sum tree data for a unit area from early growth to harvest. The model was tested for simulation of aspen stand growth in natural, undisturbed stands of average or below average density and was calibrated with data from an above average site in Saskatchewan. Grabowski and coworkers incorporated a larger, more diverse aspen database than Bella's Saskatchewan data and modeled individual tree growth rather than stand growth. They also added a mortality function that was sensitive to stand conditions, but predictions were difficult because of the highly variable mortality rates exhibited by different aspen stands. Shields and Bockheim (1981) investigated stand dynamics in Ontario and the Lake States by comparing stand basal area at a given age to the maximum basal area, which is achieved at approximately age 55 years in all site classes in that region. Maximum basal area for the most productive site class was approximately 35 m^2/ha. Average and maximum values for several mensurational variables are shown for aspen in relation to other boreal tree species in Figure 21.

Several investigators have noted the difficulties of projecting growth in young stands. Heeney et al. (1980) observed that relationships between aspen growth and site characteristics are less evident in stands 40 years or younger than they are in older stands. There are, of course, examples of sites that are poor for aspen such as dry gravelly areas where site influences show up early. In general, for young stands it is important to identify ecological and other criteria that could assist the traditional mensurational approaches for growth projections on sites of varying quality. Although even-aged stands, with all stems having originated within a 2- to 4-year period, predominate in aspen, two-storied stands of two ages (Fig. 22), one-storied stands of two ages, and all-aged stands are also known to occur (Jones and DeByle 1985b). There is commonly a wide range of diameters in even-aged stands because of variations in site quality and competition by surrounding trees; this makes it difficult to obtain correlations between tree age and diameter (Hiratsuka and Loman 1984).

Growth in clonal plants may occur through both annual ring width growth and addition of new suckers. An increasing number of stems in a clone has been noted to be associated with decreasing ring width growth in male aspen clones, but in female clones there was no significant relationship between these two variables (Sakai and Burris 1985). Male and female aspen clones are similar to each other in most aspects of vegetative growth but there are indications of a greater growth rate in female clones. For growth modeling it is important to note that comparisons of growth between stems of two different clones is difficult because growth can occur by addition of new suckers as well as by increasing the size of existing stems. An indication that an increase in the number of stems has a slight negative effect on ring-width growth of existing members of the clone suggests that a trade-off may be occurring between growth of existing stems and addition of new ones. Thus, measures such as number of stems in each clone may be necessary

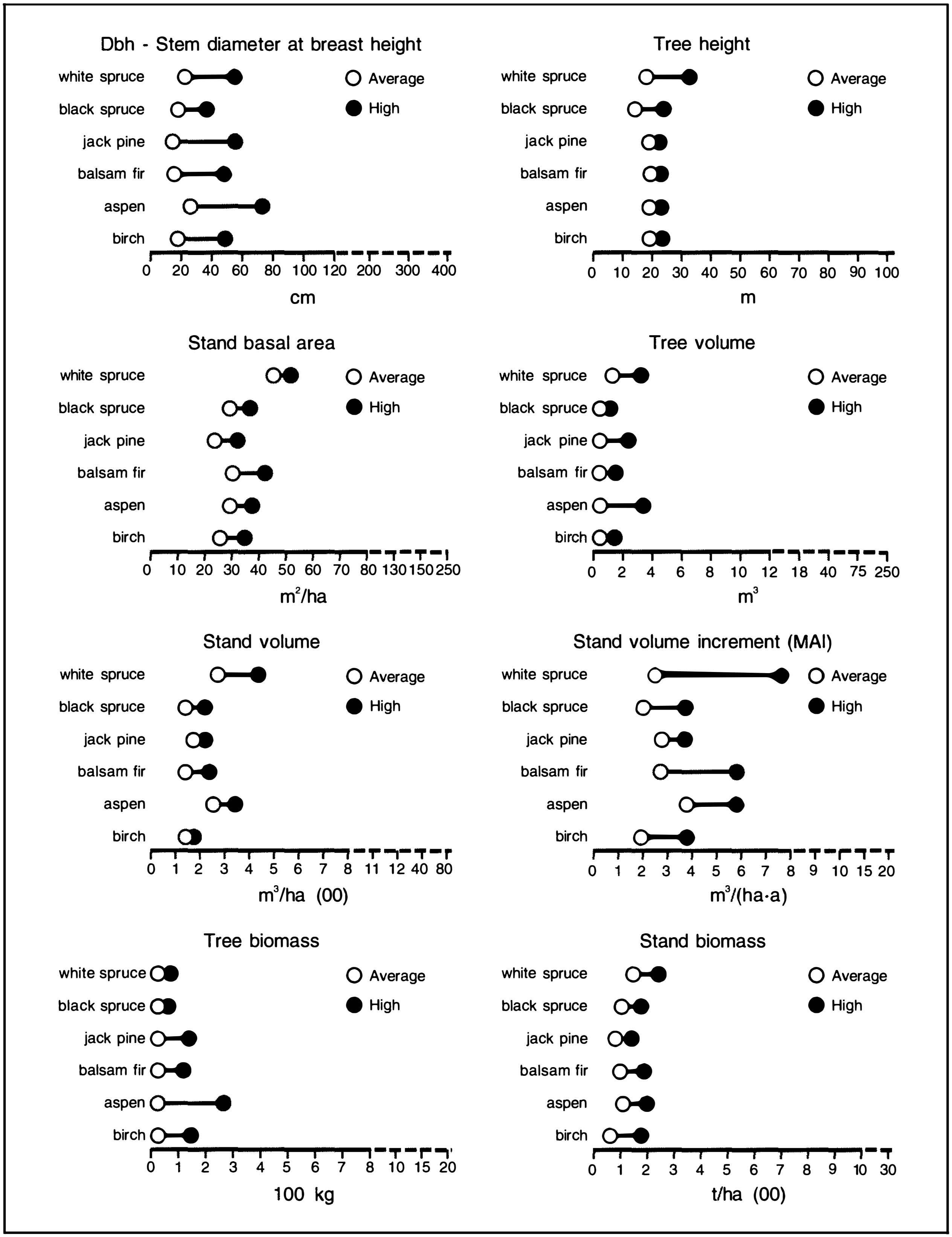

Figure 21. Average and maximum values for size, volume, and biomass of aspen in relation to other boreal tree species (adapted from Bonnor and Nietmann 1987).

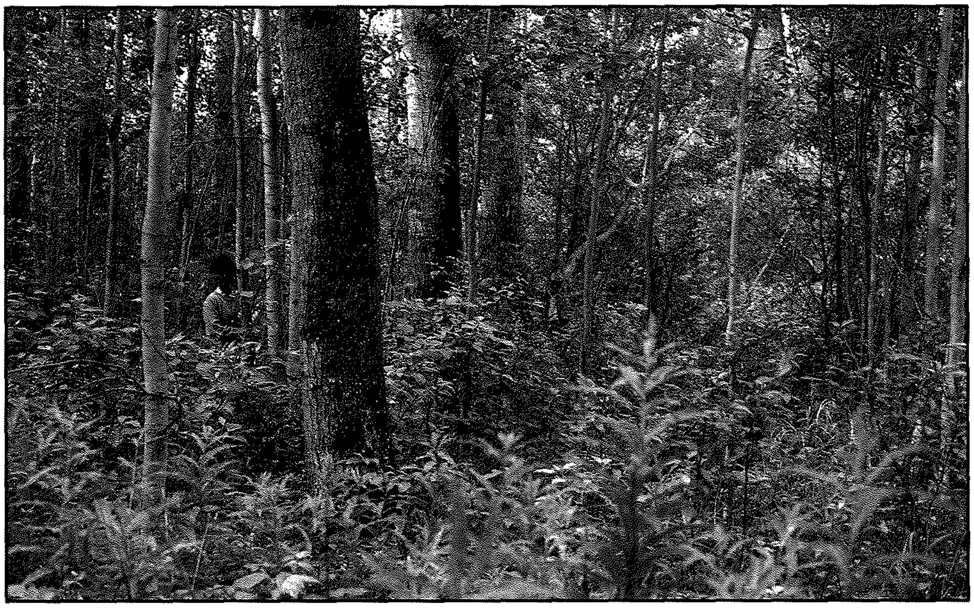

Figure 22. Aspen commonly occurs in even-aged, single-storied stands but two-storied stands can also be found as illustrated by this stand near Lesser Slave Lake, Alberta, which had an 18-year-old understory of aspen beneath an overstory that was over 120 years old.

to gain a more complete picture of the vegetative growth of clonal species such as aspen.

Gross Volumes of Aspen and Balsam Poplar Stands

Most of the growth and yield data in the following subsections are expressed on a weight (biomass) basis because of the predominant use of aspen raw material for pulp and fiber products. For the forest manager who may be interested in conventional merchantable volume estimates, however, a sample yield table is reproduced in Table 8 by metric conversion of data computed for Saskatchewan aspen by Kirby et al. (1957). Gross volume of Saskatchewan aspen stands at 100 years of age and with average stocking and density (empirical yield) ranged from about 220 m^3/ha on poor sites to about 365 m^3/ha on good sites. Merchantable volumes at age 100 involving only trees over 15 cm dbh, ranged from about 180 m^3/ha on poor sites to about 305 m^3/ha on good sites.

Information summarized by Heeney et al. (1980), based largely on data from Plonski (1956, 1974), indicated that culmination of mean annual increment (gross merchantable volume) occurred at 55 years for Ontario aspen in the best sites, 60 years in medium sites, and at 65 years in poor sites. At a rotation age of 60 years, the best aspen sites in Ontario produced 330 m^3/ha and medium aspen sites, at a rotation age of 65 years, produced 280 m^3/ha. In Ontario, the gross merchantable volume of aspen compares well with its associated species, as shown by the following information assembled by Hambly (1985), from data by Plonski (1974).

Species	Age at rotation	Gross merchantable volume (m^3/ha) at rotation
Aspen	55	300
Jack pine	45	180
Spruce	105	250
White birch	60	170
Shade-tolerant hardwoods	90	220
White pine	65	350
Red pine	45	260

The mensurational literature for aspen contains a relatively wide range of variation in estimates of age at which mean annual increment culminates. Some of these differences depend upon whether the estimates are dealing with stem wood only or with total aboveground fiber production. For example, Hambly (1985) pointed out that calculation of rotation age based on biomass productivity shortens the rotation by 10 to 15 years compared to calculations on a volume basis. Perala (1973) developed a prediction model from young stand data that showed a culmination of biomass mean annual increment

Table 8. Empirical yield per hectare for aspen in Saskatchewan (Kirby et al. 1957)

Age (years)	Height (m)	Dbh (cm)	No. trees/ha	Basal area (m^2/ha)	Total vol. (m^3/ha)	Merch. vol. (m^3/ha)[a]
			Good site			
20	10.2	5.6	5527	13.4	66.3	–[b]
30	13.8	7.6	5174	20.8	132.0	18.6
40	16.8	10.2	3116	25.1	189.5	64.0
50	19.3	13.2	1912	28.0	237.1	146.3
60	21.9	16.8	1329	30.2	275.3	211.1
70	24.1	19.8	998	31.8	304.6	247.4
80	26.0	23.4	758	32.9	329.0	272.1
90	27.6	26.4	603	33.8	346.8	289.7
100	28.7	28.7	519	34.5	364.8	304.3
			Average site			
20	8.1	4.8	6639	12.2	45.9	–
30	11.2	6.6	6215	19.0	101.6	7.1
40	13.9	8.9	3743	22.9	150.8	35.7
50	16.3	11.7	2296	25.6	192.0	89.5
60	18.6	14.7	1596	27.5	223.7	157.7
70	20.7	17.5	1198	28.9	247.7	194.0
80	22.4	20.6	912	29.9	266.0	217.3
90	23.7	23.1	724	30.8	279.7	231.1
100	24.6	25.1	623	31.4	290.6	241.2
			Poor site			
20	5.9	4.3	7415	10.6	26.8	–
30	8.7	5.8	6966	16.4	73.0	2.2
40	11.1	7.9	4196	19.7	114.6	18.3
50	13.3	10.2	2572	22.1	149.7	50.3
60	15.3	12.9	1789	23.8	175.4	103.4
70	17.2	15.2	1342	25.0	194.2	140.4
80	18.7	18.0	1020	25.8	206.8	164.0
90	19.8	20.3	810	26.6	215.5	175.9
100	20.4	22.1	699	27.1	221.3	182.6

[a] Trees 15 cm dbh and over.

[b] Not applicable.

(MAI) at approximately 26 years for Lake States aspen on good sites. Biomass yield tables for aspen stands to 44 years of age in Alberta and Saskatchewan showed culmination of MAI at 25–30 years (Bella and De Franceschi 1980). Maximum biomass MAI and current annual increment (CAI) for Ontario boreal forest aspen was calculated to occur between 45 and 60 years (Horton 1981). A sample biomass yield table prepared by Horton for productivity class 1 in the boreal forest region of Ontario is reproduced in Table 9.

Data from Johnstone (1977), as summarized by Day and Bell (1988), reveal the relationships between volume over age for mixed spruce–aspen stands in relation to pure spruce and pure aspen (Fig. 23). Generalized site index curves for aspen in the prairie provinces are presented in Figure 24, based on data from Steneker (1976b). For more northerly parts of the boreal region, taper equations and tables for total and merchantable aspen volumes were recently prepared from southern Yukon data by Bonnor and Boudewyn (1990).

Mean Annual Increment Data

Mean annual increments of aspen stands generally range between 2 and 4 t ha^{-1} yr^{-1}, dry weight, but there

Table 9. **Sample biomass yield table for aspen on productivity class 1 in the boreal forest region of Ontario** (Horton 1981)

Age (years)	Height (m) Mean	Height (m) Dominant	Mean dbh (cm)	Number trees/ha	Basal area (m^2/ha)	Ovendry mass (t/ha) Whole tree	Ovendry mass (t/ha) Stemwood	MAI[a] (t/ha) whole tree	CAI (t/ha)[b] whole tree
10	5.8	9.9	3.7	11 618	12.4	19	14	1.8	–[c]
15	8.5	12.4	5.8	6 717	17.6	39	28	2.6	4.0
20	11.1	14.7	8.0	4 404	22.2	64	46	3.2	5.0
25	13.6	17.0	10.3	3 122	26.2	92	67	3.7	5.7
30	15.8	19.2	12.6	2 370	29.6	121	88	4.0	5.8
35	18.0	21.2	14.9	1 859	32.5	150	110	4.3	6.0
40	20.1	23.1	17.4	1 485	35.1	182	133	4.6	6.3
45	21.9	24.7	19.5	1 245	37.1	210	153	4.7	5.5
50	23.5	26.1	21.6	1 061	38.9	236	172	4.7	5.2
55	25.1	27.4	23.6	922	40.3	261	190	4.7	5.0
60	26.2	28.5	25.2	828	41.4	280	204	4.7	3.9
65	27.2	29.4	26.5	762	42.1	295	215	4.5	3.1
70	28.0	30.2	27.7	710	42.8	309	225	4.4	2.8
75	28.7	30.8	28.7	668	43.3	321	234	4.3	2.3
80	29.3	31.3	29.6	635	43.7	330	240	4.1	1.9
85	29.8	31.7	30.3	610	44.0	338	246	4.0	1.6
90	30.2	32.1	30.8	592	44.2	344	250	3.8	1.1

[a] MAI = mean annual increment.

[b] CAI = current annual increment.

[c] No data.

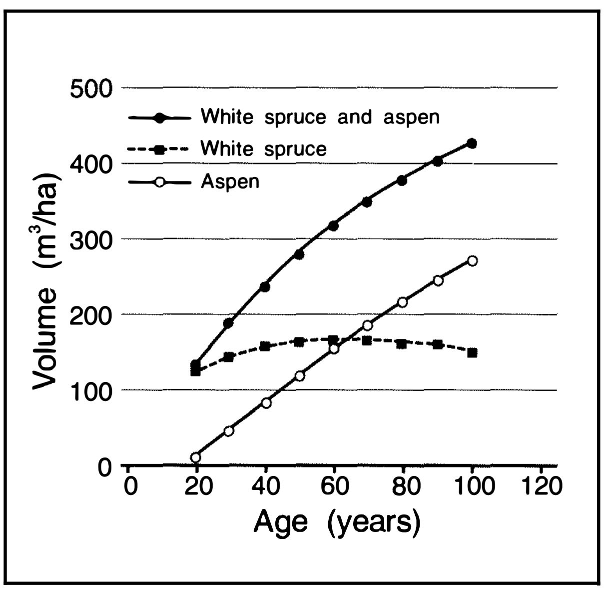

Figure 23. **Stand volume over age for mixed spruce and aspen in comparison with pure aspen and pure spruce, for site index 22.5 m at age 50** (Johnstone 1977; Day and Bell 1988).

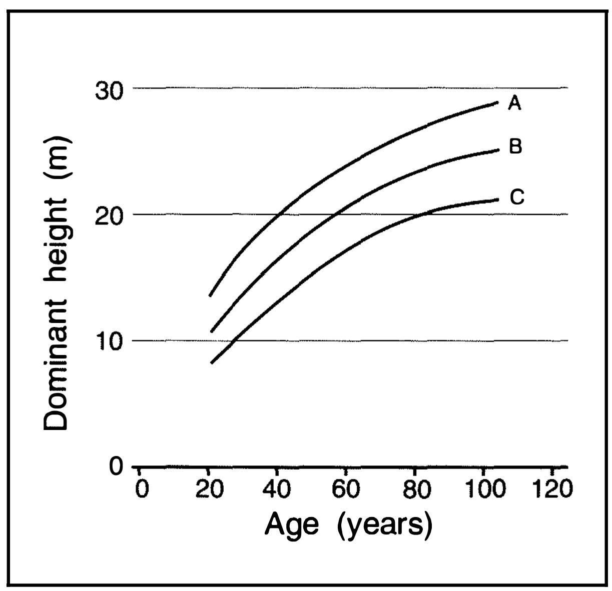

Figure 24. **Site index curves for aspen in the prairie provinces** (Steneker 1976b).

are substantial differences throughout the geographic range of aspen. For example, there have been assertions that northeastern British Columbia has "the most productive aspen-growing sites in Canada" (Teske 1989), but data availability make it difficult to make precise comparisons between aspen site productivity in British Columbia and the prairie provinces. The assertion may be based, in part, on the inventory of deciduous biomass compiled by Bonnor (1985). Bonnor's Map 6 of average biomass for northern deciduous species indicates that map units with an average standing crop greater than 100 t/ha, dry weight, occur predominantly in northeastern British Columbia, with minor occurrences in the Hudson Bay area, Saskatchewan, and a few locations in Ontario between Lake Nipigon and Lake Superior and northeast from Lake Superior towards Kirkland Lake. To put standing crop in each of 50 000 cells across Canada does not allow portrayal of higher than average standing crop that may exist on specific sites or in specific forest types. For example, Peterson et al. (1970) referred to a 55-year-old stand of pure aspen near Lesser Slave Lake, Alberta, where the standing crop was 290 t/ha, dry weight. An extremely high value of 810 t/ha was recorded by Lehn and Higginbotham (1982) from one specific aspen clone on a moist clay loam site in the Blue Ridge area of Alberta.

It takes about 6 m^3 of aspen or balsam poplar to produce 1 tonne of pulp (Ondro 1989). Based on estimates of MAI, how many hectares are needed to produce that volume of aspen raw material in a year? Mean annual increment data computed by Bickerstaff et al. (1981) suggest that the highest productivities within the boreal region are in the Alberta portion of the B.18a Mixedwood Section (Rowe 1972). This compilation indicated an average MAI of only 1.4 m^3/ha (about 1.0 t ha^{-1} yr^{-1}) for northeastern British Columbia (deciduous and coniferous combined), but 2.3 m^3/ha (1.7 t ha^{-1} yr^{-1}) for the Alberta portion of Section B.18a and 2.0 m^3/ha (1.5 t ha^{-1} yr^{-1}) in the Lower Foothills Section (B.19a). In Saskatchewan, as listed below, three boreal sections had greater MAI than the 1.0 t ha^{-1} yr^{-1} suggested by Bickerstaff et al. (1981) for northeastern British Columbia:

Sections	Mean annual increment m^3 ha^{-1} yr^{-1}	Mean annual increment t ha^{-1} yr^{-1}
Mixedwood (B.18a)	2.0	1.5
Manitoba Lowlands (B.15)	1.7	1.3
Upper Churchill (B.20)	1.7	1.3

Ecosystems that have aspen as a major component in the Saskatchewan portion of the Mixedwood Section were summarized by Corns (1989), based on data from Kabzems et al. (1986). The following MAI values were recorded for six ecosystems of increasing site quality:

Ecosystem	Site quality[a]	Mean annual increment m^3 ha^{-1} yr^{-1}	Mean annual increment t ha^{-1} yr^{-1} [b]
Populus–Rosa/Elymus	III	1.3	1.0
Picea glauca/ Populus–Corylus	III	1.8	1.3
Populus–Corylus	II	2.8	2.1
Picea glauca/ Populus–Cornus	II	3.1	2.3
Populus–Aralia/ Linnaea	II	3.7	2.8
Picea glauca/Populus– Cornus/Mitella	I	4.3	3.2

[a] I = highest site quality in samples; II = intermediate site quality in samples; III = lowest site quality in samples.

[b] Based on approximate conversion of 1 m^3/ha = 0.75 t/ha, dry weight (Bonnor and Nietmann 1987).

In Manitoba, there were also three sections, listed below, which have MAI equal to or greater than the estimated MAI in northeastern British Columbia:

Sections	Mean annual increment m^3 ha^{-1} yr^{-1}	Mean annual increment t ha^{-1} yr^{-1}
Mixedwood (B.18a)	1.9	1.4
Lower English River (B.14)	1.5	1.1
Manitoba Lowlands (B.15)	1.4	1.0

The comparisons above may not be valid because there is evidence that average MAI values in northeastern British Columbia are actually higher than 1.0 t ha^{-1} yr^{-1}. For all sites combined, the B.C. Ministry of Forests (1988) recorded a deciduous MAI of 1.7 t ha^{-1} yr^{-1} (2.3 m^3 ha^{-1} yr^{-1}) for the Fort St. John and Dawson Creek Forest Districts and 1.9 t ha^{-1} yr^{-1} (2.6 m^3 ha^{-1} hr^{-1}) for deciduous MAI in the Fort Nelson District. Analyses by Smith (1976) indicated the following ages and values at which annual growth increments culminate in British Columbia aspen:

Site class	Age of culmination	Gross volume increment at age of culmination	Net volume increment at age of culmination
2	100	3.85 m^3 ha^{-1} yr^{-1} (2.99 t ha^{-1} yr^{-1})	2.59 m3 ha^{-1} yr^{-1} (1.94 t ha^{-1} yr^{-1})
3	90	1.61 m^3 ha^{-1} yr^{-1} (1.20 t ha^{-1} yr^{-1})	1.26 m^3 ha^{-1} yr^{-1} (0.94 t ha^{-1} yr^{-1})

For Alberta's mixedwood section, the estimated MAI of 2.3 m^3 ha^{-1} yr^{-1} (1.7 t ha^{-1} yr^{-1}) by Bickerstaff et al. (1981) is similar to the 2.41 m^3 ha^{-1} yr^{-1} (1.81 t ha^{-1} yr^{-1}) estimated for hardwoods and 2.43 m^3 ha^{-1} yr^{-1} (1.82 t ha^{-1} yr^{-1}) for softwoods in the Slave Lake–Athabasca–Lac La Biche Timber Development Area (Alberta Forest Service 1986). Substantially higher MAI is, of course, possible under specific circumstances. For example, in west-central Alberta the aspen facies of the *Picea glauca/Viburnum/Rubus pubescens* ecosystem has an average gross MAI of 4.3 m^3 ha^{-1} yr^{-1}, which is equivalent to about 3.2 t ha^{-1} yr^{-1}, dry weight. The richer and often moister aspen facies of the *Picea glauca/Viburnum/Aralia* ecosystem has an average gross MAI of 5.6 m^3 ha^{-1} yr^{-1} or approximately 4.2 t ha^{-1} yr^{-1} (Corns and Annas 1986; Corns 1989).

The review by Hambly (1985) indicated that annual biomass accumulation of 5–10 t/ha is possible in aspen stands; Steneker (1976b) indicated that on good sites aspen can yield a yearly increment of about 7 m^3/ha. There is ample evidence that young aspen stands have high rates of productivity (Bella and Jarvis 1967; Person et al. 1971; Bella and De Franceschi 1980; Stiell and Berry 1986). Some examples of extreme upper limits of dry standing crop recorded in young stands by Peterson et al. (1982) included the following:

Species	Age	Above-ground dry wt (t/ha)	MAI[a] (t ha^{-1} yr^{-1})
Pure aspen	14	73.3	5.2
Pure balsam poplar	13	80.0	6.1
Balsam poplar–willow	13	130.6	10.0

[a] Assuming equal annual addition of biomass; for example, 73.3 ÷ 14 = 5.2.

Equations for Prediction of Aboveground Biomass

For seedlings and very young suckers, basal diameter of stems appears to be the preferred variable for prediction of aboveground dry weight (Woodard and Delisle 1987). For young stands, 2–5 years of age, age and number of trees per hectare have proven to be reliable predictors of biomass. Examples of regressions using these variables are outlined below.

After trying different combinations of variables, Bella and De Franceschi (1980) adopted the following model for predicting aboveground dry weight (DW) in aspen 2–5 years of age:

$$DW = a + b_1 A^2 + b_2 \ln NT$$

where:

DW = dry weight (kg/ha)
A = age in years
NT = number of trees per hectare
ln = natural logarithm

The three regressions derived for leaves (including twigs), wood, and total dry weights (kg/ha; n = 48) were as follows:

$$\text{Leaf DW} = -3008.2 + 4.852 A^2 + 460.341 \ln NT$$
$R^2 = 0.166$ SE = 561.7

$$\text{Wood DW} = -8740.0 + 248.878 A^2 + 990.105 \ln NT$$
$R^2 = 0.523$ SE = 1566.0

$$\text{Total DW} = -11746.6 + 253.722 A^2 + 1450.390 \ln NT$$
$R^2 = 0.394$ SE = 1934.1

Stand component weights derived from these regressions are shown in Table 10 for aspen aged 2–5 years and for three density classes.

For stands aged 10–35 years, Bella and De Franceschi (1980) found that the model that best predicted aboveground aspen biomass, based on 350 samples from Alberta and Saskatchewan, was as follows:

$$W = a + b_1 D + b_2 BA + b_3 H_D + b_4 H_L + b_5 (H_D \times BA)$$

where:

W = dry weight (kg/ha)
D = mean dbh, outside bark (cm)
BA = basal area (m^2/ha)
H_D = height of dominant tree (cm)
HL = Lorey's height (cm)
$H_D \times BA$ = combined variable of height of dominant tree times basal area

The five independent variables listed above explained over 99% of the variation in component and total biomass. The combined variable, $H_D \times BA$, was by

Table 10. Component dry weight of fully stocked aspen regeneration (2–5 years old) for three density classes, Alberta and Saskatchewan data combined (Bella and De Franceschi 1980)

Age (years)	Dominant height (m)	Number of trees/ha	Component dry weights (kg/ha) Woody material	Leaves	Total
2	1.7	160 000	4 120	2 527	6 648
		220 000	4 435	2 674	7 110
		280 000	4 674	2 785	7 460
3	2.4	110 000	4 993	2 379	7 373
		150 000	5 300	2 522	7 823
		190 000	5 534	2 631	8 166
4	3.0	75 000	6 356	2 237	8 594
		100 000	6 641	2 369	9 011
		125 000	6 862	2 472	9 335
5	3.5	50 000	8 195	2 094	10 289
		65 000	8 454	2 215	10 670
		80 000	8 660	2 310	10 971

Table 11. Aboveground biomass yield regression statistics for a sample of 350 Alberta and Saskatchewan aspen trees, based on W (dry weight, kg/ha) = a + b ($H_D \times$ BA), where H_D = height of dominant tree, cm and BA = basal area, m^2/ha (Bella and De Franceschi 1980)

Component dry wt (kg/ha)	Regression constant, a	Regression coefficient, b	R^2 [a]	Standard error of estimate kg	% of mean
Stem wood	864	1.487	.992	3298	6.1
Stem wood + bark	2791	1.872	.992	4289	6.2
Stem wood + bark + branches	4284	2.085	.991	5025	6.4
Branches and leaves	1925	0.258	.973	1080	9.7
Total tree (aboveground)	4979	2.128	.991	5216	6.5

[a] R^2 = The coefficient of determination. The proportion of the variance observed with the response variable, which is explained by the regression model.

far the most important independent variable, and dropping all other independent variables generally resulted in less than a 1% reduction in explained variation. On this basis, the simplified aboveground biomass yield regression statistics for Alberta and Saskatchewan aspen, using only $H_D \times$ BA as an independent variable, are listed in Table 11. Based on these regressions, biomass yield tables for Alberta aspen stands, aged 6–40 years of age and on three site quality classes, are reproduced from Bella and De Franceschi (1980) in Table 12.

For individual aspen trees in older stands, a more detailed subdivision of biomass components was provided by Johnstone and Peterson (1980), based on a sample of 254 aspen trees in Alberta ranging in age from 8 to 83 years (mean 45 years) and 60 balsam poplar trees ranging in age from 16 to 65 years (mean 32 years). Regression equations and related statistics for the various component weights are listed for aspen in Table 13 and for balsam poplar in Table 14.

Singh (1986) prepared separate biomass prediction equations for each of the three prairie provinces, but concluded that generalized equations could be used for wide application in the boreal region of western Canada. Similarity of generalized and individual

Table 12. Aspen biomass yield table with site indexes 16, 20, and 24 m (at age 50) in Alberta (Bella and De Franceschi 1980)

	Height					Stand biomass in dry weight (kg/ha)				
					Basal	Stem				
Age (years)	Dom.[a] (cm)	Lorey's (cm)	Mean dbh (cm)	No. of stems/ha	area (m^2/ha)	Wood	Wood + bark	Wood + bark + brch.[b]	Brch. + leaves	Total tree
Site index 16 m										
6	288	216	1.3	37 797	5.07	2 648	3 529	4 289	1 055	4 503
8	379	270	1.7	32 287	7.20	4 336	6 093	7 378	1 683	7 787
10	465	329	2.1	27 885	9.48	6 845	9 664	11 580	2 440	12 200
12	548	390	2.5	24 294	11.77	9 992	13 993	16 604	3 275	17 437
14	627	451	2.9	21 317	13.98	13 605	18 849	22 183	4 146	23 224
16	702	512	3.3	18 819	16.05	17 522	24 027	28 086	5 021	29 323
18	773	572	3.7	16 699	17.94	21 601	29 347	34 113	5 874	35 530
20	842	630	4.1	14 885	19.62	25 721	34 662	40 099	6 687	41 678
22	907	688	4.5	13 319	21.08	29 783	39 850	45 914	7 446	47 636
24	970	743	4.9	11 958	22.32	33 707	44 819	51 456	8 141	53 301
26	1 030	797	5.2	10 769	23.35	37 431	49 496	56 650	8 768	58 598
28	1 087	849	5.6	9 723	24.18	40 910	53 832	61 441	9 322	63 475
30	1 142	900	6.0	8 799	24.82	44 113	57 792	65 796	9 804	67 898
32	1 196	949	6.4	7 980	25.29	47 019	61 356	69 696	10 213	71 850
34	1 247	996	6.7	7 251	25.59	49 618	64 515	73 133	10 553	75 323
36	1 296	1 042	7.0	6 599	25.75	51 905	67 269	76 110	10 825	78 323
38	1 344	1 087	7.4	6 014	25.78	53 885	69 625	78 636	11 033	80 859
40	1 390	1 130	7.7	5 489	25.69	55 564	71 597	80 728	11 182	82 951
Site index 20 m										
6	366	263	1.5	34 509	6.12	3 589	4 995	6 061	1 425	6 401
8	485	341	2.0	28 792	8.99	6 656	9 403	11 266	2 381	11 879
10	599	423	2.5	24 379	12.04	10 977	15 333	18 140	3 517	19 043
12	706	505	3.0	20 888	15.07	16 256	22 383	26 218	4 756	27 411
14	808	586	3.6	18 071	17.96	22 201	30 177	35 073	6 038	36 542
16	905	665	4.1	15 763	20.62	28 545	38 379	44 328	7 313	46 053
18	998	742	4.6	13 846	23.01	35 056	46 701	53 667	8 546	55 625
20	1 085	816	5.1	12 237	25.10	41 540	54 912	62 836	9 709	64 998
22	1 168	887	5.6	10 873	26.90	47 840	62 826	71 634	10 784	73 973
24	1 248	955	6.1	9 706	28.40	53 838	70 303	79 912	11 759	82 401
26	1 323	1 020	6.6	8 699	29.62	59 442	77 242	87 563	12 627	90 176
28	1 395	1 082	7.0	7 826	30.58	64 590	83 573	94 516	13 385	97 227
30	1 463	1 142	7.5	7 064	31.29	69 243	89 254	100 727	14 033	103 514
32	1 528	1 199	8.0	6 394	31.78	73 376	94 265	106 180	14 573	109 020
34	1 590	1 254	8.4	5 802	32.07	76 984	98 602	110 873	15 009	113 747
36	1 650	1 306	8.8	5 278	32.18	80 069	102 275	114 821	15 347	117 713
38	1 707	1 356	9.2	4 811	32.14	82 644	105 305	118 049	15 591	120 942
40	1 761	1 404	9.6	4 393	31.95	84 728	107 719	120 590	15 750	123 471

Table 12. Continued

Age (years)	Height: Dom.[a] (cm)	Height: Lorey's (cm)	Mean dbh (cm)	No. of stems/ha	Basal area (m^2/ha)	Stand biomass in dry weight (kg/ha): Stem: Wood	Stem: Wood + bark	Stem: Wood + bark + brch.[b]	Brch. + leaves	Total tree
					Site index 24 m					
6	445	314	1.7	31 507	7.14	4 817	6 800	8 200	1 828	8 667
8	592	416	2.3	25 674	10.69	9 517	13 342	15 824	3 130	16 638
10	732	520	2.9	21 315	14.41	15 941	21 948	25 697	4 658	26 874
12	864	624	3.6	17 959	18.05	23 637	32 025	37 137	6 308	38 670
14	990	724	4.2	15 319	21.46	32 170	43 018	49 524	7 996	51 391
16	1 109	821	4.9	13 203	24.56	41 150	54 447	62 323	9 659	64 494
18	1 222	914	5.5	11 481	27.29	50 248	65 913	75 101	11 253	77 542
20	1 329	1 003	6.1	10 060	29.64	59 199	77 103	87 514	12 743	90 190
22	1 430	1 087	6.7	8 876	31.63	67 797	87 774	99 307	14 110	102 182
24	1 526	1 167	7.3	7 877	33.26	75 889	97 753	110 293	15 339	113 334
26	1 616	1 243	7.9	7 028	34.57	83 366	106 917	120 346	16 425	123 520
28	1 702	1 315	8.5	6 300	35.57	90 156	115 189	129 386	17 364	132 664
30	1 784	1 384	9.0	5 670	36.29	96 218	122 527	137 373	18 159	140 729
32	1 861	1 449	9.6	5 123	36.76	101 532	128 918	144 298	18 815	147 705
34	1 934	1 510	10.1	4 643	37.02	106 098	134 367	150 172	19 336	153 609
36	2 004	1 569	10.6	4 221	37.07	109 932	138 900	155 025	19 731	158 473
38	2 069	1 624	11.1	3 848	36.95	113 059	142 551	158 900	20 008	162 340
40	2 132	1 677	11.5	3 516	36.68	115 510	145 367	161 849	20 174	165 266

[a] Dom. = dominant height.

[b] Brch. = branches.

province prediction equations is shown for aspen in Figure 25 and for balsam poplar in Figure 26. The curves shown in these two figures are based on data from 60 trees of each species, using the following model:

Species	Prediction equation	R^2
Aspen	$W = 21.73 - 7.304\ D + 0.7545\ D^2 - 0.00307\ D^3$	0.977
Balsam poplar	$W = 6.54 - 3.432\ D + 0.5021\ D^2 - 0.00295\ D^3$	0.974

where:

W = ovendry weight (kg) of living tree aboveground, excluding dead branches

D = dbh outside bark (cm)

H = total tree height (m)

Based on a different model that used a combined variable, D^2H, Singh (1986) indicated that the following prediction equations could also be used for these two hardwood species in western Canada:

Species	Prediction equation	R^2
Aspen	$W = 1.41 + 0.01933\ D^2H$	0.988
Balsam poplar	$W = 12.23 + 0.01380\ D^2H$	0.966

Prediction equations summarized by Stanek and State (1978) included aspen equations from Maine (Young et al. 1964), Nova Scotia (Telfer 1969), and the Kananaskis River valley, Alberta (Peterson et al. 1970). None of these data sources and equations are considered to be applicable for prediction of aspen biomass boreal mixedwood stands.

Table 13. Regression equations and related statistics for various component weights (kg) and leaf area (m^2) of aspen trees, based on a sample of 254 trees in Alberta (Johnstone and Peterson 1980)

Regression equation	$R^{2\,a}$	$S_{y \cdot x}{}^{b}$
$Y_1 = -3.0212 - 2.5320\,D + 0.3208\,D^2 - 0.0010\,D^3 + 1.4599\,H + 0.0171\,D^2H$	0.937	33.39 kg
$Y_2 = -7.3345 + 4.6226\,D - 0.3652\,D^2 + 0.0101\,D^3 - 0.9066\,H + 0.0034\,D^2H$	0.853	10.27 kg
$Y_3 = -10.3556 + 2.0907\,D - 0.0444\,D^2 + 0.0092\,D^3 + 0.5533\,H + 0.0206\,D^2H$	0.957	32.40 kg
$Y_4 = -4.0226 + 3.0790\,D - 0.1571\,D^2 + 0.0035\,D^3 - 0.7757\,H + 0.0025\,D^2H$	0.877	8.40 m^2
$Y_5 = 1.4933 + 0.2384\,D - 0.0046\,D^2 - 0.0004\,D^3 - 0.3040\,H + 0.0144\,D^2H$	0.991	5.95 kg
$Y_6 = 0.1243 + 0.0726\,D + 0.0224\,D^2 - 0.0001\,D^3 - 0.0876\,H + 0.0023\,D^2H$	0.943	3.51 kg
$Y_7 = -1.4659 + 1.0220\,D - 0.0984\,D^2 + 0.0028\,D^3 - 0.2119\,H + 0.0009\,D^2H$	0.818	2.27 kg
$Y_8 = -0.8876 + 0.5260\,D - 0.0470\,D^2 + 0.0012\,D^3 - 0.1022\,H + 0.0004\,D^2H$	0.875	0.82 kg
$Y_9 = -0.3633 + 0.3349\,D - 0.0162\,D^2 + 0.0006\,D^3 - 0.0930\,H + 0.0003\,D^2H$	0.870	1.14 kg
$Y_{10} = -0.2682 + 0.2299\,D - 0.0113\,D^2 + 0.0003\,D^3 - 0.0650\,H + 0.0002\,D^2H$	0.857	0.45 kg
$Y_{11} = 0.0513 + 0.0839\,D - 0.0014\,D^2 + 0.0002\,D^3 - 0.0436\,H + 0.0001\,D^2H$	0.769	0.67 kg
$Y_{12} = 1.3161 + 2.5077\,D - 0.1566\,D^2 + 0.0045\,D^3 - 0.9072\,H + 0.0184\,D^2H$	0.989	9.53 kg
$Y_4 = 1.6129 + 13.0818\,Y_{11} - 0.1843\,Y_{11}^2$ [c]	0.920	4.93 kg

Note: Coefficients may not be additive due to rounding.

[a] R^2 = The coefficient of determination. The proportion of the variance observed with the response variable, which is explained by the regression model.

[b] $S_{y \cdot x}$ = A sample standard deviation of the regression coefficient.

[c] When estimating leaf area (Y_4) from foliage dry weight (Y_{11}), use measured, not estimated, dry weight.

where: Y_1 = Fresh weight stem (wood + bark) >2 cm (kg)
Y_2 = Fresh weight living branches + leaves (kg)
Y_3 = Fresh weight living tree aboveground (kg)
Y_4 = Leaf area (m^2)
Y_5 = Dry weight stem wood >2 cm (kg)
Y_6 = Dry weight stem bark >2 cm (kg)
Y_7 = Dry weight branch wood >2 cm (kg)
Y_8 = Dry weight branch bark >2 cm (kg)
Y_9 = Dry weight branch wood <2 cm (kg)
Y_{10} = Dry weight branch bark <2 cm (kg)
Y_{11} = Dry weight leaves (kg)
Y_{12} = Dry weight living tree aboveground (kg)
D = Diameter at breast height outside bark (cm)
H = Total height aboveground (m)

Table 14. Regression equations and related statistics for various component weights (kg) and leaf area (m^2) of balsam poplar trees, based on a sample of 60 trees in Alberta (Johnstone and Peterson 1980)

Regression equation	R^2 [a]	$S_{y \cdot x}$ [b]
$Y_1 = 15.0677 - 5.8148\ D + 0.5330\ D^2 - 0.0102\ D^3 + 0.5240\ H + 0.0251\ D^2H$	0.994	8.93 kg
$Y_2 = 7.8988 + 2.5020\ D - 0.0785\ D^2 - 0.0020\ D^3 - 2.3102\ H + 0.0084\ D^2H$	0.827	7.05 kg
$Y_3 = 22.9665 - 3.3128\ D + 0.4545\ D^2 - 0.0122\ D^3 - 1.7863\ H + 0.0335\ D^2H$	0.989	13.72 kg
$Y_4 = 3.5165 + 4.9402\ D - 0.1999\ D^2 - 0.0021\ D^3 - 2.7957\ H + 0.0104\ D^2H$	0.875	5.44 m^2
$Y_5 = 3.4377 + 0.1920\ D + 0.0108\ D^2 - 0.0032\ D^3 - 0.5730\ H + 0.0148\ D^2H$	0.993	3.81 kg
$Y_6 = 2.1308 - 0.9637\ D + 0.0867\ D^2 - 0.0024\ D^3 + 0.1141\ H + 0.0029\ D^2H$	0.990	1.09 kg
$Y_7 = 1.5068 + 0.4372\ D - 0.0386\ D^2 + 0.00004\ D^3 - 0.3905\ H + 0.0021\ D^2H$	0.742	1.62 kg
$Y_8 = 0.7246 - 0.1009\ D + 0.0061\ D^2 - 0.000001\ D^3 - 0.05921\ H + 0.0002\ D^2H$	0.783	0.57 kg
$Y_9 = 0.5808 + 0.3772\ D - 0.0042\ D^2 - 0.0004\ D^3 - 0.2852\ H + 0.0008\ D^2H$	0.820	0.83 kg
$Y_{10} = 0.3233 + 0.00002\ D + 0.0130\ D^2 - 0.0003\ D^3 - 0.0639\ H - 0.00005\ D^2H$	0.785	0.39 kg
$Y_{11} = 0.2256 + 0.3148\ D - 0.0137\ D^2 - 0.00002\ D^3 - 0.1707\ H + 0.0006\ D^2H$	0.834	0.44 kg
$Y_{12} = 8.9296 + 0.2566\ D + 0.0601\ D^2 - 0.0062\ D^3 - 1.4213\ H + 0.0213\ D^2H$	0.989	6.53 kg
$Y_4 = 0.2338 + 15.6688\ Y_{11} - 0.4996\ Y_{11}^2$ [c]	0.920	4.93 kg

Note: Coefficients may not be additive due to rounding.

[a] R^2 = The coefficient of determination. The proportion of the variance observed with the response variable, which is explained by the regression model.

[b] $S_{y \cdot x}$ = A sample standard deviation of the regression coefficient.

[c] When estimating leaf area (Y_4) from foliage dry weight (Y_{11}), use measured, not estimated, dry weight.

where: Y_1 = Fresh weight stem (wood + bark) >2 cm (kg)
Y_2 = Fresh weight living branches + leaves (kg)
Y_3 = Fresh weight living tree aboveground (kg)
Y_4 = Leaf area (m^2)
Y_5 = Dry weight stem wood >2 cm (kg)
Y_6 = Dry weight stem bark >2 cm (kg)
Y_7 = Dry weight branch wood >2 cm (kg)
Y_8 = Dry weight branch bark >2 cm (kg)
Y_9 = Dry weight branch wood <2 cm (kg)
Y_{10} = Dry weight branch bark <2 cm (kg)
Y_{11} = Dry weight leaves (kg)
Y_{12} = Dry weight living tree aboveground (kg)
D = Diameter at breast height outside bark (cm)
H = Total height aboveground (m)

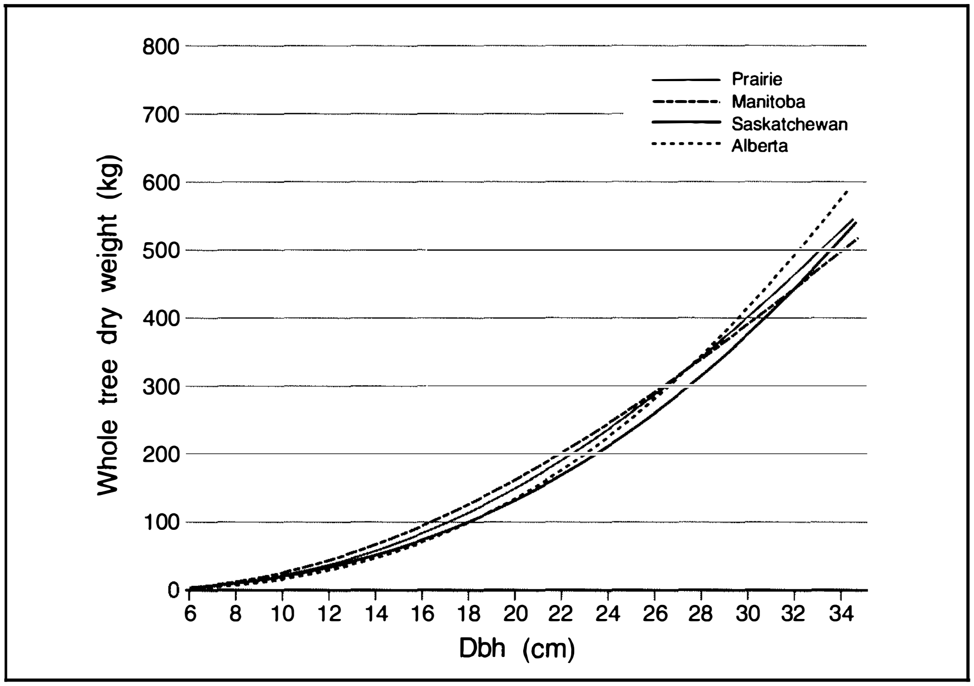

Figure 25. Predicted aboveground aspen dry weight, excluding dead branches, based on data from each of the prairie provinces and on generalized data for that region (Singh 1986).

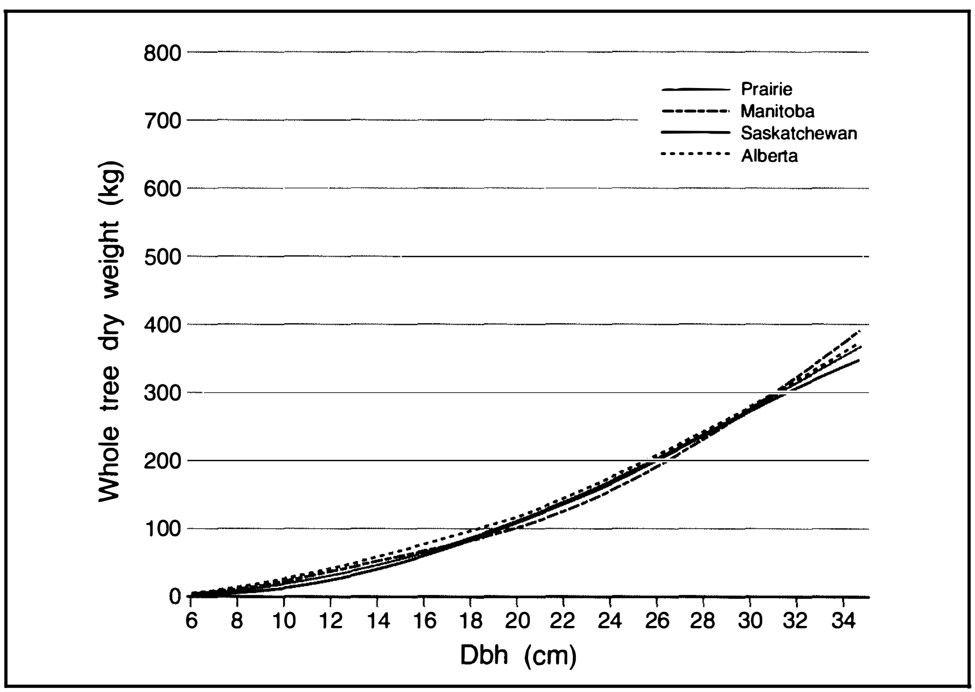

Figure 26. Predicted aboveground balsam poplar dry weight, excluding dead branches, based on data from each of the prairie provinces and on generalized data for that region (Singh 1986).

For a forest manager interested in expressing growth and yield on a weight instead of volume basis, the existence of a wide variety of equations for predicting aboveground dry weight of aspen is perplexing. Up to 1983 there were at least ten regional systems of standard equations in Canada for estimating ovendry mass of aspen trees. Fortunately, this variety of regressions has been reduced by the development of a single integrated national system of equations for aspen in Canada (Evert 1983). For the forest manager, it is significant that when Evert's national system of equations is applied to sample data from individual geographic regions in Canada, estimates of total aboveground biomass of all sample trees in any of six regions differed from observed aspen biomass values by no more than 6%. About half the estimates were within 2% of observed values. This suggests that a forester interested in using diameter and height to predict aspen aboveground dry weight can get acceptable results by using either regional regression equations, which were outlined earlier in this section, or the nationally representative equations. Evert's (1983) nationally representative equations for aspen are listed below.

Ovendry mass of aspen stem wood (kg)	$= 0.014293\ d^2h + 0.014287\ h - 0.0003103\ d^2$ ($R^2 = 0.559$)
Ovendry mass of aspen wood + bark (kg)	$= 0.01676\ d^2h + 0.022058\ h + 0.0074669\ d^2$ ($R^2 = 0.735$)
Ovendry mass of aspen stem wood + bark + live branches (kg)	$= 0.017724\ d^2h + 0.01934\ h + 0.023798\ d^2$ ($R^2 = 0.704$)
Ovendry mass of aspen stem wood + bark + live branches + twigs and leaves (kg)	$= 0.01767\ d^2h + 0.01923\ h + 0.034119\ d^2$ ($R^2 = 0.708$)

where:
d = dbh outside bark (cm)
h = total tree height (m)

For sampled aspen and balsam poplar in Alberta, Saskatchewan, and Manitoba, which ranged from 6 to 40 cm dbh and from 6 to 34 m in height, tables to predict whole-tree aboveground dry weight (without foliage) have been prepared by Singh (1982). Those weight tables are reproduced for balsam poplar in Table 15 and for aspen in Table 16.

Clonal Variation in Growth Rates

If examined over a large geographic area, there is a large variation in standing crop estimates of mature aspen stands. For example, Hambly (1985) summarized biomass values, t/ha dry weight, for the aboveground portion of aspen stands from study sites that ranged from Alberta southeast to Ontario and the Lake States. In the sampled stands, total stem, bark and branch standing crop for mature stands varied from a low of 7 t/ha to a high of 810 t/ha. The very low value (7 t/ha) was a severely understocked stand described by James and Smith (1977) in southern Ontario. The extremely high value of 810 t/ha was from one specific clone on a moist clay loam site that was excellent for aspen growth in the Blue Ridge area of Alberta (Lehn and Higginbotham 1982). The age of this specific sample stand was not specified but stands sampled in that area ranged from 55 to 82 years of age. The broad range of biomass values for mature aspen stands is probably not much different than the variability that would be revealed if stands of other tree species were compared in the same way.

For any species, differences in site quality and in stocking account for much of the variability referred to above. In the case of aspen, however, there is an additional source of variation because of clone-to-clone differences in growth rates and maximum achievable standing crop. Adjacent clones on the same site may have large differences in growth rates. A recent Alberta study demonstrated that in both a foothills study site near Nordegg and a boreal site near Blue Ridge there was a large amount of clonal variability in rate of biomass accumulation. Lehn and Higginbotham (1982) calculated that, at Blue Ridge, the best clone had a mean bole weight 43.9 kg greater than the mean bole biomass of six clones in the study area. Based on mean numbers of stems per hectare and the maximum potential gains mentioned above, biomass at 85 years could be increased by 17 885 kg/ha at Nordegg and 58 124 kg/ha at Blue Ridge if only the best clone was considered. These figures represent a 20% increase at Nordegg and a 16% increase at Blue Ridge on an areal basis.

Clonal differences of comparable magnitude were recorded for largetooth aspen in Michigan, where Zahner and Crawford (1965) recorded spreads of 2.0 to 7.3 m when the mean height of the shortest clone on a 0.8-ha plot was compared to the mean height of the tallest clone on the same plot. Randomly paired clones of 50-year-old largetooth aspen commonly showed the large-treed clones to have diameters and heights 25% greater than small-treed clones on the same site and at similar stocking levels. This translates into a volume per hectare in good clones as much as 200% of that in poor clones. In the Michigan study, not only were total heights of clones different, as one would expect among different genotypes, but the shapes of height-age growth curves were also quite varied from one clone to the next. On the same

Table 15. Balsam poplar whole-tree aboveground (without foliage) dry weight (kg) (Singh 1982)

Dbh	Height (m)														
(cm)	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34
6	2	6	10												
8	4	8	12	16											
10	9	13	18	22	27										
12		22	26	31	36	41									
14		33	38	43	48	53	58								
16			52	58	63	69	74	80							
18			69	75	81	87	93	99	105						
20				95	101	108	114	121	128	134					
22				117	124	131	138	145	153	160	167				
24					149	157	165	172	180	188	196	204			
26					176	185	193	202	210	219	227	236	244		
28						214	224	233	242	251	261	270	279	288	
30						246	256	266	276	286	296	307	317	327	337
32							290	301	312	323	334	345	356	367	378
34							326	338	350	362	374	386	398	410	421
36								377	389	402	415	428	441	454	467
38								416	430	444	458	472	486	500	514
40									472	487	502	517	533	548	563

Equation: $W = 4.02873 - 4.84860\ D + 1.85135\ H + 0.00354\ D^2H + 0.43221\ D^2 - 0.00304\ D^3$ ($R^2 = 0.98$).
Equation based on D only: $W = 7.88378 - 3.84748\ D + 0.5141\ D^2 - 0.0031\ D^3$ ($R^2 = 0.97$).

Table 16. Aspen whole-tree aboveground (without foliage) dry weight (kg) (Singh 1982)

Dbh	Height (m)														
(cm)	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34
6	15														
8		20													
10			29												
12				40											
14				57											
16				75	77	80	82	85							
18				94	99	104	110	115	120						
20				113	122	131	139	148	156	165					
22					146	159	171	183	195	207	219				
24					172	188	205	221	237	253	269	285			
26					200	220	241	261	281	302	322	343	363		
28						254	279	304	329	354	379	405	430	455	
30						290	320	350	380	410	440	470	500	531	561
32							364	399	434	470	505	541	576	611	647
34							410	451	492	533	574	615	656	697	738
36								506	553	600	647	694	741	789	836
38								564	618	671	725	778	832	885	938
40									686	746	806	866	927	987	1047

Equation: $W = 2.39343 - 6.95977\ D - 4.31874\ H + 0.02150\ D^2H - 0.23719\ D^2 + 0.00192\ D^3$ ($R^2 = 0.99$).
Equation based on D only: $W = 23.61521 - 7.88903\ D - 0.78372\ D^2 - 0.00362\ D^3$ ($R^2 = 0.98$).

site, five clones grew rapidly in early years and then slowed abruptly, whereas seven other clones had slow early growth, rapid growth from age 15 to 35 years, then slow growth later.

Comparison of Aspen Seedling and Sucker Height Growth

There is little published information on growth rates of aspen seedlings, but it is known that, compared to suckers, seedlings grow relatively slowly for the first 2 or 3 years (Heeney et al. 1980), and that early height growth of aspen seedlings is less rapid than in suckers. First-year seedling height growth is generally less than 15 cm and second-year growth adds another 15–30 cm. Under favorable conditions, seedlings may reach a total height of 1.2 m after three seasons of growth. Aspen seedlings may compete favorably with other tree seedlings but not with aspen suckers, sprouts of various shrubs, or tall herbs (Heeney et al. 1980). Aspen seedling and sucker height growth curves, based on unpublished Forestry Canada data, are reproduced in Figure 27.

Aspen suckers have a much more rapid growth rate than seedlings in the early years, a difference that can last up to 30 years before trees of seedling origin reach their period of most rapid height growth. Suckers typically grow 1–2 m in the first year, but have been recorded as high as 2.7 m after one growing season; in the second and subsequent years, growth of dominant suckers is commonly 0.5–1.0 m/yr (Horton and Maini 1964). In young aspen stands in Alberta and Saskatchewan, heights of dominant suckers averaged 1.7 m at the end of the second growing season, 2.4 m at the end of the third, 3.0 m at the end of the fourth, and 3.5 m at the end of the fifth (Bella and De Franceschi 1980). The rapid growth of aspen suckers is accompanied by rapid development of their reproductive mechanisms; aspen suckers of fire origin have been reported to produce flowers at 6 years of age (Barnes 1966), and the newly developed roots of suckers are known to produce new suckers within 3 years. In vegetative propagation experiments, Farmer (1962) noted that even a 1-year-old sucker was able to develop new suckers prolifically within 2 weeks of being severed from an actively growing stem.

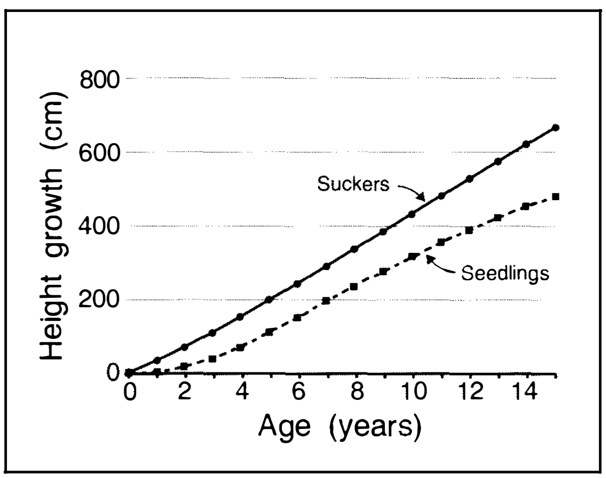

Figure 27. Comparative early height growth of aspen suckers and aspen seedlings. (Unpublished information courtesy of S. Navratil and C.J. Cieszewski.)

In addition to suckers, aspen may also reproduce vegetatively from stump sprouts and collar sprouts. Horton and Maini (1964) indicated that aspen's three forms of vegetative reproduction did not differ appreciably in height growth during the first few years. These researchers believed that rotting of the parent stump is likely to influence the growth of stump sprouts negatively because root suckers and collar sprouts rapidly develop their own root system. In an Ontario study area where 1-year-old aspen regeneration was made up of about 76% root suckers and 24% collar sprouts, Horton (1984) recorded an average height of 0.72 m for dominant suckers and 0.80 m for dominant root collar sprouts at the end of the first growing season.

Comparison of Aspen and Balsam Poplar Seedling Growth Rates

To date, the only detailed data on relative growth rates of aspen and balsam poplar seedlings are from greenhouse pot tests in which development was recorded for 9 weeks after germination, a period approximately equal to a single growing season in northwestern Ontario (Morris and Farmer 1985). Those greenhouse tests suggest that aspen seedlings may outgrow those of balsam poplar. When those species were grown at four densities (58 823, 11 235, 2030, and 323 plants/m^2) and in various mixtures (100, 75, 50, and 25% aspen and 100, 75, 50, and 25% balsam poplar), aspen was the dominant species in terms of height growth in all mixes and at all densities. The mean aboveground dry weight/m^2 was greatest at the highest densities. At high densities aspen in all mixes took advantage of the relatively slower growth of balsam poplar to produce greater biomass per unit area than in pure populations of aspen at equal densities. In fact, the total biomass/m^2 of mixtures at high densities was substantially greater than for pure populations (Morris and Farmer 1985). These greenhouse results need to be interpreted with caution because some investigators have noted from field observations that, on good sites, balsam poplar will outgrow aspen (Haeussler and Coates 1986).

Influence of Stand Density on Early Height Growth

There is evidence that stand density has little effect on aspen height growth during the first 5 years. Strothmann and Heinselman (1957) examined how stand density influenced survival and height growth of suckers during the first 10 years after clear-cutting of aspen in Minnesota. The studied sucker stand arose following commercial clear-cutting of the parent stand in the fall and winter of 1950. In July of 1951, all nonmerchantable residual aspen and hardwoods were removed to avoid irregularities in sucker distribution due to overstory shading. The study involved five levels of stocking (642, 1235, 2470, and 3706 stems/ha) and a check (control) area, which averaged about 24 860 stems/ha. New suckers that came up were removed annually except on the check plots. Survival and height growth data by treatments are reproduced in Table 17. These Lake States data suggested stand density has little effect on the height growth of aspen during the first 5 years, and survival of aspen suckers decreases with increasing stand density. When aspen stands are thinned immediately after establishment, additional suckering can be expected for at least 3 years (Strothmann and Heinselman 1957).

Aspen Root Biomass Development

Compared to aboveground components, there is limited information on changes in root biomass as aspen stands develop. Although only trees aged 19 and 45 years were represented in the sampling, detailed root data are available from the work of Strong and La Roi (1983a, b; 1985) near Lesser Slave Lake, Alberta. The 19-year-old aspen had 25.6% of its total biomass in its root system, based on aboveground and belowground dry weights of 6.1 and 2.1 kg, respectively. The 45-year-old aspen weighed 39.7 kg aboveground and 8.6 kg belowground, which represents 17.8% of total tree biomass in the root system.

Biomass distribution within various size classes of the root system were recorded by Strong and La Roi (1983b) as follows:

Size classes	Percentage of total root biomass	
	19-year-old	45-year-old
Stump[a]	35.8	34.5
5–20 cm diameter	8.9	13.0
2–5 cm diameter	32.3	17.5
0.5–2 cm diameter	18.3	23.7
0.2–0.5 cm diameter	3.1	6.5
0–0.2 cm diameter	1.6	4.8

[a] Stump was defined as the belowground portion of the tree bole.

A recent project that required information on aspen root biomass at various stand ages in Alberta (Peterson, Chan, Peterson, and Kabzems 1989) resulted in the estimates listed in Table18, derived from smoothed curves constructed from several different data sources. The estimates are for a fully-stocked pure aspen stand on a medium quality site.

The estimates in Table 18 deserve some comment because root biomass is so difficult to sample. To obtain these estimates the first approach was to examine unpublished Forestry Canada data on aspen root biomass gathered under ENFOR Project P-205. For 37 sample plots in Alberta aspen stands that ranged in age from 9 to 60 years, the stump pulling method used in Project P-205 yielded total root biomass estimates that ranged between 10 and 20 t/ha in most sampled stands (a maximum of 41.2 t/ha recorded for a 53-year-old stand and a minimum of 3.6 t/ha for a 15-year-old stand). Even though the stump-pulling method is thought to have resulted in an underestimate of root biomass, because broken roots

Table 17. Survival and height growth of aspen suckers under various stocking levels (Strothmann and Heinselman 1957)

Treatment: stems left/ha, 1952[a]	No. of stems/ha, 1956	Percent survival[b]				Average height (m)	
		1953	1954	1955	1956	1952	1956
642	593	94.9	92.3	92.3	92.3	1.28	3.17
1 235	1 087	97.3	97.3	88.0	88.0	0.91	2.10
2 470	2 256	98.7	96.0	91.3	91.3	1.10	2.99
3 706	3 096	94.7	90.3	85.8	83.5	1.34	2.96
24 860 (control)	13 837	66.1	69.4	64.7	55.7	0.73	2.44

[a] Maintained at this level annually on all except check plots by removing new suckers.

[b] Percent of the original number of stems.

Table 18. Aspen root biomass at various stand ages in Alberta

Root diameter	Stand age (years) 1	3	5	10	20	30	50	70	90	110
	Dry wt (t/ha)									
Large roots, >2.0 cm	0.00	0.00	0.25	2.05	6.37	9.96	11.51	12.32	12.57	12.62
Medium roots, 0.5–2.0 cm	0.00	0.32	0.86	3.47	7.13	8.09	8.25	7.99	7.96	7.80
Small roots, <0.5 cm	0.25	0.62	0.87	1.28	1.75	2.02	2.30	2.51	2.54	2.52
Total	0.25	0.94	1.98	6.80	15.25	20.07	22.06	22.82	23.07	22.94

would be unsampled, the 10–20 t/ha estimate is substantially higher than the 5.2 t/ha of root biomass reported for a 25-year-old aspen stand in Alaska (Tryon and Chapin 1983). The estimated total root biomass of individual Alberta trees sampled in ENFOR Project P-205 also had higher values than recorded for root systems of individual aspen trees of comparable size in Maine (Young et al. 1964).

Averaging all 37 Alberta sample plots, 78% of the sampled root biomass had large roots (over 2.0 cm diameter outside bark), 13% had medium roots (0.5–2.0 cm diameter outside bark) and about 9% had small roots (under 0.5 cm diameter outside bark). Small roots, in particular, were thought to be significantly underestimated by the data from ENFOR Project P-205. For example, the Alaskan studies by Tryon and Chapin revealed a total root biomass of 5.17 t/ha in a 25-year-old aspen stand, of which 34% (1.76 t/ha) occurred in the form of fine roots (under 0.5 mm diameter). Fertilization of aspen with nitrogen, phosphorus and potassium (N, P, and K) for 6 years caused a 38% increase in root biomass (to 7.14 t/ha) but no change in relative proportion of fine (30%) and large (70%) aspen roots in the 25-year-old stand. In general, roots comprised a much larger proportion of total tree biomass (30–50%) in aspen than in spruce in the Alaska studies (Tryon and Chapin 1983).

Probably the best available information on distribution and biomass of aspen roots is that published by Ruark and Bockheim (1987) who sampled 10-, 20-, and 32-year-old stands in Wisconsin. They recognized two size classes: small roots under 0.3 cm diameter and large roots over 0.3 cm. Their sampling recognized that large and small aspen roots have different distribution patterns. Small roots originate from long, relatively untapered scaffold roots. These small roots tend to fan out through the soil in response to soil moisture and nutrients. This habit leads to a relatively small-scale distribution pattern for this size class, but their belowground biomass levels may fluctuate widely during the year. Large roots are less branched, extend laterally near the soil surface, and are more variable in distribution than small roots. These researchers also recognized that large roots can be subdivided into two distinct populations. One population resides directly under the stem while a second population lies between the stems. The former population can be measured by extracting stumps and weighing the attached root mass, as was done in the Alberta sampling in the ENFOR Project P-205 (Peterson, Chan, Peterson, and Kabzems 1989). If sufficient stumps are removed, regression equations can be used to predict stump and root mass from stem diameter. Estimation of the second population of large roots, lying between stems, is more difficult. Both populations need to be measured for an accurate estimate of belowground biomass in aspen stands.

In three even-aged, healthy fully-stocked stands Ruark and Bockheim (1987) found that small root dry weight ranged narrowly between 1.5 and 2.9 t/ha, regardless of stand age or time of sampling. The remaining root dry weight, coinciding with the medium- and large-root size classes of the Alberta data (including stump as part of "large roots"), was 14.8 t/ha at age 10, 14.9 t/ha at age 20, and 18.6 t/ha at age 32. The observed increase in aspen root biomass from age 10 to 32 was mostly a result of increase in stump biomass, which is likely an architectural necessity in response to increasing stem biomass. The small and large root components were relatively constant on a dry weight basis from 10 to 32 years of age, but the distribution of large roots became more concentrated near the stem with age. The biomass of medium and large roots in the spaces between stems showed a steady decrease with age, mainly due to a gradual reduction in the 1–3 cm diameter class in the upper 10 cm of soil. Ruark and Bockheim (1987) attributed this to death of suppressed aspen trees whose stems and large roots degrade following natural thinning episodes.

Nutrient Relationships

Ecosystems in which aspen is a prominent component have been studied in considerable detail from a nutritional point of view. As recently reviewed by Pastor (1990) and by Ruark (1990), these studies have revealed several patterns common to most aspen stands. In general, aspen rapidly takes up large quantities of nutrients and stores them in woody tissues, particularly bole bark and bole wood. The small amounts of nutrients that are returned in leaf litter are released relatively rapidly during decay. The net result is that aspen retains nutrients effectively within the ecosystem because leaching losses are minimal and decrease quickly after fire or clearcutting. Some other general principles pertaining to nutrient cycling in aspen ecosystems are outlined below.

Aspen is adapted for rapid growth and high nutrient uptake during early stand development. Later on there is a period of lesser nutrient uptake during which nutrients are recycled from older biomass components into young growing components of the tree or clone (Pastor and Bockheim 1984; Hendrickson et al. 1987). This recycling reveals an ability for aspen to concentrate nutrients in relatively small biomass components—for example in branches instead of stems. This contributes to a lower overall nutrient demand in aspen than there is in some of its companion tree species. Not surprisingly, aspen's peak nutrient requirement occurs during the period of rapid canopy development.

Storage of carbohydrates belowground is an important adaptation in aspen because of the long-lived clonal root system (Tew 1968). Aspen roots, like many other early-succession species, have high nutrient uptake rates. More importantly, most adventitious roots formed below aspen suckers die the same year they are initiated (Gifford 1966), which suggests that this species has a relatively high root turnover rate. The suggestion by Grime (1977) and Orians and Solbrig (1977) that species with high leaf turnover rates also have rapid root turnover is supported by observations in Alaska by Chapin and Van Cleve (1981). In that region deciduous boreal trees (aspen, birch, and larch) have relatively few roots that survive the winter, whereas the dominant evergreens (black spruce and white spruce) have many active roots that are at least one year old.

A recent review by Corns (1989) stressed that aspen functions as an efficient nutrient pump, partly because aspen leaves have higher nutrient contents than conifer needles on the same site (Young and Carpenter 1967; Troth et al. 1976) and partly because aspen leaves decay rapidly, which provides an early return of nutrients to the soil (Daubenmire and Prusso 1963; Bartos and DeByle 1981). Numerous researchers have warned that single nutrient concentration measurements must be interpreted with caution because nutrient contents, particularly of leaves and twigs, change seasonally (Tew 1970b; Verry and Timmons 1976; Cragg et al. 1977; James and Smith 1978a, b; McColl 1980; Alban 1985). Nitrogen, P, and K decrease as the growing season progresses; calcium (Ca), sodium (Na), and magnesium (Mg) increase as the growing season progresses, with maximum nutrient contents late in the season before leaf fall. Variations in catkin concentrations are comparable to those of leaves and twigs (McColl 1980). Young leaves have more protein than old leaves but, even in September, leaves have sufficient protein and are important browse for deer and grouse. Quality of browse thus changes over the season, and aspen stands with high protein content have particular value in autumn for browse when other forage plants are low in protein content.

In addition to aspen's influence on nutrient relationships within the ecosystem there are influences in the opposite direction as well—that is from the site to the tree. One is the influence of nutrient levels on growth rates as described in a later chapter under the heading of fertilization. It is known that nutrient status can influence aspen's canopy structure as well as its rate of assimilation. For example, application of fertilizer to aspen in the interior of Alaska almost doubled leaf area index (the surface area of foliage per unit surface area of ground) from 0.6 to 1.1, mainly by increasing the numbers of leaves (Coyne and Van Cleve 1977). In the canopy of the fertilized, but not the unfertilized aspen stand, there were vertical gradients of mean leaf area, mean leaf mass, and mean leaf length and width, all being greatest towards the top. Coyne and Van Cleve suggested that these gradients were a response to an increase in light gradient through the canopy following the increase in leaf amount and not as a response to nutrient supply *per se*.

Alban and Perala (1990a) reported that whole-tree and merchantable bole harvesting of three mature aspen stands in Minnesota and Michigan removed 24–48% of total ecosystem carbon, but neither harvesting system influenced the weight of forest floor carbon or organic soil carbon (to a depth of 50 cm) for up to 8 years. Litter fall returned nearly to preharvest levels within 5 years. Vegetative biomass recovered equally as fast in both harvesting treatments at all study sites. Alban and Perala were not aware of any studies showing loss of productivity attributed to whole-tree harvesting of aspen, but they did reiterate that whole-tree harvesting of aspen does remove more organic matter and nutrients from the site than does bole-only harvesting. Ecosystem carbon is clearly reduced directly by removals in harvesting, but the more important question from the site productivity standpoint is whether soil carbon is reduced. Alban and Perala found no evidence that harvesting influenced carbon weight in the forest floor.

Aspen Litter Decomposition

Decomposition is a crucial part of normal ecosystem functioning; an estimated 80–90% of all net primary production in ecosystems on land is recycled by decomposers (Taylor and Parkinson 1988a). In middle-aged to mature aspen stands, estimates of total litter fall range from 1.4 to 3.3 t/ha of which 13–24% is woody (Van Cleve and Noonan 1975; Cragg et al. 1977; Bartos and DeByle 1981).

There is evidence that aspen litter decomposition patterns differ markedly from those in coniferous ecosystems. The most comprehensive studies of aspen litter decomposition in Canada have been carried out by Parkinson and co-workers over the past 20 years in the Kananaskis River valley west of Calgary, Alberta. Their work has shown that decay rates for aspen leaves are strongly influenced by temperature and less so by moisture; in contrast, decomposition of lodgepole pine and jack pine needles is insensitive to both temperature and moisture. Aspen leaves decomposed faster than pine needles under most conditions, but under very cold and dry conditions pine leaf litter decomposed faster than aspen (Taylor and Parkinson 1988a, d).

Rates of leaf litter decomposition in winter are often assumed to be low, but there is considerable evidence to the contrary. One possible explanation is that during late autumn and early spring, when temperatures repeatedly fluctuate above and below 0°C, the repeated freeze–thaw cycles break up the leaves, leading to increased rates of leaching and susceptibility to microbial attack. When this hypothesis was tested for aspen leaf litter by Taylor and Parkinson (1988b) in Alberta, it was found that simple freezing (as opposed to repeated freezing and thawing), plus decomposer activity beneath snow, are probably more important factors in winter leaf litter decomposition than freeze–thaw cycles. In an aspen site, Coxson and Parkinson (1987) found that 75% of total litter decomposition between December and March occurred at temperatures between 0 and -5°C. Wetting–drying accelerates decomposition of aspen leaves initially through cuticle damage. Decay is rapid once microorganisms penetrate the leaf surface, but decomposition slows when the labile materials are exhausted and only the tougher compounds such as lignin remain (Taylor and Parkinson 1988c).

Decomposition of a slowly decaying litter type is expected to be faster in the presence of a nutrient-rich, rapidly decaying litter type. This hypothesis was tested in the Kananaskis River valley, Alberta, by Taylor et al. (1989) where green alder (*Alnus crispa* [Ait.]) is a common understory shrub in aspen stands. Aspen's waxy leaves decompose relatively slowly (Lousier and Parkinson 1978) in comparison to the nitrogen-rich alder leaf litter. In the Kananaskis study, the decay rate for litter made up of mixed aspen and alder leaves was more similar to the decay rate of alder than to that of aspen. This confirmation that alder leaves accelerate the decay of aspen leaves was due to alder's provision of higher levels of N and P to decomposer organisms. The heterogeneous mixture of leaves also improved water retention properties and provided a more favorable microenvironment for decomposers than was the case for aspen leaves alone (Taylor et al. 1989).

Studies of litter under aspen, white spruce, and red pine (*Pinus resinosa* Ait.) in Minnesota indicated that aspen had less litter fall than the other two species but aspen's litter contained higher levels of P, K, Ca, and Mg (Perala and Alban 1982a). On two different soils in Minnesota, aspen and spruce stands accumulated more of most nutrients than did red pine (Alban 1982). In another study, significantly less organic matter in the surface soil occurred under aspen than under conifers on the same soil (Kienzler et al. 1986), a fact consistent with large numbers of bacteria and fungi present under aspen, which lead to relatively fast decomposition of organic matter under this species. Exchangeable Ca in the surface of different soils was relatively low under aspen, (Van Cleve and Noonan 1971; Perala and Alban 1982a), and the redistribution of Ca within the ecosystem was strongly dependent on tree species although the total amount of Ca was not (Alban 1982). Rates of forest floor decomposition and nutrient turnover were more rapid under aspen than spruce, and more rapid on a predominantly loamy than sandy soil at the study sites in Minnesota (Perala and Alban 1982b).

Decomposition rates of bole and branch litter were measured in Michigan aspen stands in which source trees had mean diameters that ranged from 11.8 to 17.6 cm (Miller 1983). For up to 5 years, felled bole sections were 0–10 cm above the ground, averaging 4 cm. Most branch sections for the first 5 years were not touching the ground, but many of them were overtopped by herbaceous vegetation. In upper and lower branches, N content decreased for 2 or more years and then increased; a corresponding pattern in boles may or may not have occurred. In general, N content is expected to initially increase over original levels due to importation by microorganisms. Bark sloughed faster from branches than from boles. For example, after 5 years, 71% of the bark remained on boles but only 56% on lower branches and 55% on upper branches (Miller 1983). Miller projected the times to reach half of the original values, termed half times, for several variables. They ranged from 1 to 5 years for upper and lower branches and from 2 to 11 years for boles, with P declining fastest (Table 19).

Table 19. Time to reach half of original values (half times) for bark cover and for nutrient content during decomposition of felled aspen boles, lower branches, and upper branches (Miller 1983)

Variable	Source of litter	Average half time (year)
Bark cover	Upper branch	4
	Lower branch	4
	Bole	6
Phosphorus	Upper branch	3
	Lower branch	5
	Bole	11
Potassium	Upper branch	1
	Lower branch	1
	Bole	2
Calcium	Upper branch	4
	Lower branch	3
	Bole	6
Magnesium	Upper branch	3
	Lower branch	2
	Bole	6

These tests, which placed live branches and stem segments on the ground, were a simulation of blowdown of living aspen. In reality, much of the large aspen litter is produced by dead branches or stems from causes that allow them to remain standing for a long time. Whether elements are appreciably translocated among wood or bark tissues prior to and following standing death is unknown.

Boreal Hardwood Nutrient Cycling Relationships

In general, nutrient input and uptake increase as the proportion of hardwoods increases in boreal mixedwood stands. Some of the most detailed nutrient cycling data for boreal mixedwood ecosystems that contain aspen and balsam poplar are from studies in Ontario (Gordon 1983) and Alaska (Van Cleve et al. 1983). Gordon (1981) presented a generalized nutrient cycle diagram that included the following three compartments:

1. Inputs of nutrients—this compartment is made up of: precipitation that falls through the canopy (throughfall); flow of precipitation down the stem (stemflow); litter fall from trees and from understory vegetation; and litter production by roots.

2. Uptake of nutrients—this compartment is made up of: retention of nutrients as a result of mean annual increment by overstory trees, understory vegetation and by roots; litter fall; and leaf wash. The latter refers to the difference in the amounts of elements that contact the forest canopy as precipitation and those that are washed out of the foliage.

3. Reserves—this compartment consists of: nutrients in standing dead biomass; nutrients in the organic content of soil; and nutrients in the mineral soil.

For the forest manager, the key processes of nutrient cycling are the movement of nutrients from reserves to uptake, to input, and then back to reserves. Silvicultural decisions can influence some of the movements between these three compartments. The open parts of this loop are atmospheric contributions to the input compartment and deep leaching losses from the reserve compartments. The manager of an aspen or mixedwood forest can do nothing to influence these atmospheric and leaching components of the overall nutrient cycle. Furthermore, the amount of deep leaching that occurs on boreal mixedwood ecosystems is not known.

Lacking specific data for mixedwood stands in the prairie provinces, the best estimates for nutrient cycling through the three main compartments—inputs, uptake, and reserves—are those provided by Gordon (1981) for three kinds of mixedwood stands: 25% softwood, 75% hardwood; 50% softwood, 50% hardwood; and 75% softwood, 25% hardwood. The estimates for these three compartments are summarized below, based on Gordon's boreal mixedwood data from Ontario (Table 20).

Table 20. Annual input values for boreal mixedwood ecosystems, throughfall + stemflow + litter fall + root litter (kg ha^{-1} yr^{-1})

Mixedwood stands	Total nitrogen	Phosphorus	Potassium	Calcium	Magnesium
25% softwood 75% hardwood	31.9	6.5	22.2	57.1	11.3
50% softwood 50% hardwood	27.0	4.9	17.4	46.4	8.8
75% softwood 25% hardwood	22.5	3.6	13.5	40.0	6.3

All nutrients in the input compartment show an increase as the proportions of hardwoods increase. Gordon (1981) suggested that this is a result of the greater biomass and litter fall of understory vegetation under aspen, compared to that in coniferous stands, as well as greater stemflow in aspen than in spruce (Table 21).

As with input, there is greater uptake of all nutrients as the proportion of hardwoods increases in boreal mixedwood stands. Gordon (1981) attributed this to faster growth rates in aspen than in spruce and more rapid breakdown of aspen litter. A more detailed itemization of the input and uptake compartments (kg ha^{-1} yr^{-1}) is presented in Table 22 for a boreal mixedwood stand on an upland till in Ontario (Gordon 1983). The amounts of nutrient reserves (kg/ha) held in standing dead tree biomass, roots, organic soil, and mineral soil are also listed in Table 22.

It is well recognized that when nutrients enter an ecosystem some remain readily available and are either taken up by vegetation or are lost by leaching. Others

Table 21. Annual uptake values for boreal mixedwood ecosystems, retention of nutrients by mean annual increment + leaf wash + litter fall (kg ha^{-1} yr^{-1})

Mixedwood stands	Total nitrogen	Phosphorus	Potassium	Calcium	Magnesium
25% softwood 75% hardwood	35.1	6.8	24.0	63.0	11.6
50% softwood 50% hardwood	30.2	5.2	20.1	52.0	9.4
75% softwood 25% hardwood	25.5	4.1	16.5	40.8	6.9

Table 22. Generalized nutrient budget of a mixedwood stand (mean height 21 m) of aspen, white birch, white spruce, and balsam fir on an upland till (Gordon 1983)

Compartments	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
Input compartment (kg ha^{-1} yr^{-1})					
Through fall	2.7	0.2	5.4	6.8	1.7
Stemflow	0.8	0.1	2.8	1.1	0.2
Litter fall	21.7	4.1	8.1	35.8	6.7
Root sloughage	1.8	0.5	1.1	2.7	0.3
Total input	27.0	4.9	17.4	46.4	8.9
Uptake compartment (kg ha^{-1} yr^{-1})					
Retention in trees by MAI[a]	7.3	1.0	4.3	9.3	1.0
Retention in understory	6.6	0.7	6.7	3.0	2.0
Leaf wash	1.1	0.1	7.7	6.9	1.8
Retention in litter and roots	15.2	3.4	1.4	32.8	4.6
Total uptake	30.2	5.2	20.1	52.0	9.4
Reserves (kg/ha)					
Standing dead biomass	9.4	0.5	6.0	28.2	1.4
Roots	71.1	20.3	43.3	105.6	11.4
Organic soil	1637.9	18.1	90.6	550.6	67.8
Mineral soil	2261.1	18.4	80.5	664.6	74.9
Total reserves	3979.5	57.3	220.4	1349.0	155.5
Live tree standing crop (kg/ha)	287.4	31.1	165.5	356.5	37.6

[a] MAI = mean annual increment.

become locked up in humus for many years. One measure of the locking up and release of nutrients is residence time. Data gathered by Gordon (1981) indicate that residence times for N, P, K, Ca, and Mg are longer under predominantly softwood stands than under hardwood stands in the boreal mixedwood section. The more rapid break down of aspen and birch litter relative to that of conifers is probably the main reason for the shorter residence time of nutrients in mixedwood stands that contain a high proportion of hardwoods. Nitrogen, however, is a nutrient that may be locked up for very long periods in the absence of fires, relative to P, K, Ca, and Mg, even in boreal mixedwoods that are predominantly hardwoods (Gordon 1981).

Some researchers have singled out the potentially important role of aspen for rapid cycling of Ca. For example, cycling of Ca by aspen is believed to maintain the luvisolic soils of the Fort Nelson area, British Columbia, in a relatively productive state by retarding acid leaching (Valentine et al. 1978). In Minnesota, on a very fine sandy loam, Ca in the aboveground aspen standing crop amounted to 18% of the exchangeable Ca in the total ecosystem; on a loamy sand, Ca held by aspen aboveground was 25% of that in the total complex (Perala and Alban 1982a). This led Perala and Alban to caution that intensive utilization of aspen could stress the calcium economy of these sites.

Nutrient Implications of Whole-tree Aspen Harvesting

The literature on nutrient consequences of forest harvesting in boreal mixedwoods (Gordon 1983; Timmer et al. 1983) indicates that nutrient losses will be a concern only if rotations become relatively short. Current data suggest that nutrient loss from whole-tree harvesting of aspen is not a major concern unless rotations are under 25 years. Recent research reported by Alban and Perala (1990a) indicated that if mature aspen is harvested, annual litter fall can return to preharvest levels within 6 years of harvesting. In their Minnesota and Michigan studies, these researchers concluded that aspen harvesting resulted in no short-term effects on soil organic matter or soil nutrients. Gordon (1981) also pointed out that not many years are required for nutrient replacement following full-tree harvesting of a mature mixedwood stand at full rotation. For example, in the Nipigon area of Ontario, he estimated that, in mixedwood stands made up of 25% softwood and 75% hardwood (aspen and birch), the number of years required to replace nutrients lost in a single crop removal were as follows: N replaced in 19 years; P in 15 years; K and Ca in 17 years; and Mg in 14 years.

A relatively high proportion of the aboveground nutrient content in hardwood biomass is in the foliage, and this is particularly true for N. If whole-tree removal of hardwoods occurs during the leafless season, the foliage component of the nutrient pool is not lost to the site. Unpublished Forestry Canada aspen nutrient data gathered under ENFOR Project P-205, indicate that nutrient losses from aspen harvesting may not be of concern because a high proportion of total site nutrients is contained in the soil and litter rather than in the harvestable tree components. The magnitude of the nutrient pool contained in the soil horizons of Alberta aspen ecosystems is summarized in Table 23. Maximum site nutrient losses were estimated to be 3.5% of total site N if all aboveground components were removed in young aspen stands, 7–19 years old, and 4.9% of total site S if all young aboveground aspen were harvested. The nutrient consequences of removing various components during harvesting are, of course, different when expressed on the basis of tree nutrient pool instead of total site nutrient pool (Table 24). For example, an estimated 59.8% of an aspen stand's N pool is in the foliage when stands are young (7–19 years), but 22.9% for stands 40–67 years old. Harvest removal of foliage in young stands, therefore, represents a substantial loss of aboveground nutrient pool, although it is a relatively small portion of the total site nutrient pool.

A recent study in Minnesota on several different soil types revealed that even whole-tree harvesting had no significant effect on soil nutrition levels 5 years after logging. In this experiment, whole-tree harvesting removed 90–240 t/ha of biomass, and conventional harvesting removed 20–60% less. Herb and shrub biomass increased dramatically after logging. After 5 years, total aboveground biomass was 11–15% of precut levels under both whole-tree and conventional harvesting systems. Within 5 years after harvesting, litter fall had returned to precut levels, but was composed of a higher percentage of herb and shrub materials. Five years after harvesting, the logging slash was reduced by 50%.

In the Minnesota study, organic matter in the forest floor and surface soil horizons declined for a few years after harvesting, but after 5 years it had returned to preharvest levels. Exchangeable Ca and pH of the surface mineral soils increased slightly after harvesting. Below 10 cm, no soil properties were significantly affected by harvesting after 5 years. Accelerated loss of Ca and N by leaching occurred after harvesting, but the amounts were small and insignificant in comparison to harvesting losses. At the end of 5 years, soil solution nutrient concentrations below the rooting zone did not differ between harvested areas and uncut controls (Alban and Perala 1990b).

Table 23. Percentage losses of total site nutrients for various assumed biomass removals in young and old aspen ecosystems (Peterson, Chan, and Peterson 1988)

If harvesting results in total removal of:	Percentage of total site nutrient content lost											
	Nitrogen		Phosphorus		Potassium		Calcium		Magnesium		Sulfur	
	Y[a]	O[b]	Y	O	Y	O	Y	O	Y	O	Y	O
Aboveground aspen components	3.5	2.4	0.5	0.3	0.1	0.1	0.4	0.6	0.1	0.1	4.9	7.3
Aspen roots	0.2	0.7	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	0.3	1.4
Shrubs and herbs	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
Litter	10.4	10.6	1.1	1.0	1.0	0.1	1.3	1.4	0.2	0.2	5.6	4.6
Percentage of nutrient pool in A, B, and C soil horizons	85.7	86.1	98.3	98.7	99.7	99.7	98.2	97.8	99.7	99.7	89.0	86.5

[a] Y = young stands, 7–19 years.

[b] O = old stands, 40–67 years.

Table 24. Percentage losses of total tree nutrient content for various assumed biomass removals in young, medium-aged, and old aspen stands (Peterson, Chan, and Peterson 1988)

	Percentage of total tree nutrient content lost																	
	Nitrogen			Phosphorus			Potassium			Calcium			Magnesium			Sulfur		
If harvesting results in removal of:	Y[a]	M[b]	O[c]	Y	M	O	Y	M	O	Y	M	O	Y	M	O	Y	M	O
Merchantable stem wood	–[d]	16.5	23.1	–	15.9	20.1	–	23.9	34.4	–	19.5	25.2	–	27.2	35.9	–	46.0	60.2
Bark on merch.[e] stem wood	–	4.9	8.0	–	5.0	7.2	–	4.7	5.9	–	10.4	14.8	–	5.5	8.4	–	2.5	4.2
Nonmerch. stem wood & bark	18.9	9.7	6.6	20.3	10.0	5.8	9.6	12.7	6.5	26.0	12.8	7.7	30.1	14.0	7.7	61.7	19.8	8.4
All stem wood & bark above stump	18.9	31.1	37.7	20.3	30.9	33.1	29.6	41.3	46.8	26.0	42.7	47.7	30.1	46.7	52.0	61.7	68.3	72.8
Small branches	13.6	8.6	7.2	14.7	10.4	7.0	15.1	8.7	6.1	27.2	11.9	8.5	17.3	9.3	5.8	10.4	5.3	2.8
Large branches	1.1	5.3	5.0	1.3	6.3	4.9	1.4	5.3	4.7	2.4	7.4	6.5	1.7	6.7	4.6	1.4	4.0	2.7
Dead branches	0.3	2.0	3.0	0.2	1.6	2.4	0.3	2.1	2.2	1.0	4.1	4.6	0.6	2.9	2.9	0.4	1.5	1.5
All branches	15.0	15.9	15.2	16.2	18.3	14.3	16.8	16.1	13.0	30.6	23.4	19.6	19.6	18.9	13.3	12.2	10.8	7.0
Stem wood, bark, & branches	33.9	47.0	52.9	36.5	49.2	47.4	46.4	57.4	59.8	56.6	66.1	67.3	49.7	65.6	65.3	73.9	79.1	79.8
Foliage	59.8	35.2	22.9	51.1	25.7	16.8	40.8	21.3	11.0	30.5	10.0	4.0	40.8	15.3	7.0	17.2	6.2	2.5
Total above stump	93.7	82.2	75.8	87.6	74.9	64.2	87.2	78.7	70.8	87.1	76.1	71.3	90.5	80.9	72.8	91.1	85.3	82.3
Stump wood & bark	–	3.3	2.6	–	3.4	2.2	–	2.8	2.2	–	5.1	3.2	–	3.4	2.5	–	3.8	2.7
Large roots	3.8	8.3	14.7	8.1	3.1	23.7	9.0	12.3	20.0	9.0	12.0	18.7	6.6	9.7	18.3	6.6	8.4	11.8
Medium & small roots	2.4	6.0	6.8	4.2	8.5	9.8	3.7	6.1	6.9	3.9	6.6	6.6	2.9	6.0	6.8	2.1	2.7	3.1
All roots	6.2	14.3	21.5	12.3	21.6	33.5	12.7	18.4	26.9	12.9	18.6	25.3	9.5	15.7	25.1	8.7	11.1	14.9
All roots & stump	6.2	17.6	24.1	12.3	25.0	35.7	12.7	21.2	29.1	12.9	23.7	28.5	9.5	19.1	27.6	8.7	14.9	17.6

[a] Y = young stands, 7–19 years.

[b] M = medium-aged stands, 20–39 years.

[c] O = old stands, 40–67 years.

[d] Data not available.

[e] Merch. = merchantable; nonmerch. = nonmerchantable.

Role of Boreal Hardwood Foliage in Nutrient Cycling

Boreal hardwood species contain substantially higher concentrations of N and P in their current-year foliage than do white spruce and black spruce of comparable age. Alaskan data gathered by Flanagan and Van Cleve (1983), reproduced below, indicate the magnitude of these species differences (Table 25).

Although Chapin (1980) found that under controlled low-nutrient conditions, plants from nutrient-poor sites had higher tissue concentrations of nutrients than plants from fertile sites, nutrient concentrations in aspen biomass components from sites of varying quality in Alberta did not reveal a consistent pattern (unpublished Forestry Canada data from ENFOR Project P-205). Even when two plots that had the highest aspen site indexes (24.8 m and 21.5 m at 50 years) were compared with two plots with the lowest site indexes (15.2 m and 15.1 m at 50 years), there were not consistent site-related differences in nutrient concentrations (Table 26). For N, the largest site differences are revealed in the foliage and small root components. For K, there appears to be no site influence on concentration in any of the foliage, wood, bark, or root components. Phosphorus concentrations in all biomass components appear to be higher on good sites than on poor sites. These patterns, however, were not consistent when the entire dataset was examined (Peterson, Chan, Peterson, and Kabzems 1989). In comparison, Voigt et al. (1957) recorded the following site differences for nutrient concentrations in foliage of aspen in Minnesota:

	Nutrient content as % of dry weight		
Nutrient	Good site	Medium site	Poor site
Nitrogen	1.85	1.32	0.96
Phosphorus	0.16	0.12	0.15
Potassium	1.29	1.21	0.94

There is evidence that there is less site influence on nutrient concentrations of aspen wood than there is for foliage. Wilde and Paul (1959) found that the chemical composition of wood grown on different soils in Wisconsin, supporting aspen stands 39–56 years of age, varied less than 10%.

There is still active research on the degree to which clonal species such as aspen have tree-to-tree variation in the process of resorption, which is the removal of nutrients and other substances from senescing leaves and the subsequent movement of these substances to surviving tissues (Killingbeck 1986, 1988). From studies in Rhode Island aspen clones, Killingbeck et al. (1990) observed that the timing of complete leaf abscission strongly influenced resorption efficiency. Leaves that fell first or became fully senesced first had higher amounts of N, P, and copper than leaves that senesced later. The same researchers also noted the tallest stems in a clone lost their leaves earlier than shorter stems. The result was that older, larger stems resorbed less N than younger, smaller stems in the same clone.

Role of Aspen Understory Vegetation in Nutrient Cycling

Aspen ecosystems typically have a substantial herb and shrub understory compared to coniferous stands on similar sites in the same region. Understory vegetation is considered to play an important role in cycling of nutrients in aspen ecosystems. The review by Bernier (1984) indicated that the contribution of understory vegetation to total aboveground nutrient input in *Populus* ecosystems may be higher than would be indicated by its contribution to litter biomass, because there are higher nutrient concentrations in litter from understory species than in tree litter. For example, Perala and Alban (1982a) found that in a 40-year-old trembling aspen stand in Minnesota, where understory vegetation produced 19% of the total aboveground litter production, it actually

Table 25. Average nutrient concentration (% of dry weight) for current foliage of boreal tree species from stands of approximately the same age

Species	Stand age (year)	n[a]	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
Aspen	60	18	2.01	0.24	0.91	1.33	0.29
Birch	60	18	2.20	0.22	0.96	0.63	0.35
Black spruce	62	18	0.88	0.12	0.61	0.29	0.12
White spruce	70	10	1.10	0.15	0.50	0.85	0.16

[a] Numbers of trees sampled within stand.

Table 26. Means and standard deviations of nutrient concentrations in aspen biomass components on good and poor sites in Alberta (Peterson, Chan, Peterson, and Kabzems 1989)

Sites	Nutrient concentration (%)[a]		
	Nitrogen	Phosphorus	Potassium
Two good sites			
Plot numbers: 14 and 28			
Site indices: 24.8 and 21.5 m @ 50 yr			
Stand ages: 53 and 13			
Foliage	2.93 ± .92	0.40 ± .15	1.49 ± .24
Stem tip	0.19 ± .05	0.03 ± .01	0.14 ± .05
Stem wood[b]	0.07 ± .02	0.01 ± .003	0.08 ± .03
Stem bark[b]	0.37 ± .07	0.06 ± .02	0.28 ± .05
Small roots	0.58 ± .17	0.13 ± .03	0.48 ± .06
Large roots	0.19 ± .05	0.05 ± .02	0.30 ± .12
Two poor sites			
Plot numbers: 5 and 35			
Site indices: 15.2 and 15.1 m @ 50 yr			
Stand ages: 26 and 13			
Foliage	2.55 ± .40	0.26 ± .04	1.29 ± .36
Stem tip	0.22 ± .07	0.04 ± .01	0.18 ± .06
Stem wood[b]	0.07 ± .01	0.01 ± .003	0.09 ± .04
Stem bark[b]	0.36 ± .05	0.06 ± .02	0.32 ± .06
Small roots	0.53 ± .15	0.11 ± .02	0.45 ± .08
Large roots	0.20 ± .14	0.04 ± .02	0.27 ± .04

[a] Mean of 10 trees, five from each of the two plots.

[b] Excluding the stem tip sample.

contributed 36% of the litter N, 40% of the litter P, and 59% of the litter K.

The role of herbs and shrubs in nutrient dynamics could be particularly important if fertilization were to be undertaken to promote aspen production. Some researchers have suggested that because productive aspen sites are characterized by an abundant cover of understory vegetation the potential benefits of fertilization may be lost to uptake by herbs, grasses, and shrubs (Steneker 1976b). Steneker suggested that control of understory vegetation may actually be a greater stimulus to aspen growth than fertilization would be. It is ecologically significant that the understories of many aspen stands are characterized by the presence of *Alnus*, *Shepherdia*, and several species of legumes, all of which are capable of N fixation.

Role of Phosphorus in Aspen Ecosystems

In a study to assess relationships between root location, root density, and soil nutrient status, Strong and La Roi (1985) found that phosphate (PO_4) was the only measured variable in the Lesser Slave Lake area of Alberta that consistently had a strong positive correlation with root density, including aspen stands. They reported that the relationship between roots and PO_4 content of the soil was biologically significant and that PO_4 may ultimately limit productivity of boreal upland forests. Strong and La Roi recommended fertilization trials to test the PO_4 deficiency hypothesis for aspen and other boreal forest types.

In all of the boreal forest stands studied by Strong and La Roi (1985), the highest concentration of roots was in the lower portion of the humus layer or immediately below it. Such root distribution patterns are probably adaptive and not coincidental, since the main source of recyclable nutrients, warmest soil temperatures, best aeration, most available water, and the highest water-holding capacities occur just below the ground surface. In combination, these conditions promote maximum litter decomposition and greatest nutrient release relative to lower horizons in the soil profile. Extractable PO_4 was among the nutrients that attained its highest concentrations in the near-surface soil horizons described by Strong and La Roi (1985) in central Alberta.

There are also other aspects of P cycling that are not yet clear. For example, available data on *Populus*, not specifically aspen, suggest that the turnover of P is slower than that of N (Bernier 1984). This may relate to the fate of P during translocation from senescing foliage and reflect the characteristic storage and recovery process of this element within the trees. There is evidence that in *Populus* a significant proportion of P that is otherwise retained in wood might be recovered only when sapwood is actively transformed into heartwood (Clement and Janin 1976). Bernier (1984) suggested that more research is needed to assess the extent to which P may be recovered through this pathway in *Populus*. Uncertainty about the role of P in aspen ecosystems is part of a broader problem: an overall lack of detailed understanding of nutrient availability in forest soils. The basic problem of predicting or defining the amount of nutrient potentially available to plants remains, for practical purposes, unresolved. The chemical, biological, and biochemical methods used to estimate potentially available nutrients are only indexes of the actual amounts of plant-available nutrients in the soil (Mahendrappa et al. 1986).

Meteorologic Influences

The broad geographic distribution of aspen reveals its adaptation to a wide variety of climates. Cold continental and boreal climates are more favorable for aspen than are humid or coastal environments (Haeussler and Coates 1986). Near its southern limit in the western United States, aspen tends to occur only at higher elevations and is commonly best developed on north-facing slopes. In contrast, at the latitude of northern British Columbia and farther north, aspen is most abundant on south-facing slopes. Frost resistance in aspen is high, and the species easily survives in frozen ground having no snow cover. In Alaska, it is dominant on sites where the permafrost layer comes within 20 cm of the soil surface.

Aspen is a shade intolerant species, especially at the sucker and seedling stage when full sunlight is required for optimal growth. In their ranking of shade tolerance, Klinka et al. (1990) gave balsam poplar a rating of 22 and aspen a rating of 16 in a scale of 1 to 26, in which 26 was the most intolerant.

A Michigan study (Brissette and Barnes 1984) in which aspen clones from western North America initiated shoot growth earlier in spring than clones from Michigan, indicated that under native conditions, western provenances of aspen are adapted to initiate growth at lower accumulated degree-days. Clones from northern latitudes or high elevations also ceased growth earlier than the Michigan clones because they are genetically adapted to the photoperiods and growing season temperatures of their native habitats. Woodward (1987) pointed out that there is little documentation of why species that are able to survive the low winter temperatures of the boreal zone usually do not occur naturally in warmer climates. He singled out *P. balsamifera* in this context and mentioned that this species, along with *Picea mariana*, tends not only to grow poorly but to become shorter-lived in warmer climates.

The nature of the relationship between successional status and frost tolerance remains to be defined (Woodward 1987). It is known, however, that for late successional species of deciduous trees the temperatures of the dormant buds, xylem, or cambium are critical for survival, with limits falling between -15°C and -40°C. This relationship is evidently not true for the early pioneer and short-lived genera such as *Betula* and *Populus* that have tolerances for low temperatures below -40°C, often equalling those of boreal conifers (Sakai and Weiser 1973).

There is evidence that photoperiodic sensitivity of aspen varies by latitude. As with a number of tree species for which the relationship of photoperiodic response to geographical origin has been worked out, aspen of more northerly origin responds more strongly to photoperiod than those farther south (Vaartaja 1960). For balsam poplar, Schnekenburger and Farmer (1989) found that from northern Wisconsin to the Hudson Bay lowlands this species showed little geographic variation in assimilation rate and growth rate under moderate temperatures. Most of the variation in these growth features occur as clonal variation within populations, just as balsam poplar dormancy (Farmer and Reinholt 1986) and rooting (Farmer et al. 1989) also vary mainly by clones within populations. Studies to date suggest that photoperiodic response may be the only major adaptive mechanism responsible for genetic differentiation in balsam poplar growth in the Wisconsin–Hudson Bay lowlands transect described by Schnekenburger and Farmer.

Several authors have noted the problem of sunscald injury to stems that have been abruptly exposed to sunlight, for example following thinning (Bickerstaff 1946; Anderson 1972; Hubbard 1972; Hinds 1976; Jones and Shepperd 1985a). Susceptibility to sunscald appears to vary in proportion to the amount of bloom on the bark surface; bloom is commonly more prevalent on the south sides of trunks than the north sides (Covington 1975).

Aspen and Balsam Poplar Adaptation to Cold Weather

In the Lake States, Holdaway (1988) analyzed tree growth in relation to common climatic variables, examining conifers, warm weather hardwoods, and cold weather hardwoods. Aspen was included in the latter group of species. For cold weather hardwoods, the strongest single climatic variables beneficial to tree diameter growth, in decreasing order of importance were: high June precipitation; low proportion of days with intense precipitation (over 1.2 cm) and moderate precipitation (0.3 to 1.2 cm) in summer; and lower proportion of total annual precipitation occurring in December. The strongest climatic interactions between temperature and precipitation variables detrimental to growth of cold weather hardwoods in the Lake States was high temperature with low precipitation in June. The degree to which these relationships would apply farther to the northwest in the prairie provinces is not known.

In many northern temperate hardwoods, if temperatures fall below -40°C permanent damage is done to the ray parenchyma cells, which prevents refilling of any collapsed vessels. This effectively limits the northwesterly distribution of many eastern deciduous hardwoods (Waring and Schlesinger 1985). How then, can aspen and balsam poplar figure so prominently in boreal forests of northwestern Canada and Alaska? Their most important adaptation is the presence of permeable membranes that permit rapid movement of water out of living cells. This prevents formation of destructive ice crystals inside the cells (Burke et al. 1976). It is for this reason that frost resistance is rated by Krajina et al. (1982) as high for aspen and very high for balsam poplar.

Aspens, along with white birch (*B. papyrifera*), willows (*Salix* spp.) and red-osier dogwood (*Cornus stolonifera* Michx.) have a type of freezing pattern that allows them to extend into arctic regions and to survive experimental freezing to temperatures as low as -196°C. In these very hardy woody species, ice formation begins somewhere in the plant after a few degrees of supercooling, and ice propagation proceeds through the extracellular spaces. This creates an extracellular vapor pressure deficit, and cell water is drawn from the protoplasm to the extracellular spaces where it freezes. In midwinter, many hardy woody plants survive the extreme dehydration that results when all of the freezable water crystallizes extracellularly. The unfreezable (bound) water fraction in stems of such species may amount to about 30% of the total water in their tissues during winter. In effect, aspen and other plants that are hardy because they have a high tolerance to extracellular freezing are also displaying a form of drought tolerance because removal of water from cells to extracellular ice imposes considerable drying stress on protoplasm (Burke et al. 1976).

Frost damage to aspen foliage develops first on leaf margins and progresses toward the center. As illustrated by color photographs in the handbook by Malhotra and Blauel (1980), frost damage actually involves necrosis, the death of living tissue characterized by browning and drying. Tissue necrosis spreads rapidly to the center of the leaf after a damaging frost without any preceding chlorosis (yellowing). Spring frost can inhibit both leader growth and radial growth of aspen (Strain 1966). Frost damage to immature leaves most often occurs in spring when warm weather is followed by freezing (Marr 1947; Cayford et al. 1959; Egeberg 1963). A critical point is the time when sap rises into the cambial cells.

Zalasky (1976) described two types of frost damage; outright killing (cankers and dieback); and distortion of developing plant parts surrounding the canker or dieback. Frost cankers are freeze-killed areas of bark or wood where woody calluses develop and form burls or frost ribs. Frost dieback is distinguished as a freeze-killed segment of the stem at the base, tip, or mid-portion of a branch or leader. There is also some evidence of root kill from severe frost. Trees that experience root kill may die if they are unable to form new roots due to lack of moisture, cold soil conditions, or if there is total root kill. Repeated cycles of freezing and thawing can accelerate decomposition of litter by physical damage or chemical changes to leaves, which makes them more readily degradable by decomposers (Taylor and Parkinson 1988d).

Snow and Hail Damage to Aspen

Snow-broken suckers have been reported in Colorado (Hinds and Shepperd 1987) and in the mountains of northern Utah (Jones and DeByle 1985c). Late spring and early fall snow storms, when trees have leaves and when snow is wet and heavy, can result in bent and broken branches. In northeast Alberta, a September freezing rain followed by wet snow resulted in stem breakage and uniform bending of aspen in a mixedwood area (Gill 1974). The height of stem breakage increased with increasing stand density and distance from a clearing. In this case, the upswept branches of aspen and lack of winds enhanced snow accumulation in tree crowns. Cayford and Haig (1961), however, observed that little damage occurred to leafless aspen during freezing rain followed by snow and wind during a storm in Manitoba.

Hinds and Shepperd (1987) documented hail damage to the main stems of aspen suckers but damage was primarily in the upper crowns of dominant and codominant stems at sites studied in Colorado. Hail damage to aspen crowns was also reported by Riley (1953) for sites in Saskatchewan.

Wind Damage to Aspen in the Boreal Region

Wind damage is relatively uncommon in the boreal portion of aspen's range. The same is apparently true elsewhere as well. For example, Jones and DeByle (1985c) noted that aspen is a relatively windfirm species and that most blowdowns of aspen are the result of previous decay in butts and roots. Where blowdown has been observed, it generally involved breaking off at ground level, following removal of conifers in mixed stands, or along the edges of clear-cuts when the protection of other trees was removed (Gottfried and Jones 1975; Shepperd 1986). Forbes and Davidson (1962) described windthrown (uprooted and tipped over) aspen in New Brunswick following a hurricane. When branches are broken by wind, the broken stubs provide entry courts for infection (Hinds and Krebill 1975). Swaying of aspen trees by wind may also break roots, thus subjecting them to disease infection (Basham 1958). Fralish (1972) considered wind exposure to be as significant to aspen growth as are soil water-holding capacity and water-table depth. In the mountainous areas of the western states, wind exposure inhibits aspen growth, and in the foothills of Alberta warm chinook winds are known to damage aspen branches and buds.

Soil, Soil Moisture, and Water Relationships

The basic references reviewed by Corns (1989) make it clear that aspen can occur as a dominant or codominant tree on a wide range of sites. Aspen stands develop on shallow rocky soils, loamy sands, and wet clays, but it is mainly a species of well-drained uplands (Haeussler and Coates 1986). Haeussler and Coates indicated that aspen achieves its best growth on moist but well-drained porous, loamy soils; Krajina et al. (1982) emphasized the importance of nutrient-rich substrates, especially calcium-rich soils derived from limestone, for good growth of aspen. Although aspen can survive long periods of flooding (Krajina et al. 1982), as soil internal drainage changes from moderately well drained to imperfectly drained, productivity of aspen decreases and spruce becomes a more prominent component than aspen (Corns 1989). Fralish (1972) stated that soil moisture is the most important factor affecting the growth of aspen. Water tables between 1.0 and 2.5 m in depth are best for aspen, especially in coarse- and medium-textured soils (Haeussler and Coates 1986).

For European aspen, Borset (1960) reported that wet *Sphagnum* patches are favorable microsites for aspen seedling establishment, and the same has been observed for aspen in the Lesser Slave Lake region of Alberta. Seedlings originating on such substrates, however, are apparently short-lived as aspen is poorly suited for stand development on peat.

Balsam poplar is most commonly found on moist upland and alluvial bottomland sites; its best growth is on moist, rich bottomlands with deep soil. Unlike aspen, balsam poplar rarely grows on dry, exposed sites; like aspen it does not develop into stands on peaty soils (Haeussler and Coates 1986). Good growth of balsam poplar is dependent on a reliable supply of soil moisture (Zasada and Argyle 1983). Although balsam poplar's tolerance of flooding is among the highest of boreal tree species, it does not tolerate brackish water (Krajina et al. 1982).

Several investigators have emphasized the influence of aspen litter upon soil properties (Dormaar and Lutwick 1966; Troth et al. 1976; Alban 1982). In northern Utah, Tew (1968) observed that in the upper 15 cm of soils under aspen there is a higher organic matter content and higher moisture-holding capacity than in soils developed under adjacent herb–shrub sites. Soils under aspen, however, generally contain less organic matter than those under conifers. Based on studies in Minnesota, Kienzler et al. (1986) attributed these differences to the greater abundance of bacteria and fungi in the soils under aspen. The more abundant microorganisms in soils of aspen ecosystems leads to faster decomposition than under coniferous ecosystems.

As emphasized in the last section of this report, there is a need for expanded research on humus types of aspen-dominated ecosystems. Taxonomic classification of humus types has been shown to be of practical silvicultural importance in coniferous forest ecosystems (Klinka et al. 1981; Green et al. 1984), but humus has not been given much attention in the development of silvicultural prescriptions in aspen forests. Corns (1989) singled this out as a topic of importance, citing Pierpoint et al. (1984), who also called for humus research in ecosystems where boreal hardwoods are dominant or prevalent.

Aspen Site Quality in Relation to Soil Moisture and Soil Texture

Early aspen reports in North America were strongly influenced by impressions that the best aspen sites appeared to have plentiful moisture. In the past 30 years, however, many aspen researchers have emphasized that the effects of water regime on productivity cannot be isolated from other factors. For example, properties that give soils favorable moisture conditions include high organic matter, a silt and clay content of 55–65%, and a water table for which the optimum varies by parent material (Sucoff 1982). A shallow water table is associated with high aspen productivity on coarse-textured soils, but the opposite may be true on fine-textured soils. Subsurface gravel layers under sands or loams may reduce site index, whereas fine-textured heavy soils under sands increase site index (Stoeckeler 1960; Sucoff 1982).

Recent modeling of aspen site quality (Fralish and Loucks 1967, 1975; Gale and Grigal 1990) has attempted to incorporate additional variables beyond soil texture and soil moisture. For example, Fralish and Loucks concluded that aspen site index in Wisconsin is mainly controlled by availability of water, which, in turn, was best predicted by a regression model based on available water-holding capacity in the top 30 cm of soil, water table depth, and exposure in terms of aspect and topographic position. In the Wisconsin study, aspen site index was most strongly correlated with exposure, which indicates the importance of considering evaporative demand in site–moisture relations.

Although laterally moving water within the root zone influences site quality of aspen (Sucoff 1982), soil texture is commonly cited as an important factor influencing the site quality of aspen-dominated ecosystems. Textural differences are, of course, expressed in other ways because the silt and clay content of the soil influences both the moisture regime and the fertility level, as expressed by cation exchange capacity. Some examples of site features that researchers have singled out as characteristic of excellent, good, or the best aspen sites are summarized in Table 27.

Aspen's Adaptations for Growth in Dry Sites

Aspen leaves lose water more rapidly than many other temperate zone tree species, but despite relatively high transpiration rates, aspen can occupy moderately dry sites. To achieve this, the most important adaptation is to regenerate by way of root suckers. Young aspen stands of sucker origin obviously have very high root:shoot ratios. It is in seedling form that aspen is most susceptible to drought. Therefore, in those stands that can regenerate and spread by root suckers, instead of by seedlings, a critical drought-related phase can be bypassed (Sucoff 1982). The review by Perala and Russell (1983) stressed that young aspen stands of sucker origin are particularly tolerant of drought because they are connected to well-established root systems. In contrast, drought is the most common cause of seedling mortality.

Aspen adapts well to drought with a root system that, in some cases, extends to depths of 3 m. The relatively low leaf area that is characteristic of pure aspen canopies also helps to lessen water demand. Potentially counteracting these adaptations is the consumption of soil moisture by the comparatively lush herb, grass, and shrub understories that can develop under the somewhat sparse and open canopies of aspen. Understory species are less deeply rooted than aspen and do not severely compete with aspen for water at soil depths below 1 m (Sucoff 1982).

There is evidence that drought encourages natural thinning of aspen but does not kill entire groups of trees. Direct drought kill of entire aspen stands, or even small groups of trees, is not documented in the literature, but several researchers have related natural thinning to moisture deficits. The wave-like patterns of thinning that occur in young aspen stands on light soils in Michigan were considered by Graham et al. (1963) to be a combination of drought and insect and disease interactions. They suggested that as stands develop, the increased foliage area increases transpiration to the limit of available soil moisture. Natural mortality of some stems then follows, after which there is a period of rapid growth until soil moisture again becomes limiting. The suggestion that pests induce more mortality during dry periods than during wet periods is based on three premises: the same amount of damage is more destructive when the tree is already stressed; pest invasions are often more successful when the tree is growing slowly; and dry weather can directly influence insects and diseases.

The Role of Water

The very detailed review by Sucoff (1982) summarized the movement of water from the soil through aspen to the atmosphere. From study sites in Utah, Colorado, Minnesota, and the U.S.S.R., it was estimated that winter transpiration from leafless twigs is very low, measured at 0.025 g water/g of 1-year shoot/day, compared to 35 g water/cm^2 of leaf/day in summer. Because aspen suckers use the clone's preexisting root system, their evapotranspiration rates quickly approach those of mature stands, generally within 10–16 years. Compared to pine, birch, and spruce, aspen transpiration rates are relatively high per unit of leaf area. Aspen stands, however, may not actually transpire more than stands of other species because aspen carries less foliage per hectare than many other tree species. Understory species are estimated to account for 10–15% of total evapotranspiration from aspen stands (Sucoff 1982).

Based on studies with *P. grandidentata*, there is evidence of competition for water within a clone. When the crown of one tree within a clone was exposed to increased wind and radiation, stem moisture potential decreased in a second tree within the clone. It is not known whether water moved from the stem that was

Table 27. Site conditions associated with good or excellent aspen growth

Site characteristics	Location	Reference
Nutrient-rich substrates, especially calcium-rich soils derived from limestone; hygric hygrotope and subeutrophic trophotope	British Columbia	Krajina et al. 1982
Water table between 1.0 and 2.5 m	British Columbia	Haeussler and Coates 1986
Fresh to moist (good to moderate) soil moisture and sandy loam or clay loam (not sand or clay) soil texture	Alberta Saskatchewan Manitoba	Steneker 1976b
Soils with free lime or with high calcium content	Ontario	Heeney et al. 1980
Silt or clay loams with a silt and clay content of 50–70% and a fresh to very fresh moisture regime	Ontario	Heeney et al. 1980
Water table 0.7–2.0 m below the surface	Lake States	Fralish 1972; Stoeckeler 1959; Wilde and Pronin 1949
Silt plus clay content in excess of 31% (percent of total cubic volume in upper 1 m of soil) and depth to water table greater than 60 cm	Lake States	Brinkman and Roe 1975
Porous, loamy, humic soil with an abundance of lime	Lake States	Zehngraff 1947
Loam and silt loam soils on boulder clay or clayey moraine	Lake States	Kittredge and Gevorkiantz 1929; Kittredge 1938
Loams with heavy (clayey) subsoil and moderately high water table	Lake States	Roe 1934, 1935
Rich herbaceous vegetation	Lake States	Kittredge 1938; Roe 1934

transpiring less into the stem that was transpiring more, or whether the common roots sent more water to the exposed stem at the expense of the untreated one (Sucoff 1982). At the time of Sucoff's review, aspen root resistance to uptake or transport of water had not been studied.

The water content of aspen stems changes seasonally. The xylem of aspen stems is wettest in winter, then dries somewhat after leaf out, and fluctuates during summer. Bendtsen and Rees (1962) recorded winter moisture content of 113% ovendry weight, but only 80% in summer. On one site during winter, bark with a moisture content of 66% ovendry weight was adjacent to xylem at 131%, a difference that Sucoff (1982) suggested as a possible explanation of frost cracking.

Water is unevenly distributed in aspen stems. Bendtsen and Rees (1962) reported that in summer the outer five annual rings were always wetter than the next five rings inward. Moisture also decreases with tree height, especially in the outer rings. In winter, the inner rings were always wettest and there was less vertical gradient. Sucoff (1982) reported that, over the year, wetwood had a higher water content (142% ovendry weight) than heartwood (106%) or sapwood (88%), and that the presence of *P. tremulae* reduced the water content of sapwood.

The Role of Aspen Leaves in Water Regulation

Aspen leaf surfaces have three important roles: they are sites of evaporation; they provide the major resistance to water flux through the soil–plant–atmosphere complex; and they are the site where water loss is regulated by closure of stomates. Literature summarized by Sucoff (1982) indicated that stomatal guard cells averaged 31.2 ± 3.5 microns in length and stomate length averaged 17.9 ± 4.7 microns. The number of stomates/mm^2 has been measured to range from 12 to 168. Water loss occurs through both surfaces of aspen leaves, even though stomates occur only on the lower leaf surface. Cuticular water loss from the upper surface was estimated by Sucoff to represent only 6–9% of total daytime transpiration from aspen leaves.

Except for expected diurnal changes, the diffusive resistance of water movement through aspen leaves has been found to vary mainly with shoot type. Short shoots, which are secondary branches with almost no internodes between leaves, have leaves that display diffusive resistances up to 4 times greater than on long shoots; the latter are shoots typical of suckers or rapidly growing primary branches in which there is at least 1 cm of internode between each leaf petiole. The proportion of short shoots increases as aspen trees develop and age. The higher diffusive resistance of short shoots indicates that trees with higher proportions of short shoots would be more drought resistant than those with many long shoots.

Flooding Tolerance of Aspen and Balsam Poplar

Aspen has a low tolerance to flooding, but balsam poplar commonly occurs in alluvial ecosystems that are subject to flooding. To tolerate burial by soil, trees need to form new roots. Based on observations from northern Wisconsin north to the vicinity of Bearskin Lake in northern Ontario (longitude 90°W, latitude 54°N), Farmer et al. (1989) hypothesized that, under natural conditions, the presence of preformed root primordia on balsam poplar probably has some survival value under circumstances where flooding may deposit soil around tree bases. Farmer and co-workers hypothesized that there is considerable variation in selection pressure for preformed root primordia within balsam poplar provenances from high pressure along terraces and deltas of rivers to essentially none on uplands. Some variation in rooting characteristics, therefore, would be expected within provenances. These researchers concluded that little genetic differentiation in number of preformed root primordia took place among provenances, but that there is considerable genetic variation within provenances. There was wide variation in rooting ability among cuttings from a single stock plant and also among different cuttings taken from a single 40-cm-long shoot.

Physiological Responses

In addition to the physiological indicators of variations in nutrient status, meteorological phenomena, and soil moisture, aspen or balsam poplar may respond physiologically to other factors such as physical injuries, pollutants, herbicides, allelopathy, and myccorhizae. The most important of these responses are summarized in this section.

Physical Injuries

Aspen stems are subject to several physical injuries, most of which are not fatal. Generally, injured trees either outgrow their injury or simply grow with reduced capacity and vigor. Physical injuries to aspen, however, may create infection courts for pathogens. The soft living bark of aspen makes this part of the tree particularly susceptible to damaging agents (Hambly 1985). Many of the physiological indicators of physical injury were referred to in a previous section in relation to meteorological influences. Aside from defoliation and outright breakage of crowns or branches, physical injuries may result in stem lesions. A given intensity of physical abrasion to aspen or balsam poplar bark will result in the most severe damage in the period from bud burst in spring until midsummer. That is the period when the cambium is most active and when bark is most easily peeled from stems. Consequently, physical damage in that period, whether from thinning operations or from other disturbances, results in more and larger bark wounds than at other times of the year.

Fire damage can be injurious to juvenile and pole-sized aspen stems, which commonly have thin and succulent bark. Basal wounds, usually from low-intensity wildfires, are a common entry point for canker disease organisms (Hinds and Krebill 1975). Severity of injury varies with the type and amount of fuel available to burn (Brown and Simmerman 1986; Brown and DeByle 1987). Charring is the most obvious injury but wind-blown hot air can also sear the bark on one side. Zalasky (1976) described pinhead openings in fire-injured aspen bark. Gum oozes from these openings and they serve as entry points for canker-causing fungi.

In addition to the furrowing and darkening that naturally occurs with the aging of aspen bark, darkened and raised callus tissue develops where black gall is present (Fig. 28) or where superficial bark wounds have occurred. For example, the claw marks of bears (*Ursus* spp.) that have climbed aspen trees or the stem segments on which there is intense antler rubbing by elk (*Cervus elaphus* Linnaeus), are preserved as dark-colored bark long after the event has occurred. Other common causes of physical injury to aspen bark are abrasions from

Figure 28. Darkened and raised callus tissue develops from black gall or where aspen bark has received wounds (photo courtesy of A. Kabzems).

logging equipment or from construction equipment along the edges of cleared rights-of-way.

Foliar Responses to Pollutants

Aspen and balsam poplar foliage is more sensitive than coniferous needles to the effects of contact with hydrocarbons. When hydrocarbons contact deciduous foliage, curling and distortion of the leaf and darkening of the leaf surface occur within a few hours. Defoliation occurs a few weeks later. Sprays of heavy-weight hydrocarbons, unless they contain light-weight fractions, usually do not cause permanent injury to the buds, phloem, or cambium of aspen (Malhotra and Blauel 1980).

Deciduous foliage also responds to salt injury faster than coniferous needles do. In aspen, leaf tips and margins first become slightly chlorotic then turn a dark green color, which produces a water-soaked appearance. As the toxicity advances, the damaged areas become bright yellow (reflecting the zone of salt accumulation), and eventually develop necrosis and curling. Such symptom development is often followed by premature leaf drop. High salt concentrations can also kill buds and cambium, preventing any new growth the following year. Tree mortality from salt toxicity is common in areas of salt-water spills (Malhotra and Blauel 1980).

Balsam poplar and aspen were rated by Malhotra and Blauel as moderately sensitive to sulfur dioxide (SO_2), in contrast to alpine fir, balsam fir, green alder, tamarack, and white birch, which are all highly sensitive. Black and white spruce are relatively tolerant of SO_2. The first visible symptoms of SO_2 exposure on aspen is a wetting of the leaf undersurface and light chlorosis (reduction of green pigment). After prolonged fumigation with SO_2, the water-soaked appearance is followed by chlorosis between the leaf veins, severe chlorosis and browning around leaf edges, then widespread brown discoloration of the entire leaf, followed by leaf curling and shriveling in response to rapid drying of leaf tissue.

Smelter emission injury is different from injury attributed solely to SO_2 because the combined effects of heavy metals and SO_2 can be additive or synergistic. Aspen foliage responds to smelter emissions initially by developing chlorosis between the veins, followed by browning of larger areas of tissue. After browning, leaves become very dry and brittle before being shed. Because SO_2 and heavy metals do not stimulate formation of an abscission layer, dried brown leaves remain on the tree for some time before being shed (Malhotra and Blauel 1980).

It is not known whether airborne pollutants are affecting regional growth rates of boreal hardwoods. A recent review by Addison and Jensen (1987) indicated that it is not possible to accurately predict how an entire forest ecosystem, rather than individual tree crowns, might respond to airborne pollutants. Fraser et al. (1985) suggested that the long range transport of air pollutants is likely to lead to reductions in productivity of Canadian forests. In North America, however, it has not yet been possible to attribute any observed changes in forest productivity to air pollution, even though pollutants have been demonstrated to affect tree growth at many other locations in the world. In all such cases, however, the effects have been seen around point sources of pollution where concentration or deposition gradients are both strong and known (Addison and Jensen 1987). Effects have been expressed as foliar responses rather than growth rate responses. Aspen foliage symptoms in response to the following pollutants include: sulfur dioxide; light- and heavy-weight hydrocarbon emissions; salt water; elemental sulfur and sulfuric acid mist; nickel–copper–zinc smelter emissions; cement dusts, salts, and calcareous materials; nitrogen oxides; ammonia vapor; and sodium chlorate (Malhotra and Blauel 1980).

Regional pollution effects are subtle and there is still controversy over whether certain reductions seen in tree growth can be attributed to deposition of atmospheric pollutants. This controversy, whether dealing with aspen, balsam poplar or any other boreal tree species, is likely to persist because air pollution cannot be considered to act independently in the environment any more than any other factor does. Insects and disease, fire, water stress, or nutrient limitations may all have an influence on how trees are influenced by airborne pollutants (Addison and Jensen 1987). A more detailed review of the subject can be found in Malhotra and Blauel (1980).

Herbicides

The use of herbicides as a tool to control aspen and to record aspen's response to herbicides has been the topic of several articles: Day et al. (1952), Shiue et al. (1958), Waldron (1961), Heeney et al. (1980), Harniss and Bartos (1985), Perala (1985), Drouin (1989), and Bancroft (1989). Although the recent commercial interest in aspen is tending to lessen the overall incentive for herbicidal removal of this species, several of the recent references cited above still prefer to use herbicides to control aspen and balsam poplar for conifer release. For example, the review by Bancroft (1989) was in response to the continuing strong interest in the southern interior of British Columbia to release conifers from aspen competition by application of herbicides to aspen at some appropriate time before the conifer harvest. In the Prince George region of British Columbia, aerial application of Roundup (glyphosate) is currently used to control aspen in portions of cut blocks that require conifer release (Casteel 1989).

In northeastern British Columbia and Alberta, bluejoint reed grass (*Calamagrostis canadensis* [Michx.] Beauv.) and aspen are among the most aggressive competitors of white spruce. Investigations by Herring (1989) revealed that reed grass abundance had an inverse relationship with the density of aspen suckers. Reed grass is operationally controlled in the Peace River region of British Columbia by glyphosate applications. There is a decline in the effectiveness of glyphosate on reed grass in older aspen/grass communities as aspen dominance and canopy interception increase. Control of mixed aspen/reed grass communities with glyphosate should therefore be carried out before aspen canopy development is advanced in order to prevent a prompt reinvasion of reed grass. Herring observed that blade scarification displaces a substantial amount of aspen roots, reducing suckering by as much as 50%. Further reductions in aspen density are achieved by subsequent disk or plow cultivation. Glyphosate proved extremely effective at controlling well-developed sucker shoots, although small shoots may survive applications. It is, therefore, recommended that glyphosate not be applied until the second growing season following site disturbance to allow time for small suckers to reach sufficient size for adequate glyphosate absorption. Testing of liquid hexazinone, applied in a broadcast spray, provided only intermediate control of aspen suckers. Better control was achieved with concentrated spot distributions. Absolute control of seral reed grass and aspen communities is not possible with single-pass mechanical and chemical treatments. Such treatments only reduce competition for two years at best. Other accounts of chemical control of aspen in northeastern British Columbia were prepared by Baker (1989) and Presslee (1989).

Herbicides have been used more for reduction of aspen than they have for control of vegetation that may be competing with aspen. Work by Waldron (1963), Perala (1971), and Danfield et al. (1983), however, included elimination of brush, weeds, and grass competition in aspen stands. Dickmann et al. (1987) described methods for controlling brush and grass in hybrid poplar plantations. Reduction of aspen by application of herbicides is not always for the purpose of conifer release. Waldron (1961), Steneker (1976b), Perala (1977), and Davison et al. (1988) make reference to use of herbicides for elimination of overmature aspen to encourage regeneration of young sucker stands. Based on tests in the western United States, Harniss and Bartos (1985) concluded that encouragement of aspen regeneration required less herbicide than is needed for conifer site preparation or conifer release. Harniss and Bartos found that the use of 2,4-D at a rate of 2.2 kg/ha acid equivalent, low volatile mixed with a water carrier, kills most aspen overstory and initiates aspen regeneration. Lower rates of 1.1–1.6 kg/ha may be effective in checking the aspen overstory and initiating suckering; however, this needs to be tested.

Dicamba and 2,4-D mixtures have been recommended for *Populus* spp. control (Hamel 1983). These have been recommended for use mostly for conifer site preparations. Glyphosate has been used experimentally in southern Utah in the fall for conifer release in stands with abundant aspen suckers. The recent summary by Drouin (1989) identified over 25 herbicides that show potential for forestry. His list is reproduced in Table 28, with each potential silvicultural herbicide identified by trade name, common name, manufacturer, and potential for use.

Table 28. Herbicides showing potential for use in forestry (Drouin 1989)

Trade name	Form[a]	Common name	Manufacturer/ distributor	Potential for use
Ally	SG	Metsulfuron methyl	Dupont	Brush, broadleaf weeds
Antor 4ES	L	Diethatyl ethyl	Hercules	Grass, broadleaf weeds
Banvel	L	Dicamba	Sandoz Agro	Annual broadleaf weeds, brush
Devrinol	L	Napropamide	Stauffer	Grass, annual broadleaf weeds
Dowpan	L	Dalapon	Dow	Annual and perennial grasses
Dycleer	L	Dicamba	Sandoz Agro	Grass, brush
Esteron 600	L	2,4-D (ester)	Dow	Brush, broadleaf weeds
Formula 40F	L	2,4-D (amine)	Dow	Brush, broadleaf weeds
Fusilade	L	Fluazifop-butyl	Chipman	Brush, broadleaf weeds
Gesagard 80W	L	Prometryne	Ciba-Geigy	Grass, annual broadleaf weeds
Goal	L	Oxyfluorfen	Rohm and Haas	Grass, annual broadleaf weeds
Herbec 20P	SG	Tebuthiuron	Elanco	Brush control
Hoe	L	Linuron	Hoechst	Grass, annual broadleaf weeds
Hyvar-XL	L	Bromacil	Dupont	Grass, broadleaf weeds
Poast	L	Sethoxydim	BASF	Annual grass, quack grass
Pronone 10G	G	Hexazinone	Pro-Serve/Pfizer	Selective brush, grass, broadleaf weeds
Primatol Nine-O	SG	Atrazine	Ciba-Geigy	Grass, broadleaf weeds
Princip Nine-T	SG	Simazine	Ciba-Geigy	Grass, broadleaf weeds
Spike 5G	SG	Tebuthiuron	Elanco	Brush, grass, broadleaf weeds
Spike 80W	WP	Tebuthiuron	Elanco	Brush, grass, broadleaf weeds
Garlon 4	L	Trichlopyr	Dow	Brush, broadleaf weeds
Velpar L	L	Hexazinone	Dupont	Selective brush, grass, broadleaf weeds
Velpar Gridballs	GB	Hexazinone	Dupont	Selective brush, grass, broadleaf weeds
Vision (Roundup)	L	Glyphosate	Monsanto	Brush, grass, broadleaf weeds
Oust	SG	Sulfomethuron methyl	Dupont	Grass, broadleaf weeds

[a] G = granular, L = liquid, WP = wettable powder, E = ester, SG = soluble granule, GB = grid ball.

There is less information on balsam poplar response to herbicides than there is for aspen. In the southern interior region of British Columbia, herbicide trials revealed that hexazinone, applied at 12 and 15 L/ha by spot application in spring, showed promise of controlling balsam poplar (Thompson 1989); no comparable data were provided for the effects of glyphosate on balsam poplar.

Much of the recently published information on aspen response to herbicides is a result of trials to improve forage for livestock and wildlife (Bailey 1972; Bailey and Anderson 1979; Bowes 1975, 1976, 1982, 1983; Hilton 1970; Hilton and Bailey 1972, 1974; Waddington and Bittman 1987; Cessna et al. 1989). Recent studies by Bailey (1986b) found the use of herbicides to be unnecessary for conversion of woodland to grassland. Burning, seeding, and short-duration heavy grazing have been found to be attractive alternatives to use of herbicides in aspen parkland areas. Heavy grazing soon after burning is the key component and provides palatable forage while controlling woody regrowth. Burning alone resulted in 79, 83, and 96% mortality for balsam poplar, aspen, and willow. Burning followed by herbicide spraying proved the most effective treatment to control woody sucker regrowth of aspen, balsam poplar, and willow at Beaverhill Lake, east of Edmonton, Alberta (Bailey and Anderson 1979).

When herbicidal removal of aspen is undertaken to improve forage availability for livestock, selective application can be encouraged through the use of roller applications. The goal in this case is to reduce the amount of herbicide reaching the soil and forage legumes. Tests of roller applications of Picloram and 2,4-D to young aspen in Saskatchewan revealed that 2% or less of the herbicides remained in the aspen tissue, of which 80% occurred in the leaves. Between 11 and 16% of the applied Picloram reached the soil (Cessna et al. 1989).

During experimental trials in 1965, aerial spraying with 2,4-D was successful in removal of unwanted overmature aspen in the Riding Mountain area, Manitoba (Pratt 1965). In addition to the overmature trees, aspen suckers and hazel (*Corylus cornuta* Marsh.) were also killed, but the 2,4-D had little effect on balsam poplar suckers and other brush species. Application of 2,4-D or 2,4,5-T is not, however, an assured way to permanently remove aspen from sites where it is unwanted. For example, in Ontario when 5-year-old aspen suckers were severely damaged by 2,4-D and 2,4,5-T spraying their diameter growth was reduced for only 2 years; by year 6 normal growth rates had resumed (Basham 1981). Comparable survival of aspen 22 years after spraying was reported in Wyoming by Bartos and Lester (1984) where abundant aspen were found on the previously sprayed areas.

As with other forest ecosystems, aerial application of herbicides to aspen remains controversial because the entire ecosystem is exposed to the spray, with often unwanted effects on understory vegetation (Malik and Vanden Born 1986) or wildlife (Biggs and Walmsley 1988). Biggs and Walmsley expressed concern about the quality of deer and moose winter browse after glyphosate and triclopyr were applied to aspen and willows for conifer release in northeastern British Columbia. A lesser concern involves the effects of herbicides on native grasses such as *C. canadensis*, which are important for certain wildlife species in northeastern British Columbia.

Suggested ways to avoid the adverse effects of aerial applications is to apply herbicides to individual stems by basal sprays or injections. In the case of brush control, the use of wipers to apply herbicides to the foliage can reduce damage to the forage understory (Cessna et al. 1989). Herbicide pellets also provide an alternative to aerial spraying. In Ontario, mixedwood sites where aspen was the main competition for a white spruce plantation were treated with hexazinone herbicide pellets at a spacing of 1 × 1 m. At this spacing, the pellets created openings suitable for white spruce establishment. Seven years after treatment the beneficial effects of hexazinone pellets were still evident. Pellet application has several advantages: no special equipment is needed; there is no problem of drift as with spray applications; and there is greater herbicidal effectiveness because it is possible to precisely position localized concentrations (Sutton 1986). Similar trials with herbicide pellets near Faust, Alberta, gave complete control over unwanted vegetation 5 years after application (Drouin 1989). For the forest manager interested in more detail, the report by Drouin provides results for five herbicides in relation to conifer growth, weed control, timing of application, techniques, and equipment performance.

Allelopathy and Competition

Plant chemicals that inhibit the germination, growth, or occurrence of other plants are referred to as allelochemicals and their action is referred to as allelopathy (Kimmins 1987). As indicated by Kimmins and by Rice (1984), allelopathy is a widespread phenomenon, although it is often inconspicuous to the observer of a forest ecosystem. These reviewers suggested that allelopathic effects are probably far more important in both forestry and agriculture than is generally realized. Competition is a term that covers a broader range of processes than allelopathy. Interspecific competition occurs wherever two different species depend upon the same resource when that resource is in limited supply; it can also occur when a resource is not in short supply but one species interferes with the other's use of it (Kimmins 1987).

There is remarkably little information on allelopathic relations and competition involving aspen and balsam poplar. It is, however, known that balsam poplar does have allelopathic effects on the growth of alder (Jobidon and Thibault 1981, 1982; Rice 1984). Water extracts of balsam poplar leaves, buds, and leaf litter inhibited alder height growth, root elongation, seed germination, dry weight increment, and root-hair development. Leachates from balsam poplar negatively affected nodulation and infection by *Frankia* involved in nodule formation, thereby influencing microorganisms associated with the nitrogen cycle (Thibault et al. 1983). In Utah, McDonough (1979) indicated that aspen seedling emergence was inhibited by allelopathic effects of litter compounds.

Ellison and Houston (1958), working in Utah, reported that production of four native herbaceous species was found under an aspen canopy less than on adjacent open ground. Similarly, Younger et al. (1980) demonstrated that freshly fallen, decomposing aspen leaf litter inhibited seedling growth of herbaceous species. Hubbes (1962, 1966) indicated that pyrocatechol, a chemical constituent of aspen bark, provides a natural inhibition to *Hypoxylon* infection. It is for this reason that bark wounds are so significant for *Hypoxylon* infection, because it is through such wounds that *Hypoxylon* is able to infect sapwood that does not contain the inhibitor.

In the boreal mixedwood region, competition is commonly mentioned in the context of young conifers and aspen suckers that are competing for the same root and crown space (Lees 1966). The competition from aspen is generally considered to be a result of the advantage provided to suckers by the established clonal root system. Trials with seedlings of aspen and jack pine, however, revealed that aspen seedlings also outproduce those of jack pine (Farmer et al. 1988). Observations in jack pine plantations containing naturally-established aspen indicate that aspen has a greater interspecific competitive effect on pine than is the case from intraspecific competition within the pine population (Mugasha 1986, 1989). In contrast to jack pine, aspen benefited from a decreasing proportion of aspen in mixtures; aspen had the highest weights in mixtures containing 75% of pine, conditions where aspen appears to be released from intense intraspecific competition (Farmer et al. 1988). A similar relationship in aspen mixed with balsam poplar was noted by Morris and Farmer (1985). No quantitative data were mentioned in the review by Haeussler and Coates (1986) on the effect of balsam poplar competition on young conifer growth.

Mycorrhizae

Compared to conifers, not much is known about mycorrhizae in *Populus*. The most detailed review of available information is by Walker (1980), who listed all assumed or proven mycorrhizal fungi associated with *Populus*. Managers of natural aspen or mixedwood stands in the boreal region will probably not be involved with mycorrhizae very much because the usual context for these relationships in *Populus* is short-rotation intensive culture of screened *Populus* clones. A better understanding of physiological interactions in the root zone is needed to improve cultural practices and yields of poplars. Mycorrhizae are part of the most important interactions in the root zone (Schultz et al. 1983).

With few exceptions, all plants in nature develop mycorrhizae to various degrees (Schultz et al. 1983). Ectomycorrhizae grow vegetatively over the surfaces of feeder roots, forming an external fungal mantle. After mantle formation, hyphae develop as a net between cells in the root cortex; this net is the main diagnostic feature of ectomycorrhizae. This occurs naturally on many of the important forest tree species of the world. All members of the family *Pinaceae* are ectomycorrhizal, as are certain angiosperm tree genera such as *Salix* and *Populus*. Endomycorrhizae form a loose network of hyphae on feeder-root surfaces but do not develop the dense fungal net found in ectomycorrhizae. Endomycorrhizae are known to occur on cottonwoods within the genus *Populus* (Schultz et al. 1983).

Fungi forming mycorrhizae are aerobic organisms that contribute to the degradation and decomposition of organic substances. Fungal hyphae release enzymes that permit them to digest and penetrate substrates, assisting the chemical breakdown of organic susbstances, which are then utilized by the fungus and/or its host as nutrients (Laursen 1985). Moore (1985) determined that interior Alaska forest soils under birch and aspen contained a resident biomass of living fungal hyphae that permeated the upper substrates of soil just as in coniferous litter types. Moore found that belowground standing crop of fungal biomass in upland permafrost-free soils under aspen forests exhibit within-season population changes attributable to changes in microclimatic conditions, particularly soil temperature and soil moisture. Soil moisture was by far the overriding causative factor. Compared to soils developed in birch sites, aspen soils were found to have a more favorable chemical environment for microbial activity due to increased cation exchange capacity, increased exchangeable bases, elevated soil pH, and a greater soil moisture content; the result was a significantly greater fungal biomass under aspen than birch sites. Trials with fertilization produced significantly decreased fungal biomass in aspen soils while increasing it in birch soils. Because of this, there have been suggestions that long-term fertilization treatment of aspen forests could be detrimental to mineral cycling (Van Cleve 1974; Moore 1985). Under both aspen and birch forest types, hyphae of basidiomycetes involved in saprophytic decomposition were reduced significantly by fertilization treatment. Similar work by other investigators in Alaskan taiga has produced conflicting results regarding fertilization (Van Cleve and Moore 1978; Van Cleve and Oliver 1982), a fact attributable to different reactions to specific soil chemical, physical, and biotic conditions.

Studies to date indicate that aspen displays little specificity for ectomycorrhizal fungi. In experimental trials, 29 out of 52 species of fungi formed ectomycorrhizae on aspen seedlings, indicating a relative lack of specificity. As little as 4 days after the introduction of inoculum was sufficient for some species of fungi to form ectomycorrhizae on aspen (Godbout and Fortin 1985). In a search for a method that would allow for rapid formation and direct observation of ectomycorrhizae, Fortin et al. (1983) described a growth pouch in which nonasceptic synthesis of ectomycorrhizae on aspen seeds was possible.

Fortunately, poplars can develop either with an association involving mycorrhizae (mycotrophic) or without it (autotrophic). This adaptability is an advantage for pioneer species that are sometimes the first inhabitants of disturbed sites where mycorrhizal fungal inoculum may not be available (Schultz et al. 1983).

Diseases Important to Aspen and Balsam Poplar Management

There is abundant literature on the pathology of mature aspen stands. For example, recent reviews by Hiratsuka and Loman (1984), Navratil (1987), and Hiratsuka et al. (1990) provide guidance on decay management for established stands. The detailed keys prepared by Ostry et al. (1989) provide the field forester with methods to identify insect, disease, and animal pests of the genus *Populus*. The recent overview of the main causes of decay and stain, prepared by Hiratsuka et al. (1990), is summarized in the following text. More than 250 species of fungi are known to be associated with decay in North American aspen (Lindsey and Gilbertson 1978). Most of these, however, are decay fungi of standing dead or fallen trees and are of minor importance to live aspen. Thomas et al. (1960) identified 17 species of fungi that cause the decay of standing live aspen in Alberta. Decay and stain of aspen can be divided into three major categories: trunk rot and stain; root and butt rot; and sapwood decay and stain in stored logs (Hiratsuka et al. 1990).

With regard to young aspen stands, Zalasky (1970) reported that problems initiated by pathogenic organisms are relatively rare in aspen and poplar regeneration, with most injuries resulting from nonbiological causes such as frost, mechanical injury, or fire. Other investigators, however, have stressed that young aspen stands do host a number of endemic insects and pathogens that cause injury (Perala 1984). Some researchers contend that young suckers without at least one injury per stem are rare (Millers 1972).

The most common and most important cause of aspen trunk rot in Alberta is *Phellinus tremulae* (Bondartsev) Bondartsev & Borisov (= *Phellinus igniarius* [Linnaeus: Frie] Quéllet, *Fomes igniarius* [Linnaeus: Fries] J. Kickx fil. f. *tremulae* Bondartsev). In Alberta, Thomas et al. (1960) estimated that 38.6% of trunk decay volume is caused by this fungus. In Ontario, Basham (1960) reported that 63.2% of 1754 trees on 47 plots had trunk rot and almost 75% of the volume loss was attributed to *P. tremulae* (Fig. 29). The second most prevalent cause of decay in aspen is *Peniophora polygonia* (Persoon: Fries) Boudier & Galzin (= *Corticium polygonium* [Persoon: Fries], *Cryptochaete polygonia* [Persoon: Fries] K. Karsten) (Fig. 30). Although this fungus does not cause large columns of advanced decay as does *P. tremulae*, it is found more often in decayed and discolored wood. On balsam poplar, *P. tremulae* is recognized as the most common and dominant decay-causing species, followed by *Pholiota destruens* (Fig. 30D). *Armillaria* (*Armillaria ostoyae* [Romagn.] Herink or *Armillaria sinapina* [Bérubé & Dessureault], Fig. 31) is the most common cause of aspen butt rot in Alberta. *Armillaria* root rot has, until recently, been considered to be caused by *Armillaria mellea* (Vahl:Fr.). Recent research, however, has shown that many closely related species of *Armillaria* can cause root and butt rot of trees. In North America, nine species of *Armillaria* root rot pathogens have so far been identified. Mallett (1990) has found *A. ostoyae, A. sinapina*, and *Armillaria calvescens* (Bérubé & Dessureault) in the prairie provinces. *Armillaria ostoyae* is the prevalent species; all three species have been found on aspen and *A. ostoyae* and *A. sinapina* have also been found on balsam poplar.

Other common root and butt rot fungi are *Ganoderma applanatum* (Persoon) Patouillard, *Fomitopsis pinicola* (Swartz: Fries) P. Karsten (=*Fomes pinicola* [Swartz: Fries] Cooke), and *Gymnopilus spectabilis* (Fries: Fries) A.H. Smith (=*Pholiota spectabilis* [Fries: Fries] Gillet). Another common aspen decay organism is *Radulum casearium* (Morgan) Ryvarden (=*Hydnum casearium* Morgan). Stain or discoloration of wood is caused by various microorganisms, including fungi of various groups (yeasts, ascomycetous fungi, and fungi imperfecti) and bacteria. One of the mineral stains of sapwood in stored logs is likely caused by invading blue stain fungi belonging to such genera as *Ceratocystis* and *Verticicladiella*. In addition, many kinds of sapwood stain are known to develop without microorganisms (Hiratsuka et al. 1990).

The recent account of decay and stain in Alberta aspen (Hiratsuka et al. 1990) classified internal stem defects into five new categories on the basis of color and hardness. The traditional classification for aspen wood defects involved three categories (advanced decay, incipient decay, and stain). An improved system of classification was sought because the three categories previously used created problems in measuring and recording defects consistently and objectively. The following subsections are structured according to the five categories recommended by Hiratsuka et al. (1990) for decay and stain measurement in aspen. Their five categories are summarized in Table 29, and their key for identification of the five defect types is reproduced in Table 30.

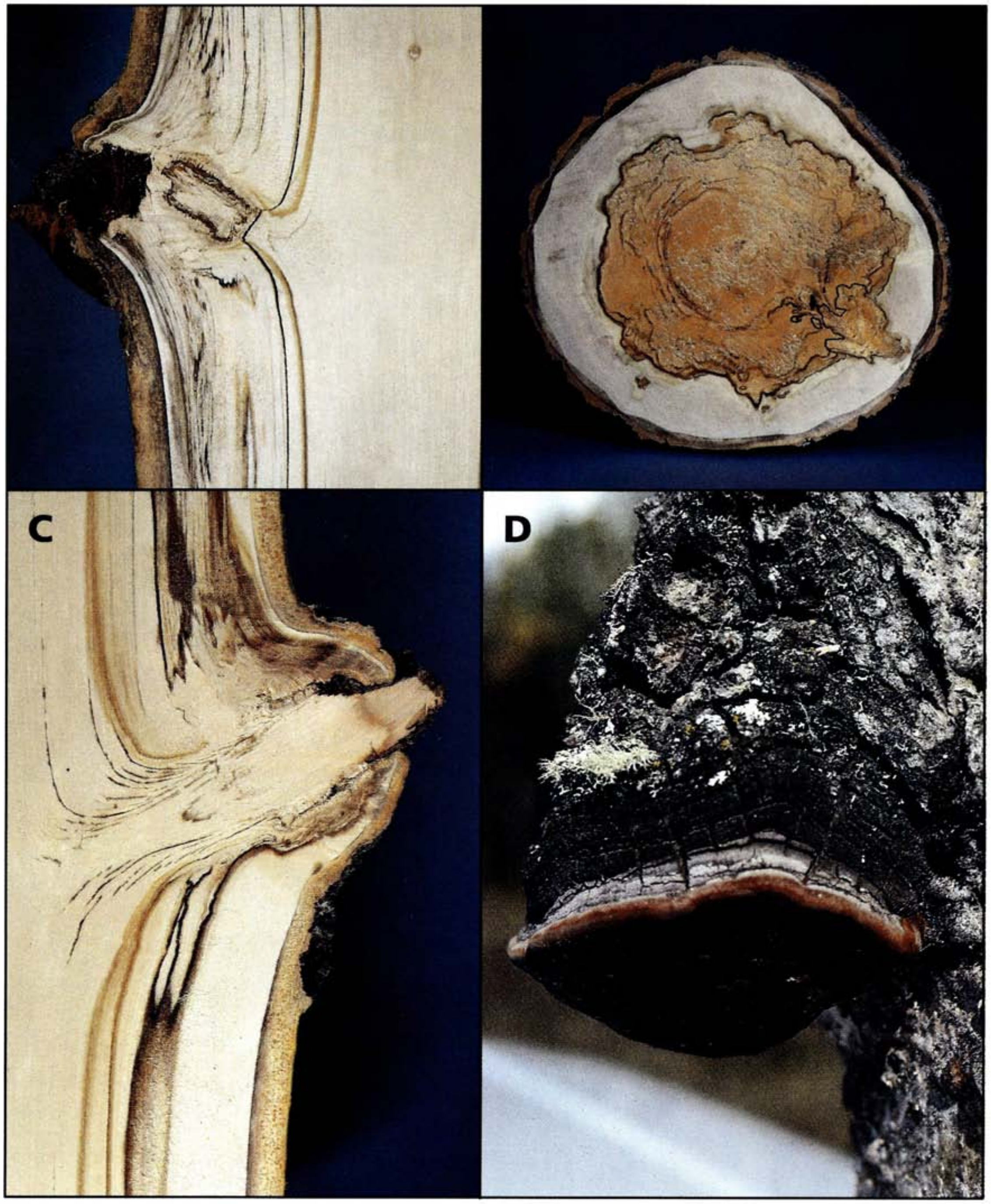

Figure 29. Aspects of *Phellinus tremulae*. A. Vertical section of an aspen stem with a fruiting body of *P. tremulae* and a column of advanced decay bordered by characteristic black lines. **B.** Cross section of an aspen stem with advanced decay caused by *P. tremulae*. **C.** Relation of rotten knot and decay column of *P. tremulae* in aspen. **D.** A fruiting body (conk) of *P. tremulae* on aspen. (Hiratsuka and Loman 1984.)

Figure 30. Aspects of *Peniophora polygonia*. A. Fruiting structure of *P. polygonia* on aspen. **B.** Large scars (cracks) on mature balsam poplar. **C.** Dead branch and column of discolored incipient decay of aspen caused by *P. polygonia* inside of stem shown in photograph (A). **D.** Fruiting bodies (mushrooms) of *Pholiota destruens* on balsam poplar. (Hiratsuka and Loman 1984.)

Figure 31. ***Armillaria* root rot. A.** Butt rot caused by *Armillaria*. **B.** Mushrooms of *Armillaria ostoyae*. (Hiratsuka et al. 1990.)

Table 29. Causes, defect symptoms, external indicators, and defect distribution for five main types of aspen wood defect (Hiratsuka et al. 1990)

Type of defect	Causes	Description of defect and external indicators	Defect distribution
A	*Phellinus tremulae*	White spongy rot bordered with black lines. Usually associated with hoof-shaped conks.	Defects usually occur along most of the main stem, less frequently in the bottom part of the trunk.
B	Mostly *Armillaria* spp.	Yellow, stringy rot often surrounded by dark brown fungal and wood material. Black shoestring-like fungal structures (rhizomorphs) present in and around the decay. May find *Armillaria* mushrooms in the late summer or autumn.	Butt rot. Decay up to 1 m above the ground.
C	Mostly *Peniophora polygonia*, occasionally *Radulum casearium*	Stained column with irregular pockets of pinkish to brownish decay. Often associated with pink scale-like fruiting bodies.	Often occurs along large portions of the main stem.
D	Various causes (fungi, bacteria, nonbiotic factors)	Stain of various causes that does not reduce wood hardness.	Variable in distribution.
E	Blue stain fungi	Grayish-black sapwood stain.	Occurs in sapwood. Initiates from cut end or through damaged bark on stored logs.

Table 30. Key to five main types of wood defect in aspen (Hiratsuka et al. 1990)

Wood not discolored, no indication of defect	Sound wood
Wood discolored or with other visible indications of defect	
Heartwood defect	
Columns of structural decay	
White trunk rot bordered with black line	Type A
White or brown butt rot, seldom extending more than 1 m above the ground	Type B
Stained columns with irregular decay pockets and soft areas, mostly pink to brownish pine	Type C
Stained columns of various colors and forms without loss of hardness	Type D
Sapwood defect	
Grayish-black or brown sapwood stain	Type E

In addition to the fungi involved in the five main categories outlined above, a number of other decay-causing fungi are also common on aspen and balsam poplar in the prairie provinces. These common fungi, based on Thomas et al. (1960) as modified by Hiratsuka and Loman (1984), are listed in Table 31. In addition to these fungi that cause decay of trunks, butts, and roots, there are a number of other common infectious foliage and stem diseases of aspen and poplars in the prairie provinces. These gall, canker, leaf blight, leaf spot, leaf rust, and mildew diseases are listed in Table 32, based on Hiratsuka (1987).

In addition to those aspen and poplar diseases listed in Tables 31 and 32, *Cytospora* canker (*Cytospora chrysosperma* [Pers.] Fr.) was recorded on poplar by Cerezke and Emond (1989). A new aspen leaf spot disease, presumed to be caused by the fungus, *Pollaccia borealis* (Funk), was discovered in 1987 by Funk (1989) in northeastern British Columbia and adjoining areas of Yukon and Northwest Territories. Symptoms of this disease are either purple-brown spots on aspen leaves or shot holes in the leaves, which resemble holes created by insect feeding. These two symptoms, colored spots or holes in the leaves, never occur together on the same leaf or tree, a circumstance that Funk attributed to clonal differences in response to *P. borealis*.

In young stands, aspen shoot blight (*Venturia macularis* [Fr.] Müll. & Arx) is considered to be one of the most important diseases affecting sucker regeneration. In years of severe blight, sucker stands with 100% terminal infection are common, and such stands tend to stagnate. The stubs of the terminals that remain following shoot blight infection become new infection sites for other canker and rot-causing agents (Gross and Basham 1981). Several other pathogens have also been noted in young aspen stands. For example, in a study of mortality during the first 7 years of aspen stand development at Petawawa, Ontario, Pollard (1971) noted that all of the large dead stems were infected with *Diplodia tumefaciens* (Shear) Zalasky. Also in Ontario, a canker caused by *Neofabraea populi* (G.E. Thompson)was noted on aspen 3–6 years of age, but not many of the infected stems were killed (Thompson 1939).

In summary, the main diseases of aspen and balsam poplar in the prairie provinces are well known. For excellent references to these diseases, see Hiratsuka and Loman (1984); Hiratsuka (1987); Hiratsuka et al. (1990). The remaining challenge for aspen silviculturists and aspen procurement foresters is to apply the recently proposed guidelines for sampling, measurement, and interpretation of internal stem defects for aspen wood based on color and hardness criteria. This is an important challenge because, to date, aspen decay estimates from different studies have rarely been comparable.

Phellinus tremulae Decay in Aspen and Balsam Poplar

Decay from *P. tremulae* is referred to by Hiratsuka et al. (1990) as the Type A defect (Tables 29 and 30).

Table 31. The most common decay-causing fungi, with percentage of infections in trunk and butt, on aspen and balsam poplar in the Slave Lake area of Alberta (Thomas et al. 1960 as modified by Hiratsuka and Loman 1984)

Fungus	Aspen		Balsam poplar	
	Trunk	Butt	Trunk	Butt
Phellinus tremulae (= *Fomes igniarius*)	34.4	0.2	26.8	–
Radulodon americanus (= *Radulum casearium*)	14.2	1.2	–	–
Peniophora polygonia (= *Corticium polygonium*)	12.8	1.5	–	–
Coriolus zonatus (= *Polyporus zonatus*)	2.1	trace	–	–
Bjerkandera adusta (= *Polyporus adustus*)	1.5	0.7	2.5	0.1
Pholiota adiposa	0.5	0.2	–	–
Phlebia strigosa-zonata	–	2.2	–	–
Armillaria spp.	–	0.9	trace	1.6
Gymnopilus spectabilis (= *Pholiota spectabilis*)	0.1	1.2	1.3	4.2
Pholiota destruens	–	–	17.7	0.4
Corticium expallens	–	–	5.2	0.4
Trechispora raduloides	0.5	trace	0.8	0.1
Corticium vellerum	–	–	0.3	0.1
Pholiota subsquarrosa	–	0.4	–	–

Table 32. The most common infectious foliage and stem diseases of aspen and poplars in the prairie provinces, excluding decay fungi that cause trunk, butt, and root rots (Hiratsuka 1987)

Ciborinia whetzelii (ink spot)
Diplodia tumefaciens (Diplodia gall and rough-bark)
Hypoxylon mammatum (Hypoxylon canker)
Linospora tetraspora (leaf blight)
Marssonina balsamiferae (leaf spot)
Marssonina populi (leaf spot)
Marssonina tremuloides (leaf spot)
Melampsora medusae (leaf rust)
Melampsora occidentalis (leaf rust)
Mycosphaerella populicola (leaf spot)
Mycosphaerella populorum (leaf spot)
Rhytidiella moriformis (rough bark)
Septogloeum rhopaloideum (leaf spot)
Stereum purpureum (silver leaf)
Uncinula salicis (powdery mildew)
Venturia macularis (leaf and twig blight)
Venturia populina (leaf and twig blight)

Aspen stem decay of this origin is characterized by a distinct black line that surrounds or occurs within decayed areas (Fig. 29). The rot caused by this fungus is white, spongy, and soft. These authors reported that most of the decay that earlier investigators identified as advanced decay was likely caused by *P. tremulae*. This fungus produces a long decay column that continues throughout most of the main stem, and the decay is usually more than 2 m above ground level. The average length of decay columns above and below conks is 370 ± 21 cm (Hiratsuka et al. 1990).

Hoof-shaped conks are characteristic external indicators of *P. tremulae*. This fungus is often called false tinder conk because of the similarity of the conks to those produced by *Fomes fomentarius* (Linnaeus: Fries) J. Kickx fil., which is called tinder conk or tinder fungus because of its use as tinder to start fires (Hiratsuka et al. 1990). Hiratsuka et al. (1990) reported that Alberta aspen with extensive *P. tremulae* defects had fewer external conks than the 86% of infected trees with conks reported by Basham (1958).

There is no evidence that *P. tremulae* is passed to suckers after parent trees are removed. If scarification is done 3–7 years after cutting, however, then there is substantial incidence of *Phellinus* stain in developing suckers. This observation suggests that scarification should not be carried out after suckers have emerged (Navratil and Bella 1988).

Armillaria as a Source of Butt and Root Rot in Aspen

Aspen wood that is defective because of *Armillaria* is referred to by Hiratsuka et al. (1990) as a Type B defect (Tables 29 and 30). It occurs only at the bottom of the tree and tapers off quickly, usually within 1 m of ground level. The yellow, stringy rot is often covered by dark brown fungal mycelium mixed with wood (Fig. 31A).

The only external indicators of *Armillaria* are its mushrooms which are present only in late summer or early autumn. The mushrooms (Fig. 31B) have honey-colored to yellowish-brown caps, 7–12 cm in diameter. Black rhizomorphs that resemble shoestrings are always associated with *Armillaria*; they occur in both the decayed wood and in the soil around the bases of infected trees. This unique structure is the basis for *Armillaria*'s common name of black shoestring rot.

Hiratsuka et al. (1990) indicated that, for Alberta, the potential for *Armillaria* to cause mortality or to reduce growth in aspen was not known. Data from Ontario and Minnesota, however, indicate that *Armillaria* root rot may limit rotation length and the number of times that aspen stands can successfully regenerate vegetatively (Stanosz and Patton 1987a). *Armillaria* root rot in aspen suckers and root collar sprouts from short-rotation plots on highly productive sites in Minnesota and Ontario were reported by Stanosz and Patton. The consistently higher root rot incidence in root collar sprouts than in suckers was considered to be evidence of the ability of *A. mellea* to spread through the slowly dying but interconnected root systems of the original parent clone. The Minnesota plots, in particular, showed the effects of cumulative infection and mycelial spread that may have begun before the initial harvest and continued during successive short rotations. Sprouting was severely reduced at both the Minnesota and Ontario locations after three or more rotations of 4 or 5 years duration. Researchers in those regions believe that repeated short rotations will encourage *Armillaria* root rot in aspen stands.

On a Wisconsin site that was considered favorable for aspen, root systems associated with healthy-appearing dominant or codominant aspen were found to have *Armillaria* root rot at ages 3, 9, and 15 years after clear-cutting. Infection occurred by rhizomorph penetration, mycelial growth through the roots of the parent stumps, and by contact with colonized roots. Both the number of infected trees and the number of lesions per infected tree were greater as the time interval after cutting increased: 72% of the 15-year-old stands were infected compared to 44% of the 9-year-old stands and 24% of the 3-year-old stands (Stanosz and Patton 1987b).

Peniophora polygonia and *Radulum casearium* as Sources of Stain

Peniophora polygonia and *R. casearium* cause stain but leave aspen wood relatively firm. This stain, referred to as Type C in the new classification by Hiratsuka et al. (1990), displays a discoloration of wood, together with pockets of decayed wood throughout the affected column (Fig. 30). Decay and discoloration of wood caused by *P. polygonia* are pink to brownish pink and occur along large portions of the main stem. The fungus seldom causes large columns of soft structural decay, and most of the affected wood stays relatively firm. Although hardness in general may not be reduced significantly, the infected wood may be more brittle than sound wood, and cut surfaces have a rough appearance. The adjacent sound wood cuts cleanly. A distinct splitting of the wood often occurs between affected and healthy wood areas, causing ring shake, which is shrinkage and separation of the annual rings (Hiratsuka et al. 1990). *Peniophora polygonia* is difficult to detect in the field because it does not have conspicuous external indicators. The fruiting bodies are pinkish scaly patches with white margins that curl away from the stem surface (Fig. 30B). They are usually found on rotten branch stubs or on old exposed scars (Hiratsuka et al. 1990). Both *P. polygonia* and *R. casearium* require laboratory isolation to confirm their identity. Defects from these fungi have been the major area of confusion in the past and were likely recorded as incipient decay or stain under the traditional classification system.

Hiratsuka et al. (1990) and Navratil and Winship (1978) suggested that *P. tremulae* (cause of Type A defect) and *P. polygonia* (major cause of Type C defect) are mutually exclusive or antagonistic to each other. Most of the trees with Type C defect do not have Type A defect, and in trees where both types coexist there are clear demarcation lines between the areas infected by each organism. Based on research by Basham (1958), Hiratsuka et al. (1990) categorized *P. polygonia* as a preliminary fungus that alters the host sufficiently for the principal fungi, mainly *P. tremulae* and *G. applanatum*, to become established. Earlier studies in several provinces indicated that *P. polygonia* occurred mainly on young aspen stems but, in Alberta, Hiratsuka et al. (1990) commonly observed it on older trees as well. They stressed the need for further study of the ecological succession of microorganisms leading to various kinds of decay and stain.

Aspen harbors a variety of heartwood and sapwood stains that do not reduce wood hardness. These stains, referred to by Hiratsuka et al. (1990) as Type D defects, are variable in distribution and extent (Fig. 32). These defects, which do not reduce wood hardness, but which may increase bleaching costs, especially with chemithermomechanical pulping (CTMP) methods, are caused by a variety of fungi, bacteria, and nonbiotic factors. Gray to black sapwood stains also develop in stored aspen logs. These stains, called Type E defects by Hiratsuka et al. (1990), are caused by blue stain fungi of the genera *Ophiostoma, Ceratocystis*, and *Verticicladiella*. Because these stains are caused by fungi it is incorrect to refer to them as mineral stain, as is sometimes done. Stains resulting from these fungi develop on the ends of cut logs (Fig. 33).

Stem Abnormalities not Associated with Stem Decay or Stain

Aspen stems often display surface abnormalities that are not indicators of internal decay or stain. These abnormalities commonly result from damage to the bark from logging equipment, animal feeding or rubbing, or mechanical abrasion from other sources. Although not directly correlated with stem decay or stain, such bark and stem wounds can be entry points for decay and stain organisms. Stem cracks caused by frost can also serve as entry points for these fungi, as can the distinct holes created in aspen bark by the yellow-bellied sapsucker (*Sphyrapicus varius varius* Linnaeus). In the latter case the extent of internal decay and stain is usually localized (Hiratsuka et al. 1990).

Hypoxylon Canker

The recent review by Ostry and Anderson (1990) confirmed that the *Hypoxylon*–aspen disease system is an extremely complex host–parasite interaction that involves many biological and environmental factors. A specific type of wound is required for infection by the fungus, and certain environmental conditions are required for disease development. The tree responds to wounds by forming a callus that closes the wounds, preventing infection or inhibiting canker expansion. Clonal differences in these responses are common, suggesting that it may be possible to select superior genotypes for reduction of *Hypoxylon* incidence. Stand density influences the incidence of the disease through several interacting factors, and this spatial resistance may also provide a management strategy to minimize the disease impact (Ostry and Anderson 1990).

Hypoxylon mammatum (Wahl.) J.H. Miller canker is most common in poorly stocked aspen stands, trees under stress, or trees injured by hail, animals, or other means, indicating the secondary nature of the disease. Recently, Belanger et al. (1990) documented clonal

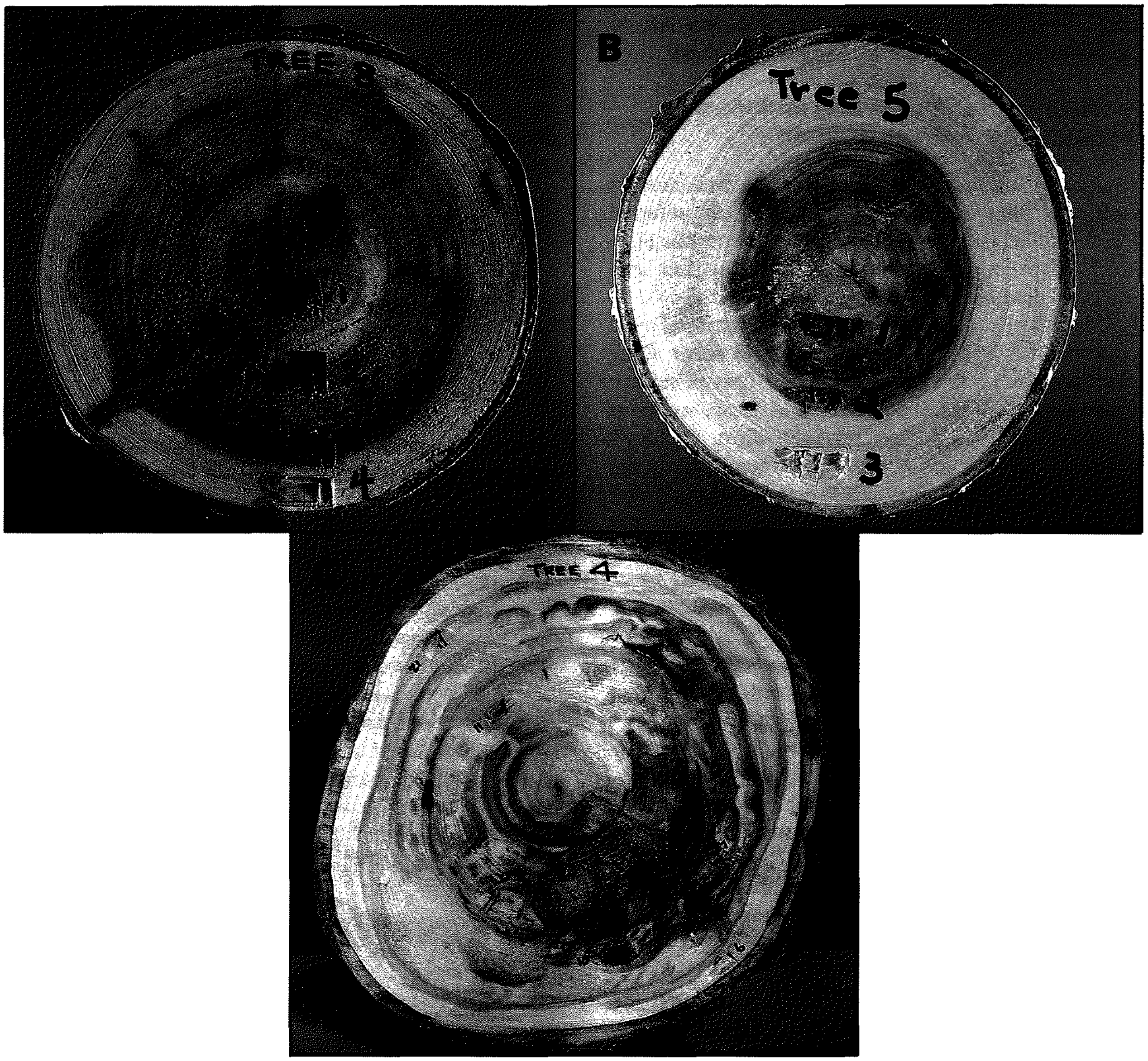

Figure 32. Various types of stain that do not reduce hardness of aspen wood (Hiratsuka et al. 1990).

susceptibility to *Hypoxylon* in relation to water stress in aspen plantlets. Stands 15–40 years old are most susceptible but appreciable losses also occur in older stands (Davidson and Prentice 1968). Trees with infection on the lower main stem usually die within 5 years. The *Hypoxylon* canker weakens the stem, which is often broken by wind at the point where the canker occurs. Trembling aspen is very susceptible to this disease, large-tooth aspen is moderately susceptible, and balsam poplar is the least susceptible. *Hypoxylon* is common not only in the prairie provinces but throughout much of the North American range of aspen. Based on descriptions by Davidson and Prentice (1968) and Hiratsuka (1987), the following text describes the symptoms, disease cycle, damage, and control of *Hypoxylon.*

The *Hypoxylon* canker starts as a slightly sunken, yellowish-orange area on the stem. The cankers enlarge rapidly and eventually girdle the stem. Mottled or laminated black and yellowish patterns of the cortex and a mycelial fan on the cambium layer are reliable field symptoms and signs of the disease. Older cankers are characterized by black hyphal pegs, which are pillar-like structures that push to the outer periderm from the underlying cortical tissue. After a few years of infection, cankers produce fruiting bodies that are made up of 5–20 perithecia embedded in round stroma, 5–15 mm in

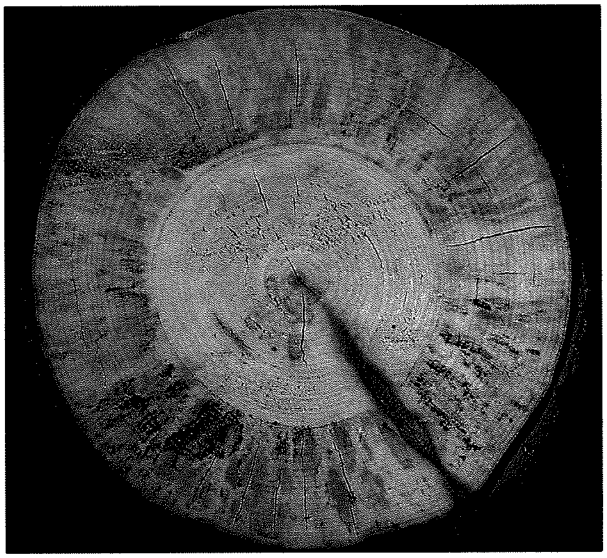

Figure 33. Stains resulting from blue stain fungi (Hiratsuka et al. 1990).

diameter. Various stages of canker development are shown in Figure 34.

Spread of this disease takes place by ascospores. How the infection starts on aspen is not clearly understood, but the fungus most likely gains entry through injuries on the stem or through dead branch stubs. Insect and woodpecker transmission have been suggested but not yet confirmed. The pathogen can live as a saprophyte on dead wood and causes white rot; ascospores can be produced for several years after the death of the host trees (Hiratsuka 1987). Hubbes (1966) concluded that *Hypoxylon* is a sapwood pathogen and not a typical bark parasite as formerly believed. This conclusion was based on the following facts: (1) living aspen bark is highly toxic to *H. mammatum*; and (2) it was demonstrated that the fungus grows in sapwood under sound bark. To successfully infect the tree, the fungus probably enters through a wound or dying bark tissue that has lost its toxicity through oxidation. This would explain why *Hypoxylon* can attack aspen in spite of the natural protection provided by chemical inhibitors present in its bark (Davidson and Prentice 1968). More recent work summarized by Ostry and Anderson (1990) confirms that the green layer in aspen bark contains pyrocatechol, two glycosides, and a phenol that can inhibit spore and mycelial development in *Hypoxylon*. This fungus, however, produces a toxin that detoxifies the fungistatic chemicals in aspen's green bark layer (Schipper 1978).

Research by Ostry and Anderson (1979) indicated that there is a relationship between the incidence of *Hypoxylon* canker infection and the presence of aspen branches, perhaps indicating that conditions necessary for initial infection occur more often on branches than on the stem. Once established on a branch, however, the fungus may grow down into the main stem of the tree. The relation between canker incidence and branch distribution may partially explain the greater incidence of *Hypoxylon* in thinned than in unthinned aspen stands. Trees in thinned or understocked stands have more branches, which also persist longer, thus increasing the chance of being infected by *Hypoxylon*. Other factors associated with stand density that have been suggested as favoring *Hypoxylon* infection include decreased soil moisture and nutrients, and increased sunlight and air movement in aspen stands (Ostry and Anderson 1990). These suggested relationships are the basis for silvicultural recommendations that encourage maintenance of fully stocked aspen stands as a way to minimize the impact of *Hypoxylon* canker. There is evidence that proximity of diseased trees does not always increase the chances of adjacent trees becoming infected (Falk et al. 1989). These researchers found that trees infected with *Hypoxylon* were randomly distributed. The review of *Hypoxylon* research by Manion and Griffin (1986) stressed that *Hypoxylon* is a very widely distributed and genetically variable disease. Chemical defenses and responses of the host are well known but there remains much uncertainty about when and where host infection takes place. Manion and Griffin suggested that there is a more complex involvement of toxic pathogen metabolites in host–parasite interactions than was initially thought.

No reliable control measures are known for *Hypoxylon* canker. In addition, Manion and Griffin (1986) stated that interacting environmental factors are still too confusing to be effectively used in management recommendations. For the aspen manager, the most practical recommendation is to harvest and replant a site once the stand is heavily infected. This step could include gradual conversion of poorer aspen sites to other species because poor sites are the most susceptible to *Hypoxylon* infection. Because this disease is more common in poorly stocked stands, special efforts to achieve high initial stocking may be helpful. Since different degrees of resistance to the disease have been recognized among various aspen clones, selecting and breeding may be feasible where more intensive cultivation of aspen is considered (Davidson and Prentice 1968; Hiratsuka 1987). Recognition of site differences in any *Hypoxylon* control program may also be beneficial for control of other diseases as well. For example, rough-bark disease, *Nectria* cankers, and crown galls are examples of pathogens that Graham et al. (1963) found to be more common on slowly growing aspen of poor sites than on trees of good sites.

Figure 34. ***Hypoxylon*** **canker of aspen. A.** An advanced canker. **B.** Several round stromatic fruiting structures made up of 10–20 perithecia. (Hiratsuka 1987.)

Mortality of aspen from *Hypoxylon* may be a result of initial weakening by an unrelated agent. Any openings through aspen bark, especially those caused by boring insects, are infection points for *Hypoxylon.* The fact that viable *Hypoxylon* spores are present in many wounds that do not become cankerous suggests that successful *Hypoxylon* infection may be dependent upon interactions with insects. Graham and Harrison (1954) suggested that the presence of exuding sap, common in bark openings created by boring insects, is a prerequisite to *Hypoxylon* infection.

Intensive aspen management requires recognition of insect–*Hypoxylon* relationships. There is now a history of nearly 70 years of research on *Hypoxylon* canker of aspen (Manion and Griffin 1986). It is not surprising, then, that relationships between insects and *Hypoxylon* infection have also been known for a long time (Graham and Harrison 1954). These relationships have continued to be a subject of research (Barter 1965; Anderson et al. 1979; Anderson and Martin 1981; Ostry and Anderson 1990). Notably, this research has not included study sites from the prairie provinces. The information summarized below, mainly from studies of Lake States aspen, should be verified for the stand conditions, the species of aspen wood-borers, and the *Hypoxylon* infection patterns typical of the prairie provinces and northeastern British Columbia.

Graham and Harrison (1954) reported that in 95% of all *Hypoxylon* cankers observed in the Lower Peninsula of Michigan, where the cause of the infection court could be positively determined, insects were responsible for the initial injury. In that part of aspen's range, 60% of the infection courts for *Hypoxylon* were a result of the activities of three types of borer: poplar borer (*Saperda calcarata* Say), *Agrilus* spp., and a species of *Dicerca*.

Saperda calcarata is an important borer in aspen and balsam poplar in the prairie provinces (Ives and Wong 1988); consequently, it could be expected to be an important source of *Hypoxylon* infection courts in that region, as it is in Michigan. In the prairie provinces, the most likely *Agrilus* to be found is *A. liragus* (Ives and Wong 1988). Ives and Wong did not list *Dicerca* species as present on aspen in the prairie provinces.

More recent observations of *Hypoxylon* incidence in aspen plantations in Minnesota and Wisconsin (Ostry and Anderson 1990) revealed that oviposition wounds of *Saperda inornata* Say, *Magicacada septendecim* L., and *Telamona tremulata* Ball provided infection sites for *Hypoxylon* canker. Foraging by the downy woodpecker (*Dendrocopos pubescens nelsoni* Oberholser) on *Saperda* galls also facilitated infection. None of these insect species were recorded by Ives and Wong (1988) for aspen or balsam poplar in the prairie provinces, although other species of *Telamona* and *Saperda* do occur in the region.

The relationships outlined above stress the influence of wood borers and other insects upon *Hypoxylon* infection. There is, however, some evidence of a reciprocal relationship as well. Studies by Barter (1965) in New Brunswick indicated that survival of the bronze poplar borer (*A. liragus*) is highly dependent on host condition. Any weakening factor predisposes trees to borer attack and enhances borer survival. *Hypoxylon* canker was among the predisposing factors listed by Davidson and Prentice (1968) for the bronze poplar borer; other factors were several successive years of defoliation by forest tent caterpillar, wind breakage, and drought.

The early work by Graham and Harrison (1954) recognized that *Hypoxylon*–insect relationships play an important role in natural thinning of aspen stands. This may be particularly true for *Agrilus*, which is more common in suppressed trees than in dominant ones. To the extent that *Agrilus* is an encouragement for spread of *Hypoxylon* into suppressed trees, this insect–disease combination can mimic, with no financial outlay, what a forester might wish to do in a program to thin out suppressed aspen stems in a stand. The same cannot be said for most of the other aspen wood borers because they tend to be attracted to the more desirable trees in a stand (Graham and Harrison 1954).

In the case of *Saperda*, sudden creation of canopy openings can lead to increased borer attack on surrounding trees. In Michigan, this phenomenon is frequently associated with the death of scattered old aspen trees. In general, clear-cutting that also cuts down residual nonmerchantable aspen stems will avoid the presence of residual old trees in future stands. Stands of even-aged suckers will be less subject to insect and disease damage associated with the sudden creation of canopy openings, as occurs with the *Saperda–Hypoxylon* combination.

External Stem Indicators of Decay in Aspen Stands

There are no reliable external indicators of cull in aspen stems; unpredictability is the hallmark of cull estimates. From the experience of foresters who have worked with aspen, some 130-year-old aspen stems are sound whereas other stems 40 years old may be well rotted; some conk-free stems are decayed whereas some stems with conks are acceptable for use. For the aspen manager, tree size is probably the most practical way to estimate the amount of cull to be expected once an aspen stand is harvested.

The suggestion of estimating the amount of cull from tree size resulted from a recent cull survey in the Whitecourt Forest, Alberta, which measured advanced decay, incipient decay and stain in 928 aspen and 57 balsam poplar trees (Maier and Darrah 1989). All sample trees were from three stand age classes: 80–100 years; 100–120 years; and over 120 years. One-third of the 100 stands sampled came from each of the three age classes. Results indicated that tree size is of greater value in estimating decay than age. A combination, however, of dbh and height was used as the independent variable in regression equations to predict volumes of defect. This allows stand merchantability to be predicted from operational cruise data on an individual tree basis.

In the sampled aspen trees, advanced decay averaged 7% of total gross tree volume, advanced plus incipient decay averaged 10%, and total decay (including stain) averaged 39%. Not enough balsam poplar were sampled to statistically compare decay estimates in aspen and balsam poplar. All sampled stands were found to be usable for chip production, but the use of overmature stands for pulp production was restricted by the large amount of stain. No significant differences were noted in decay levels of aspen occurring in pure hardwood versus mixedwood stands. There were too few sample trees in each location or severity class of external decay indicators to allow the mixedwood stands to be used as a predictor of internal decay. Although some previous studies had indicated that the number of visible conks was positively correlated to the volume of defect, this was not confirmed by sampling in the Whitecourt Forest. In the latter case, the presence of a conk was more important than the number of conks.

In the Whitecourt aspen decay study, stump age was a poor predictor of stem decay because of the difficulty in determining individual stump ages. Even if individual stump ages could be accurately determined, stand age would have been difficult to define because two-thirds of the sampled stands contained trees whose range of ages was greater than 20 years. Aspen trees of the same dbh but different age classes within the same stand appeared to have similar amounts of decay; it was for this reason that Maier and Darrah (1989) recommended tree size (dbh) as a better predictor of decay than age. Although this recent cull study made progress in defining stand merchantability in stands over 80 years old, it did not define age of stand breakup beyond which no merchantable products could be derived.

Influence of Scarification on Decay in Aspen Root Systems

Studies by Basham and co-workers in Ontario revealed that 4, 6, and 10 years after scarification several basidiomycetes, including *Armillaria*, were more frequent on suckers in scarified than in nonscarified areas. The microorganism most frequently isolated from defective wood in aspen root systems, both scarified and nonscarified, was *Phialophora alba* van Belma. The frequency with which this species was isolated from decayed roots suggests that it may be the primary cause of root system decay. For this reason, Basham (1988) suggested this deuteromycete as a subject for further study to ascertain its role in the decay of aspen root systems, especially those exposed to scarification wounds.

There is evidence that root systems in young aspen stands in Ontario are, in general, more defective than their associated stems, whether the stand has originated from fire or from clear-cutting (Basham and Navratil 1975; Gross and Basham 1981). There are several suggested reasons for this difference: there is a wide variety of soil fungi available to envelop the roots; roots have more wounds or potential fungi entry points than there is on an equivalent length of stem; parent roots of suckers often originate from decayed stumps; and defects in parent roots can spread into root collars and into the adventitious roots of suckers. It is significant that the two most important parts of the sucker root system identified by Zahner and Crawford (1965)—the root collar and the distal parent root—were the two parts of the root system with more defects in suckers originating in scarified areas than in suckers from nonscarified areas.

Data gathered by Basham and Navratil (1975) and Kemperman et al. (1976) reported on aspen trees that were severely wounded by scarification at age 13 years. Both studies indicated that 10 years later about 7% of their stem volume was affected by advanced decay, compared to 0.5% of decayed stem volume for relatively undisturbed aspen stems of the same age.

Viruses as Aspen Pathogens

Viruses slow the growth of some aspen clones, and regeneration by suckering can maintain viral infections (Perala and Russell 1983). There has been relatively little aspen-related viral research, however, because viruses are more difficult to recover from trees and more difficult to study than other aspen pathogens. The greatest interest is in virus and virus-like diseases involved in intensive culture of hybrid aspen or poplars. The review by Hinds (1985) cited the account by Navratil (1979) of virus and virus-like diseases on poplar in Ontario and Saskatchewan; poplar mosaic virus was confirmed on various poplar hybrids but not on aspen. Martin et al. (1982) isolated a virus from declining clones of native aspen in Wisconsin. The decline symptoms included necrotic leaf spots early in the growing season, with leaf bronzing symptoms scattered throughout the crown in late July and August. Branches with bronzed leaves died the next year.

Insects Important to Aspen and Balsam Poplar Management

For the field forester interested in identifying insect problems in aspen or balsam poplar stands, two key sources of information are handbooks prepared by Ives and Wong (1988) for the prairie provinces and by Ostry et al. (1989) for the United States. Over 300 insects have been recorded on aspen by the Forest Insect and Disease Survey, Forestry Canada. Many of these insects cause little, if any, damage and the importance of others is unknown (Davidson and Prentice 1968).

When classified by feeding habits, the largest group of insects attacking aspen are the defoliators. These defoliators belong mainly to two orders: *Lepidoptera* (moths and butterflies); and *Coleoptera* (beetles). Both the larvae and adults of *Coleoptera* are leaf feeders, but only the larvae of *Lepidoptera* cause damage to aspen or balsam poplar foliage. The main species of *Lepidoptera* of importance to aspen are forest tent caterpillar, large aspen tortrix, Bruce spanworm, and aspen leaf miner. The main *Coleoptera* of importance are aspen leaf beetle, American aspen beetle, poplar borer, poplar and willow borer, bronze poplar borer, and aspen agrilus (Davidson and Prentice 1968). These species singled out by Davidson and Prentice are described in more detail in the following sections, based on a summary of the distribution, life cycle, and damage information assembled by Ives and Wong (1988). The latter authors and Volney (1989) also identified aspen leaf beetle (*Chrysomela crotchi* Brown) as a species that occasionally causes extensive damage to aspen, but this insect is not described below because 1989 surveys reported by Emond and Cerezke (1990) indicated that it was more common in southwestern and central Alberta and central Saskatchewan than it was further north in the mixedwood section. In the region of commercial aspen production in Canada, radial growth losses and tree mortality caused by defoliation have not been serious enough to warrant any insect management programs (Sterner and Davidson 1983).

Although the gypsy moth has not yet spread westward as far as the prairie provinces, it is probably only a matter of time until it does (Ives and Wong 1988). Aspen is one of the favored food sources for gypsy moth larvae (Gottschalk et al. 1987). Some possible interactions between gypsy moth defoliation and *Armillaria* incidence in Michigan aspen stands have recently been described by Hart (1990).

Forest Tent Caterpillar

The forest tent caterpillar, *Malacosoma disstria* Hübner, is aspen's most serious defoliator. Outbreaks of forest tent caterpillar typically last 4 or 5 years, but some persist for several more years. The average period between the first years of severe defoliation at any given location is about 10 years, with a range of 6–16 years. This means that there is nearly always an outbreak in progress somewhere within aspen's range in the prairie provinces (Ives and Wong 1988). The life cycle of forest tent caterpillar, which has one generation per year, is described by Ives and Wong as follows. Larvae hatch early in the spring, usually coincident with the flushing of aspen foliage. Larvae are black and hairy and are about 3 mm long. If the foliage has not flushed the larvae will mine the buds. The larvae are gregarious and although they do not form a tent they spin a trail of silk wherever they go. When not feeding they rest in a mass on a silken mat spun on the trunk or larger branches. Mature larvae are about 45–55 mm long and are covered with conspicuous silky hairs. Their typical appearance is shown in Figure 35F. Five or 6 weeks after hatching from the egg, the mature larvae form silken cocoons that contain a powdery yellow substance. The cocoons are spun between aspen leaves if the stand is not completely defoliated but may be spun in almost any available site if the trees are stripped of foliage.

The larvae pupate soon after the cocoons are spun, and the moths emerge about 10 days later. The moths live only a few days and are light yellow to buff brown and have a wingspan of 35–45 mm. The female deposits eggs around a small twig in a band that usually contains between 150 and 200 eggs. The eggs are covered with a frothy substance called spumaline, which is silvery colored when the eggs are laid but soon becomes dark brown. Weak females often deposit egg bands that are only partially covered with spumaline. The embryos become fully developed larvae about a month after the eggs are laid, but the larvae do not normally emerge until the following spring. The most important of these life cycle stages are shown in Figure 35.

The effects of forest tent caterpillar defoliation upon aspen growth are variable, and opinion is divided on the degree to which defoliation by forest tent caterpillar influences aspen growth. Probably the most accurate general statement is that the influence on growth depends upon the amount of defoliation. Ives and Wong (1988) indicated that light defoliation has little effect on tree growth. Two or more years of moderate-to-severe defoliation, however, causes a severe reduction in radial

Figure 35. Forest tent caterpillar, *Malacosoma disstria*. **A.** Adult *M. disstria*. **B.** Egg mass covered with spumaline. **C.** Egg mass only partially covered with spumaline. **D.** Newly hatched larvae. **E.** Bud mined by feeding larvae. **F.** Mature larva. **G.** Cocoon spun in aspen leaves. **H.** Colony of feeding larvae. **I.** Larvae resting on aspen trunk. **J.** Severely defoliated aspen stand. (Ives and Wong 1988.)

growth and may cause considerable branch and twig mortality. Normally, there is very little tree mortality directly attributable to defoliation, even when the trees are completely stripped of foliage because the trees produce enough new leaves to carry on essential photosynthesis. Except for increment loss, the insects cause little lasting damage.

Hildahl and Reeks (1960) found that 1 or 2 years of light-to-moderate defoliation and 1 year of severe (almost complete) defoliation depressed the radial growth at stump height and at mid-crown height only in the year of highest defoliation. Recovery of growth the following year was practically complete. Trees with 1 year of light and 2 years of severe defoliation did not show recovery until 1 or 2 years after the last year of severe defoliation.

Studies by Hildahl and Campbell (1975) indicated that in Manitoba and Saskatchewan between 1951 and 1954 increment losses due to severe tent caterpillar defoliation in average-stocked aspen stands amounted to almost 4.5 m^3 (stacked) per ha (1/2 cord per acre) annually over the 4-year period. Hildahl and Campbell referred to data from Alberta that indicated 80–90% loss in radial increment after 3 years of severe defoliation.

Although Ives and Wong (1988) suggested that very little aspen mortality is attributable to defoliation, Hildahl and Campbell (1975) indicated that there is evidence that if complete loss of leaves occurs for more than four consecutive seasons as many as 80% of the aspen can be killed.

Mattson and Addy (1975) suggested that normal insect grazing in the range of 5 to 30% of the annual foliage crop usually does not impair annual primary production. In fact, their model of aspen annual biomass production with and without forest tent caterpillar indicates that insect consumption of foliage may actually accelerate growth. Although severe outbreaks can reduce plant production temporarily, such outbreaks often occur in stands that are senescent, under stress, or have already passed their peak efficiency of biomass accumulation rates. There is also some evidence from the work of Mattson and Addy that, after an outbreak, residual vegetation is more productive than it was before the outbreak.

Mattson and Addy (1975) showed that defoliation by tent caterpillar temporarily reduced aspen wood growth by 14–92%. At the same time, leaf production temporarily increased because defoliated trees often refoliate the same year, with the biomass of the second crop of leaves as much as two-thirds that of a normal first crop. The model prepared by these researchers indicated that aspen diameters and heights were smaller in defoliated stands than in stands that were not defoliated if defoliation continued into the fifth and sixth consecutive years. There is, however, evidence that aspen stands defoliated for 2 or 3 years may actually show larger height growth and slightly more diameter growth than that shown before defoliation. Wood production may increase after severe defoliations, possibly because the circulation of N, P, and K is enhanced or because the distribution of light and moisture is more equitable. Moderate-to-severe defoliations can increase normal N, P, and K contributions in the litterfall by 20–200%. This occurs because litterfall is not only greater but also richer than normal due to the exceptionally high concentrations of nutrients in dead insect bodies, insect excrement, and wasted food parts. This enhances soil organisms and may result in increased plant growth.

In commenting on Mattson and Addy's estimates of defoliation influences upon aspen wood production, Volney (1988) reported that the effects of such outbreaks in the northern mixedwood forest are uncertain. He believes that conditions in the boreal mixedwood forests are sufficiently different from other areas where forest tent caterpillar studies have been done to make extrapolation of results questionable. Outbreaks of the tent caterpillar seem to be more frequent in the mixedwood forests of the prairie provinces and occur over larger areas than they do elsewhere. Whether this results in an accelerated decline of the aspen component of stands in the prairie provinces, or the tent caterpillar interacts with aspen differently, is not certain. It would appear, however, that repeated defoliation of aspen would be reflected in compensatory growth in understory vegetation (Volney 1988).

Mass starvation because of exhausted food supplies before caterpillars are fully grown is one factor that initiates population decline. There are also over 40 known species of insect parasites that attack this caterpillar during its various stages of development (Hildahl and Campbell 1975). None of these insects, however, have been used to control forest tent caterpillar. The most common natural controlling factor is cold weather shortly after eggs hatch in the spring. Above-average fall temperatures can also cause a rapid decline in caterpillar populations by killing many of the larvae within the eggs.

Large Aspen Tortrix

Although the large aspen tortrix, *Choristoneura conflictana* (Wlk.), typically eats the foliage of balsam poplar and willows, sometimes it is primarily a defoliator of aspen. Its outbreaks, which tend to precede those of the forest tent caterpillar, last for 2 or 3 years and often end soon after contemporaneous forest tent caterpillar populations reach outbreak proportions (Ives and Wong 1988).

Large aspen tortrix reproduces one generation per year. The overwintering larvae emerge from hibernation when aspen buds begin to swell, about 10 days before the leaves appear. The young larvae have yellowish or pale green bodies and black heads. They mine the buds, and the second molt occurs within the bud. Older larvae pull leaves together with silken threads and feed within the folded leaves. Mature larvae are 15–21 mm long and are dark green, almost black, in color. Pupation occurs in mid-June, and the adult moths emerge about 10 days later. The empty pupal cases can often be seen protruding from the clumps of folded leaves. Adult females have a wingspan of 27–35 mm, and the males are slightly smaller. The fore wings are light gray and have an inner patch, a median band, and an outer patch of dark gray. The eggs are laid in clusters, mainly on the upper surface of the leaves but almost anywhere if no aspen foliage is available. The eggs hatch in about 2 weeks. The young larvae form a web from leaves and feed on the epidermis of the leaves. They will also feed on leaves webbed together by the preceding generation. In mid-August the larvae cease feeding and seek suitable sites under bark scales, dead bark, or moss for the spinning of hibernicula, in which they overwinter (Ives and Wong 1988). The most important of these life cycle features are shown in Figure 36.

Defoliation by large aspen tortrix causes a reduction in radial increment of the tree, but the outbreaks seldom last long enough to cause any appreciable tree mortality. Large amounts of silk are sometimes spun by larvae in severe infestations (Ives and Wong 1988); this silk can be annoying to those walking through aspen forests.

Bruce Spanworm

Outbreaks of Bruce spanworm, *Operophtera bruceata* (Hulst), have been reported in eastern and western Canada, including the foothills of Alberta, but none have been reported in Manitoba or Saskatchewan. Outbreaks of this insect are typically short-lived, and severe infestations seldom last more than 2 or 3 years. The Bruce spanworm overwinters in the egg stage and reproduces one generation per year. The eggs are deposited in bark crevices or in moss at the base of tree trunks. They are pale green at first but soon turn bright orange. The larvae hatch in the spring at about the same time as foliage flushes. If the synchronization between emergence and flushing is altered by cool weather the larvae will mine the buds. The larvae are stout-bodied loopers, measuring about 18 mm in length when fully grown. They are typically light green in color. There is a large amount of color variation, however, and some individuals have blackish heads and dark gray bodies with three whitish bands or broad stripes along each side. The larvae may form a web from leaves and feed within the enclosed space, or they may feed openly, giving the foliage a ragged appearance. During severe infestations the trees may be festooned with silk. Larval feeding is usually finished by the third week in June, and pupation occurs in thin silken cocoons spun in the leaf litter beneath the trees. Adults emerge in late fall. The males are slender-bodied moths with a wingspan of 25–30 mm. The females are wingless and are covered in rough scales. The adults are very cold-tolerant and may be active when there is snow on the ground (Ives and Wong 1988). The life cycle features summarized above are illustrated in Figure 37.

Ives and Wong (1988) indicated that outbreaks of Bruce spanworm seldom last long enough to cause any permanent damage to the host trees, even if defoliation is severe. There will be a loss in radial increment during an outbreak, but no mortality directly attributable to the insect is likely to occur.

Poplar Leaf Miners

There are three species of leaf miners common on aspen and balsam poplar in the prairie provinces. The aspen serpentine leafminer, *Phyllocnistis populiella* Chambers, forms serpentine mines in the upper and lower surfaces of aspen leaves. The larvae of two species of *Phyllonorycter*, *Phyllonorycter salicifoliella* (Chambers) and *Phyllonorycter nipigon* (Freeman), form blotch mines on the underside of aspen and balsam poplar leaves, respectively. Although larvae of all three of these moth species occasionally become locally abundant, none are of economic importance (Ives and Wong 1988).

The serpentine leafminer reproduces one generation per year and overwinters in the adult stage. The tiny moths have a wingspan of about 5 mm and emerge from hibernation about the time that aspen leaves flush. They feed on nectar produced by glands near the base of young aspen leaves. Eggs are laid on both the upper and lower surfaces of the leaves, although most are on the upper surface. The young larva enters the leaf by chewing its way through the bottom of the egg. The larvae meander back and forth in the leaf, leaving a streak of frass. They are 3–6 mm long when fully grown. Adults emerge in late July or early August. They are active for several weeks before they disappear, presumably to hibernate in the duff (Ives and Wong 1988).

Phyllonorycter nr. *salicifoliella* reproduces one generation per year and overwinters in the adult stage. The

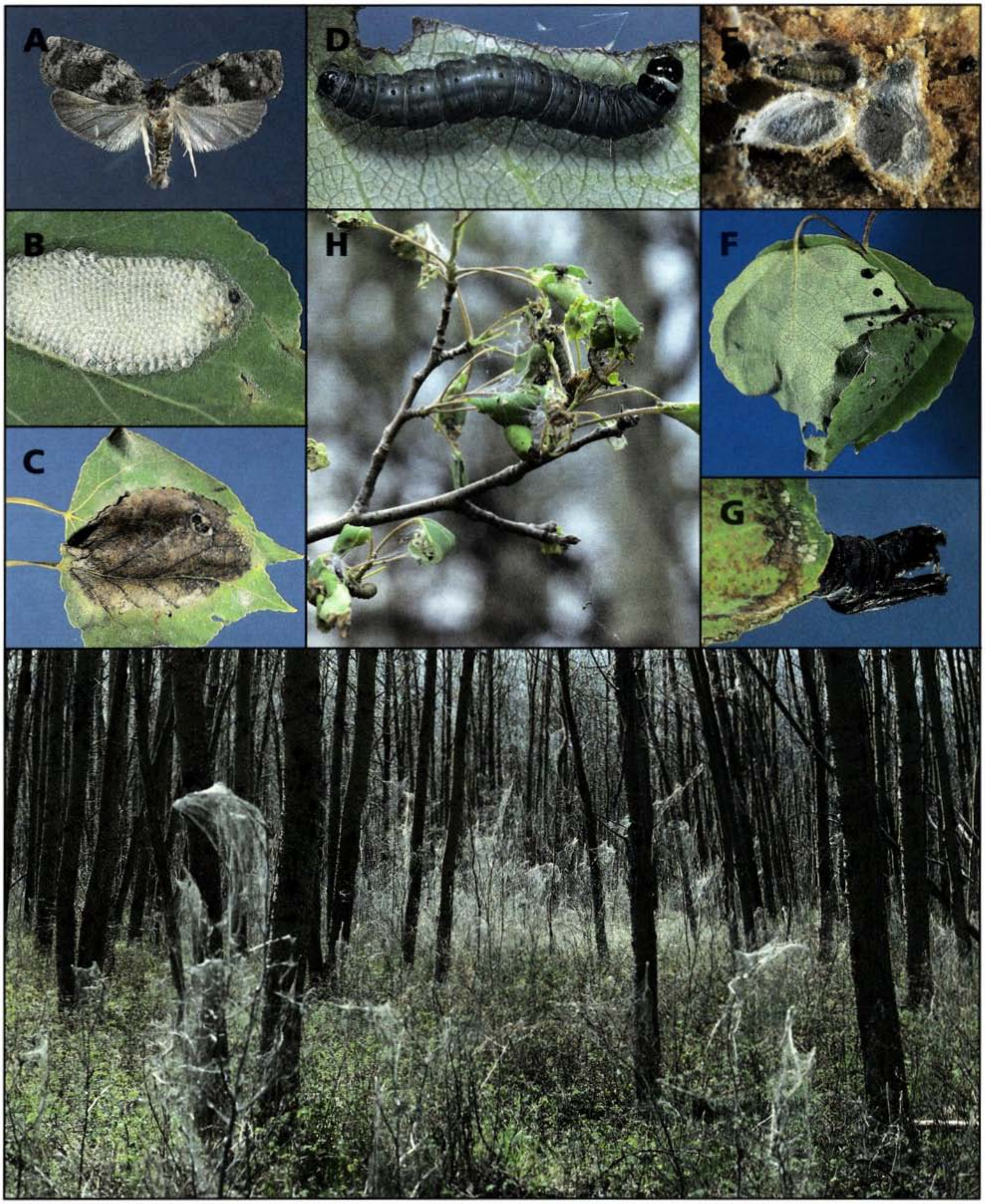

Figure 36. Large aspen tortrix, *Choristoneura conflictana*. **A.** Adult *C. conflictana*. **B.** Egg mass. **C.** Young larvae of the current generation in leaves webbed together by preceding generation. **D.** Mature larva. **E.** Overwintering larvae in hibernacula. **F.** Leaves webbed together by feeding larvae. **G.** Pupal case protruding from leaves. **H.** Groups of leaves webbed together by feeding larvae. **I.** Defoliated aspen stand. Note the copious amount of silk spun by wandering larvae. (Ives and Wong 1988.)

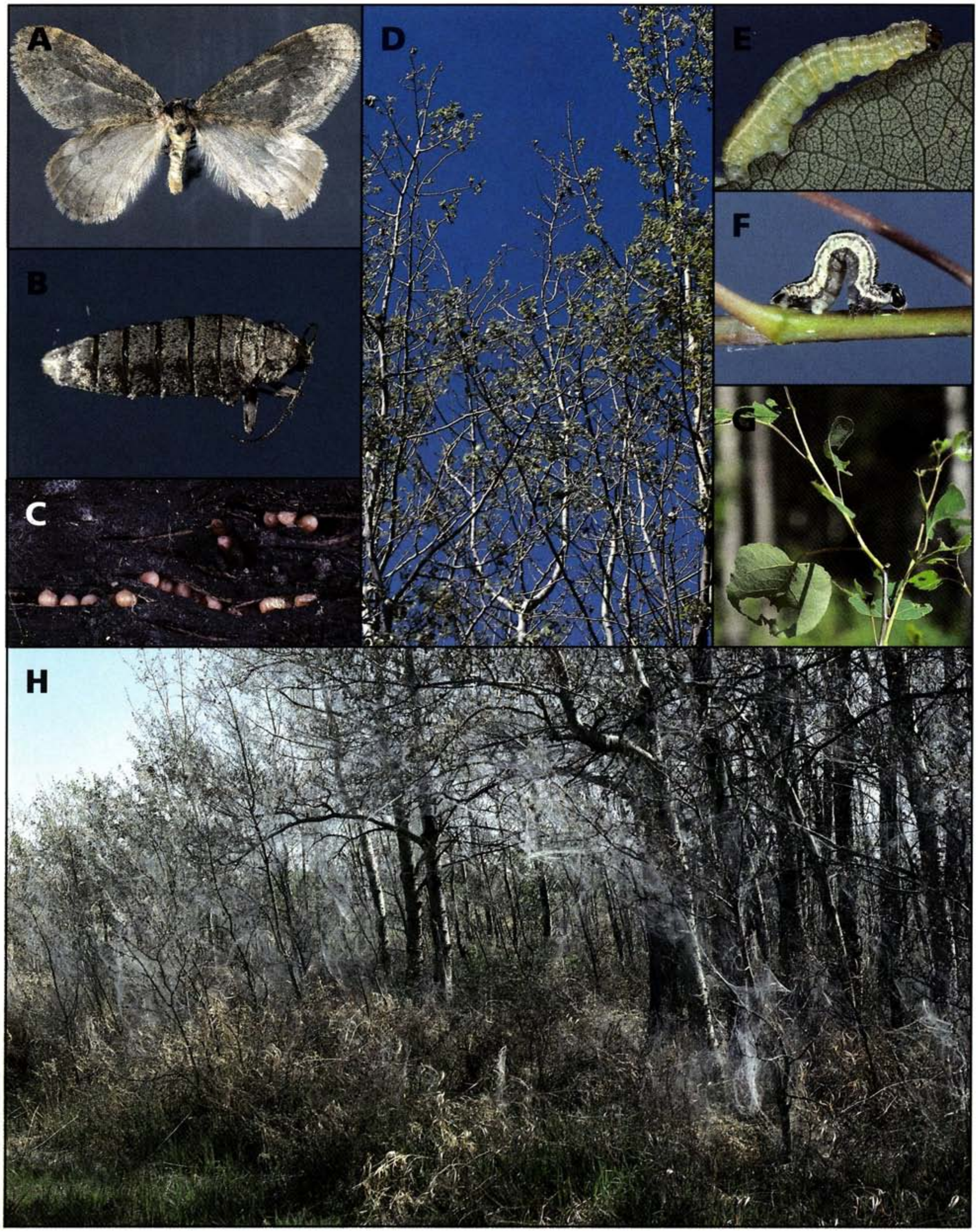

Figure 37. Bruce spanworm, *Operophtera bruceata*. **A.** Adult *O. bruceata* male. **B.** Adult *O. bruceata* female. **C.** *O. bruceata* eggs in bark crevices. **D.** Aspen defoliated by *O. bruceata*. **E.** *O. bruceata* larva, light color phase. **F.** *O. bruceata* larva, dark color phase. **G.** Close-up of *O. bruceata* defoliation. **H.** Aspen stand heavily infested with *O. bruceata*. Silk has been spun by wandering larvae. (Ives and Wong 1988.)

small brown and white moths have a wingspan of 8–9 mm and emerge from hibernation when the leaves on aspen are expanding. Eggs are laid on the undersides of leaves, usually near the edge. The larvae bore through the bottom of the egg and through the epidermis to feed on spongy parenchyma cells in the leaves. The fourth-instar larva spins a heavy layer of silk on the inside of the epidermis. The silk contracts as it dries, creating a bulge typical of blotch miners. Mature larvae are about 6 mm long. Adults emerge during late August and are active for a short period before hibernating. The location of the hibernation site is unknown, although there is speculation that it occurs under the bark scales of coniferous trees (Ives and Wong 1988).

Little is known about the life cycle of *Phyllonorycter* nr. *nipigon*, although it is probably very similar to that of *P.* nr. *salicifoliella* (Ives and Wong 1988). Key features of leaf miner life cycles are shown in Figure 38. Although leaf miners have little adverse effect on aspen and balsam poplar, the mining of the leaf tissue causes the leaves to dry out and turn brown, and may lead to premature leaf drop, especially during severe infestations (Ives and Wong 1988). This may be undesirable in parks or residential areas.

Leaf and Bud Galls on Aspen and Balsam Poplar

As outlined by Ives and Wong (1988), some mites and aphids stimulate aspen or balsam poplar to form galls that bear little resemblance to the original leaf or bud. Three of these types of galls are commonly found on various poplars in the prairie provinces. *Aceria* nr. *dispar* (Nalepa) is a minute mite that causes damage on aspen. This damage ranges from leaf rolling to complete distortion of the terminal leaf clusters, depending upon the amount of development of the host leaf tissue at the time of attack. Severe infestations sometimes occur on aspen regeneration. The poplar budgall mite, *Aceria parapopuli* Keifer, is particularly abundant on plantings of northwest poplar and other poplar hybrids in the southern parts of the prairie provinces. The poplar vagabond aphid, *Mordwilkoja vagabunda* (Walsh), produces conspicuous galls on the terminals of a number of poplar species. It has occasionally been locally abundant on aspen and balsam poplar in Manitoba and Saskatchewan but is of little economic importance (Ives and Wong 1988). Key life cycle stages of several gall-producing species are shown in Figure 39.

Root Borers in Aspen and Balsam Poplar

The poplar borer, *S. calcarata*, inhabits the stem, root crown and roots of young aspen and balsam poplar. Ives and Wong (1988) noted that open-growing trees seem to be most vulnerable to attack. The insect is particularly troublesome in the aspen parkland region of the prairie provinces, where up to 75% of trees 7–10 cm in diameter have been infested. The insect also occurs in forested areas but is not usually considered to be a problem.

The poplar borer has a long life cycle. Most individuals require 4 years to complete development, but this period may vary from 3 to 5 years. The adult beetles are about 25 mm long, as are the antennae. The adults emerge in late June and July and live for up to 6 weeks. They feed on aspen and willow foliage and begin laying eggs about 1 week after emergence. The females cut crescent-shaped notches or punctures into the bark and deposit one or two creamy-white eggs in each hole. Oviposition tends to be concentrated on exposed parts of the trunk or in the lower crown. The eggs hatch in about 3 weeks, and the young larvae feed on the inner bark. First-year feeding ceases in October, and the larvae hibernate near the end of the burrows. Second-year feeding begins in late April or early May; the larvae eject sawdust as they bore through the sapwood into the heartwood. The second winter is spent in a cell formed from tightly packed frass at the upper end of the burrow. Third-year feeding also begins in late April or early May. The larvae cease feeding in August and construct a hibernation cell at the end of the burrow in the heartwood. The insects spend the third winter as prepupae. Pupation starts by mid-May or early June of the fourth year, and adults develop soon after (Ives and Wong 1988). Some key features of the poplar borer's life cycle are illustrated in Figure 40.

As shown in Figure 40C, trees that harbor poplar borers often exude varnish-like sap that gives a characteristic stain to the bark surface. The same trees are often attacked repeatedly. Trees are not usually killed by poplar borer attack, even when riddled with tunnels, but the weakened stems are liable to break during windstorms, and the wood is almost useless for lumber or other purposes. Woodpeckers cause appreciable damage to the wood while searching for the larvae of poplar borers, and the openings maintained by the larvae for ejection of masticated pulp and waste material provide infection courts for various fungi (Ives and Wong 1988).

Other insects that bore into the roots and basal stems of aspen or balsam poplar in the prairie provinces include three species of ghost moths: *Sthenopis quadriguttatus* (Grote) on aspen; and *Sthenopis argenteomaculatus* (Harris) and *Sthenopis purpurascens* (Packard) on balsam poplar. None of these borers were considered by Ives and Wong (1988) to be of economic importance, but their tunnels are entry points for disease organisms. Larval feeding by the flatheaded apple tree borer, *Chrysobothris*

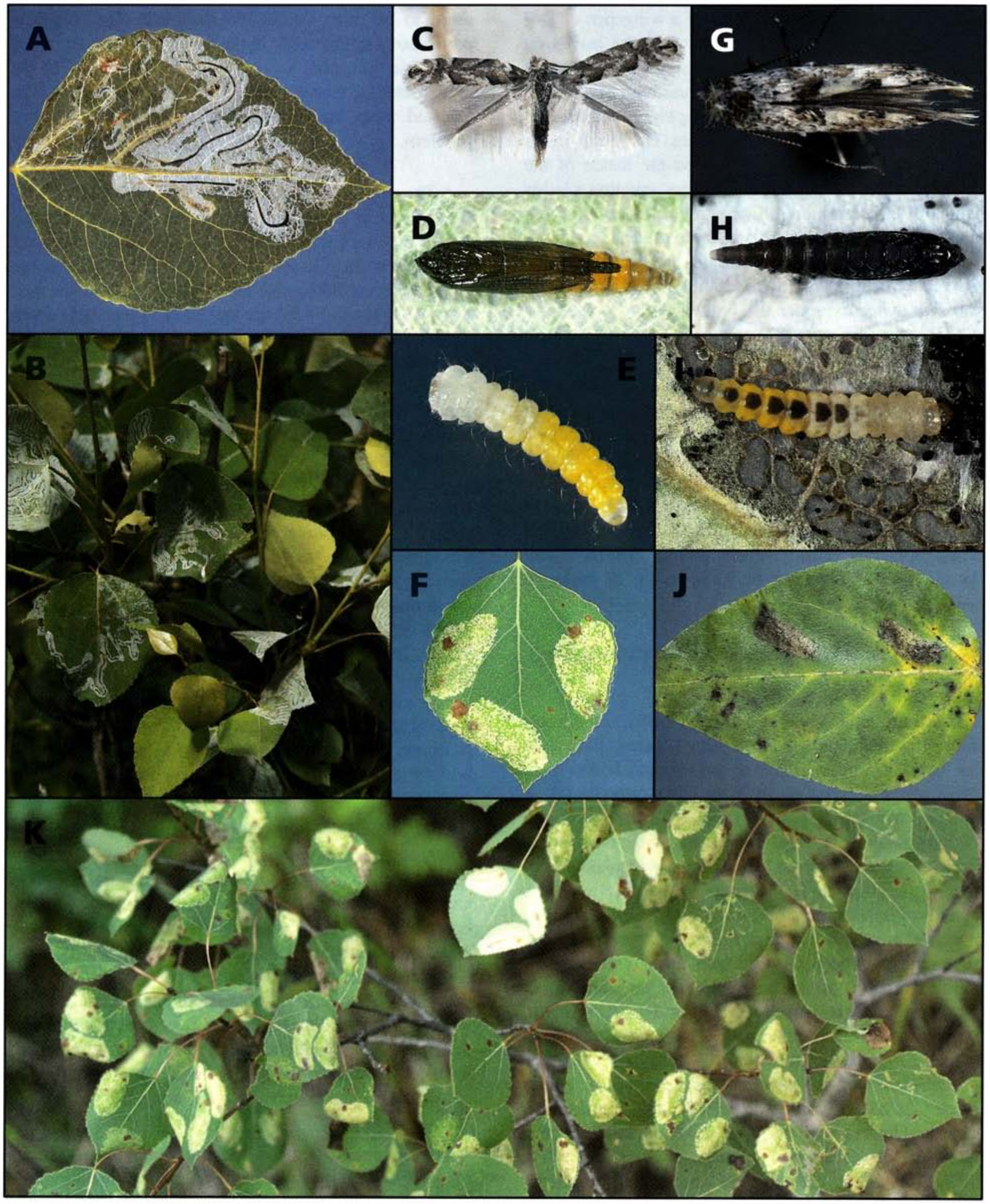

Figure 38. Poplar leaf miners. **A**, The aspen serpentine leafminer, *Phyllocnistis populiella*, in an aspen leaf. **B.** Trembling aspen leaves mined by *P. populiella*. **C.** Adult *Phyllonorycter* nr. *salicifoliella*. **D.** *P.* nr. *salicifoliella* pupa. **E.** *P.* nr. *salicifoliella* larva. **F.** Group of *P.* nr. *salicifoliella* mines in an aspen leaf. **G.** Adult *P.* nr. *nipigon*. **H.** *Phyllonorycter* nr. *nipigon* pupa. **I.** *P.* nr. *nipigon* larva. **J.** Balsam poplar leaf mined by *P.* nr. *nipigon*. **K.** Aspen leaves mined by *P.* nr. *salicifoliella*. (Ives and Wong 1988.)

Figure 39. Leaf and bud galls on poplar. **A.** Close-up of galls on trembling aspen caused by the mite, *Aceria* nr. *dispar*. **B.** Young aspen heavily infested with *A.* nr. *dispar*. **C.** Close-up of gall caused by the poplar budgall mite, *Aceria parapopuli*. **D.** Twig heavily infested with *A. parapopuli*. **E.** Close-up of gall on balsam poplar caused by the poplar vagabond aphid, *Mordwilkoja vagabunda*. **F.** Balsam poplar heavily infested with *M. vagabunda*. (Ives and Wong 1988.)

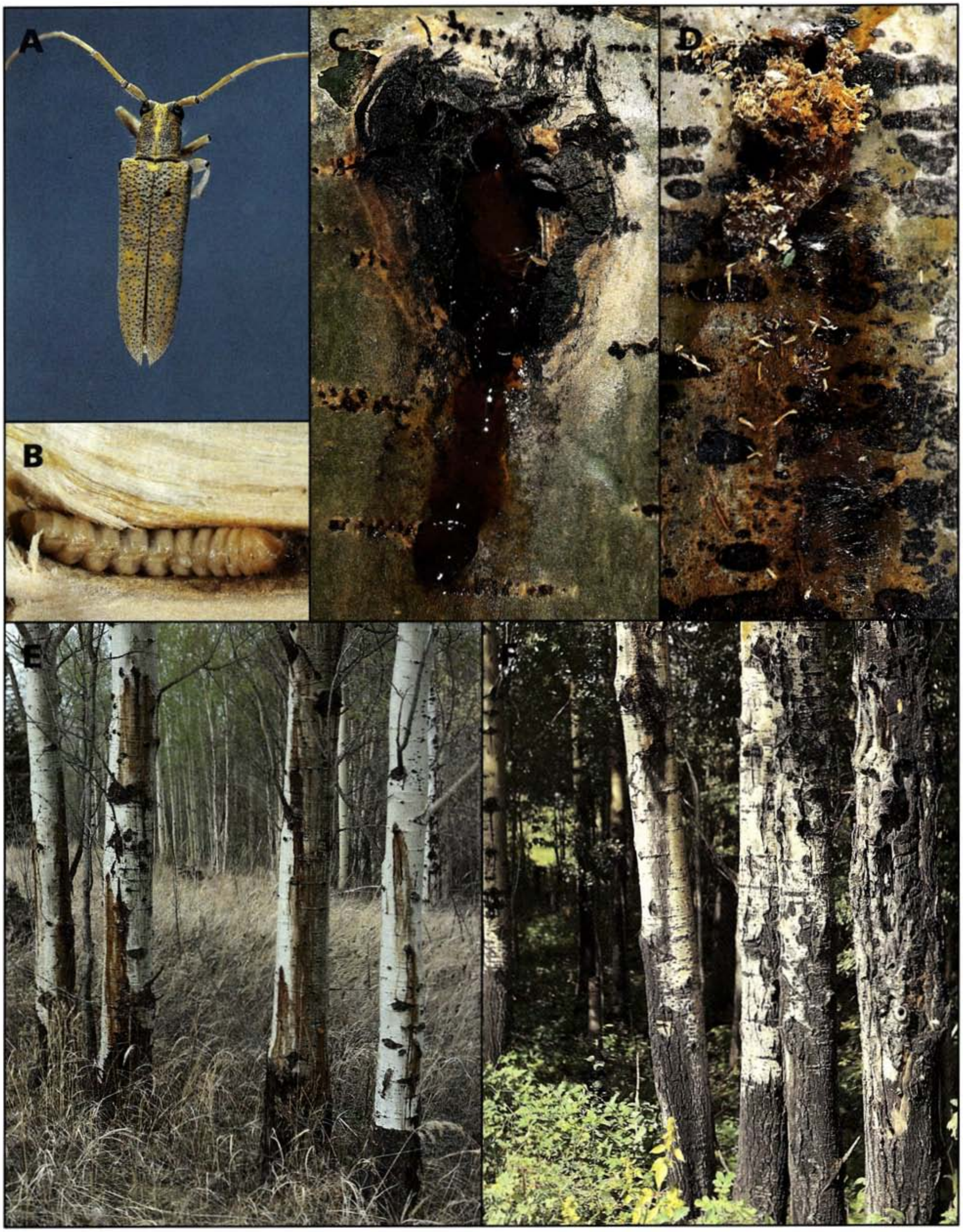

Figure 40. Poplar borer, *Saperda calcarata*. **A.** Adult *S. calcarata*. **B.** *S. calcarata* larva. **C.** Sap flow caused by *S. calcarata* larva. **D.** Sawdust ejected by *S. calcarata* larva. **E.** Fresh *S. calcarata* damage. **F.** Old *S. calcarata* and woodpecker damage. (Ives and Wong 1988.)

femorata (Olivier), appears to be a factor in the death of young aspen suckers. Fortunately, some borers, especially *S. calcarata*, cause most of their damage to aspen or balsam poplar on poor sites, which diminishes their potential economic importance (Ives and Wong 1988).

Insect Relationships in Young Aspen Stands

More is known about insect relationships in mature aspen stands than in young stands; remarkably little literature exists on the influences of insects on young aspen stands. Webb (1967) indicated that in heavily stocked aspen stands the death of a number of the trees, particularly the suppressed and intermediate individuals most vulnerable to borer and fungi attack, will improve the health of residual trees. He suggested that gradual removals of these aspen stems by insects and diseases result in less disturbance and are less costly than silvicultural thinnings. Some forest entomologists have hypothesized that dense aspen sucker stands can withstand the effects of insects simply because the stands are so dense and have few openings and edges. This raises the question of whether insect influences will be more prevalent if future managed stands have lower sucker densities than fire-origin stands (W. Ives, pers. com., November 1988). In Ontario, there has been some concern that postharvest sucker stands may not be as uniformly dense as sucker stands of fire origin (Basham 1981). Because the entomology of the young stages of today's predominantly fire-origin sucker stands is generally unresearched, it is not possible to predict what the insect influences might be if future forest managers are dealing with stands that have lower sucker densities, more discontinuities and greater amounts of edge per unit area of land.

Site and Successional Relationships

Many boreal forest ecologists have contributed to the sound information base on site and successional relationships in ecosystems that contain aspen and balsam poplar in the prairie provinces and northeastern British Columbia (Moss 1932, 1953, 1955; Heinselman and Zasada 1955; Rowe 1956, 1961; La Roi 1967; Annas 1977; Van Cleve and Viereck 1981; Corns 1983; Corns and Annas 1986; Kabzems et al. 1986; DeLong 1988; Corns 1989). Aspen is a substantial component of forests in most of Canada's provinces. It is not surprising that this species is also a component of one or more types within each of the diverse site and land classification systems that have been developed in Canada over the past 60 years. For further information, a comprehensive recent review of Canada's site classification programs was prepared by Burger and Pierpoint (1990). Only a few key points are made in this section, together with several sample descriptions of sites on which aspen is a prominent tree in western Canada.

There are differences of opinion about the nature of succession in boreal forest stands that involve both hardwoods and softwoods. One approach, typified by the work of Van Cleve and Viereck (1981), is to characterize aspen to spruce succession as a textbook example of predictable, unidirectional change of species composition. In contrast, some boreal and mixedwood foresters (Rowe 1961) do not think that fire-dependent forests fit the traditional view of succession. Both of these approaches are outlined in several subsections below.

The three broad categories of aspen succession recognized in the mountainous western United States probably have only limited applicability in the boreal mixedwood forests of the prairie provinces and northeastern British Columbia. The three kinds of succession described by Harniss (1981) for the western states were as follows: i) "decadent" aspen, which is characterized by low levels of aspen stocking, high stem mortality, little sucker regeneration, and no replacement by conifers; ultimately such stands succeed to brush, forbs, or grasses; ii) "stable" aspen, which is characterized by high levels of aspen stocking, no unusual mortality, no or few conifers, and evidence of successive generations of aspen; and iii) "seral" aspen, which is characterized by high levels of aspen stocking after a disturbance, but with conifers increasing, aspen mortality increasing, and aspen regeneration decreasing as the stand develops. If one were to attempt to apply this classification to the boreal range of aspen's distribution, probably only the "seral" category would be meaningful for understanding aspen-related succession in northern mixedwoods.

As the review by Corns (1989) emphasizes, aspen can occur as a dominant or codominant species on a wide range of sites. There is, however, a similarity among the sites on which aspen occurs from British Columbia to Ontario. It has also become evident to the developers of these site classifications that aspen productivity and stand responses to logging, site preparation, or regeneration practices are site dependent and predictable. Although the vegetational and edaphic details vary across the east–west expanse of the boreal mixedwoods, the matrix of soil texture, moisture, and drainage conditions for good, intermediate, and poor aspen sites, reproduced in Figure 41, is a good practical guide for the aspen manager. Navratil, Bella, and Peterson (1990) also stressed that mixedwood cover types occur over a wide range of moisture regimes, soil textures, and organic layer thicknesses, all of which influence density and growth of aspen regeneration through effects on soil

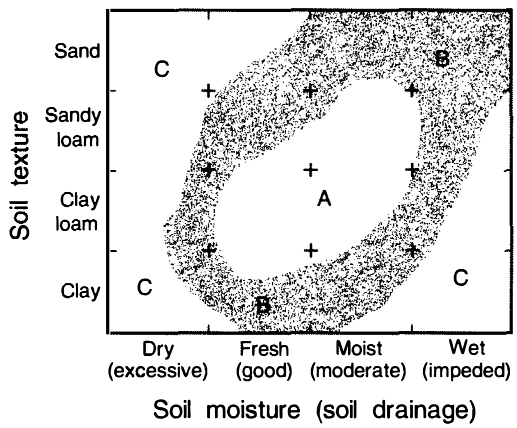

Figure 41. Matrix of soil texture, moisture, and drainage conditions for good (A), intermediate (B), and poor (C) aspen sites (Steneker 1976b).

temperature and herbaceous and shrub cover. Often on the most productive mixedwood sites, factors such as a thick duff layer, a rise in the water table after harvest, low soil temperature and invasion of alder and willow may hinder aspen regeneration. These post-logging changes have been observed on many sites in the area around Hudson Bay, Saskatchewan. On such sites, the balsam poplar component often increases compared to the original stand. In this context, ecologically based site classification that also incorporates soil moisture dynamics may be particularly useful in mixedwood management.

There is more information on successional relationships between aspen and conifers than there is between aspen and balsam poplar. These two species often occur together on mesic sites, commonly with very few or no conifers. In some cases in Alberta as much as one-third of the basal area in stands identified as aspen is actually balsam poplar. Although many such stands will be of root sucker origin, there are certain sites, such as newly exposed alluvium or mineral soils exposed after fire, where these two species can establish by seedlings. There is little information available on interspecific relations in sites where aspen and balsam poplar develop concurrently. As described elsewhere in this review, greenhouse trials were conducted by Morris and Farmer (1985) to assess the relative growth rates of aspen and balsam poplar when they grow in various proportions. Their results should be tested under natural conditions in the boreal mixedwood ecosystems of the prairie provinces to provide forest managers with local information about interspecific relations in mixed stands of aspen and balsam poplar.

As shown by the early work of Rowe (1956), there are major understory differences between spruce-dominated stands and aspen-dominated stands (Fig. 42). The most conspicuous difference is the relatively poor development of herb and shrub cover, and substantial development of moss cover, under spruce canopies. In contrast, no distinct moss layer occurs in aspen-dominated stands, but herb and shrub understories are exceptionally well-developed. Many ecologists have attributed the relatively lush understory of aspen stands to the sparse crown development in the aspen canopy. The greater light penetration beneath an aspen canopy, in contrast to that beneath coniferous stands, may be the main reason for the well-developed herb and shrub layer beneath aspen canopies (Fig. 43). The well-developed understory, however, may also be influenced by the fact that such ecosystems are relatively nutrient-rich, with the capability to support a significant shrub and herb biomass.

One distinctive feature of the aspen understory, not widely reported in the literature, is the occasional presence of a juvenile understory of aspen beneath a mature or overmature aspen overstory. There is a tendency to think of aspen in terms of predominantly single-storied,

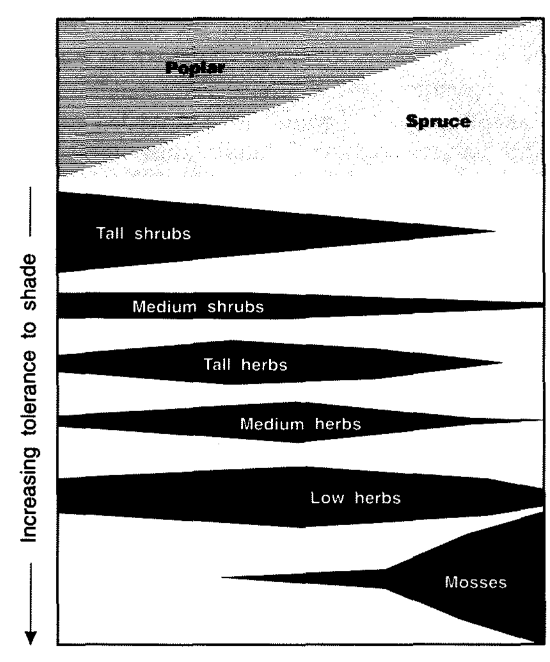

Figure 42. Cover and abundance of various understory strata as the relative proportions of *Populus* and *Picea* change in the mixedwood section of the prairie provinces (Rowe 1956).

Figure 43. In Saskatchewan and Manitoba, hazel (*Corylus cornuta*) is a prominent understory shrub in aspen stands (photo courtesy of A. Kabzems).

even-aged stands, but there are a number of circumstances where a two-aged aspen stand can develop (Peterson 1988).

The traditional view of boreal mixedwood succession is a progressive change from mainly hardwoods to mainly conifers. For example, the descripton of the forest succession of the Tanana River floodplain near Fairbanks, Alaska, by Van Cleve and Viereck (1981) involved balsam poplar, aspen, and white spruce and was considered by those researchers to be applicable to most of the North American boreal zone. Although alluvial surfaces are ideal locations for seed germination (Fig. 44), frequent flooding, sediment deposition, and erosion make these sites highly unstable for plant establishment. On alluvial surfaces 1 to 2 years old, surface evaporation of groundwater commonly results in concentrations of calcium sulfate and various chloride- and carbonate-bearing salts. In Alaska, these salt accumulations have been observed to reduce aspen seed germination by as much as 80%. Balsam poplar also shows reduced germination success where there are high salt concentrations, but to a lesser degree than aspen. Aspen seedlings germinated on salt crusts showed a substantially lower rate of growth and smaller cotyledons and hypocotyls than seedlings from salt-free sites. Establishment of these boreal hardwoods on alluvial sites is dependent on continued sediment deposition that raises the surface above the upward capillary movement of salt-laden groundwater.

A closed shrub stage commonly develops in 5–10 years, followed by a young balsam poplar stage on alluvial surfaces 20–40 years old. Mature balsam poplar with an understory of older and young white spruce typically occur on surfaces 80–100 years old. Old balsam poplar remain in the stand until about 175 years. Sites that have remained unburned for 200–300 years are typified by mature white spruce with a well developed moss layer and forest floor (Van Cleve and Viereck 1981).

On upland sites, succession from aspen to white spruce after fire (Fig. 45) can follow either of two separate patterns. In most cases there is a rapid and dominant development of aspen and birch long before spruce is conspicuous. Another possible pattern, if a seed source is available and site conditions are optimal, is for white spruce to invade concurrently with the hardwoods. In such cases, even-aged white spruce stands will develop without a preceding hardwood stage (Van Cleve and Viereck 1981).

The Alaskan successional examples previously outlined are also recorded in the prairie provinces. For example, the mixedwood monograph by Kabzems et al. (1986) includes a photograph of a stand that developed following a severe fire, in which spruce and aspen coexist in a comparable height class because both started to grow at the same time after the fire created a suitable regeneration medium. A companion photograph portrays a stand that developed after a light fire, where aspen established immediately and spruce regeneration came in slowly over a long period of time.

Variations in ecosystem development may also be a result of influences other than fire. For example, Rowe (1955) described variations in successional trends in north-central Saskatchewan that are explained by land type rather than fire history. In that area, aspen stands that occur on low, narrow till ridges between intervening depressions of black spruce develop into a black spruce cover type. But on dry, sandy landforms in the same region, aspen stands may change gradually to self-perpetuating jack pine forest, or to white spruce–jack pine on south-facing slopes and to black spruce–birch on north-facing slopes. Such variability is one reason why

Figure 44. Early successional stages on floodplains and after fires are characterized by dense stands of aspen and balsam poplar, Chinchaga River, Alberta.

Figure 45. The trend from coniferous to hardwood forest cover is aided by both fire (left side of river) and by harvest removal of conifers (cut block on right side), Chinchaga River, Alberta.

site classification is so important to boreal and mixedwood silviculture.

Documentation by Van Cleve and Viereck (1981) indicated that, following fire on upland sites in Alaska, the first invasion is by light-seeded species such as fireweed (*Epilobium angustifolium* L.) and willows, or by herbs such as *Geranium* or *Corydalis*, which germinate quickly from seeds buried in soil. From 6 to 25 years after a fire, willows and saplings of deciduous trees dominate burned sites. This is a period of very heavy litterfall, a factor that may hide the many white spruce seedlings that are also often present. From 26 to 50 years, young aspen and birch form a dense canopy that shades out intolerant shrubs such as willows, with a proportionate increase in the more shade tolerant shrubs. For the next 50 years, aspen continues to dominate the site, but white spruce becomes progressively more conspicuous in the understory (Fig. 46). White spruce is often dominant by 100 years after a fire. The mature spruce stage, with often no aspen and only scattered remnant birch, is reached in about 200 years. By this time there is a continuous moss mat (Van Cleve and Viereck 1981). The successional fate of mature white spruce forests in the absence of recurring fires is not well understood for the boreal and mixedwood regions from Alaska southeast to Manitoba.

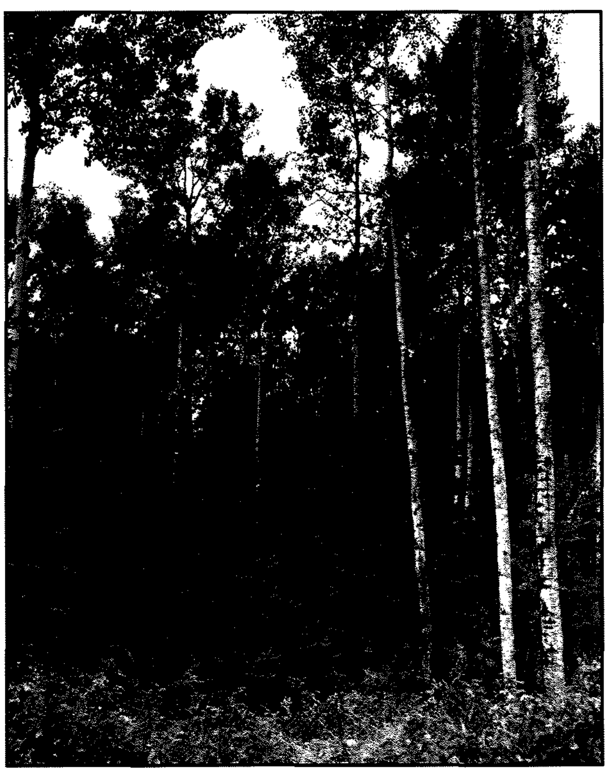

Figure 46. In mixedwood stands, shade tolerant spruce is the typical tree understory beneath mature aspen (photo courtesy of Sask. Govt. Photo by Alan Hill).

The predominance of young ecosystems in the boreal region upsets the traditional view of succession. Traditionally, succession is viewed as a consistent, unidirectional change of species composition over time. Most of the vegetation changes in fire-dependent forests, however, do not fit this concept. Most species of the northern mixedwood region become established in the first few years after fire, and many individuals of many species are not eliminated from the site by fire. Even if aboveground parts are killed, vegetative reproduction and seed germination, either from organic layer seed banks or canopy-stored seeds, ensure a rapid new crop. Many stands regenerate to a composition almost identical to that of the burned stand. Most of the visual changes in boreal mixedwood stands as they mature simply reflect different growth rates of species. Often there is no succession in the tree stratum because the first generation trees reestablish simultaneously, because there are no replacement species, or because fire returns too soon (Rowe 1961).

Boreal and mixedwood forests are typified by young ecosystems. They are young in two contexts. First, the entire mixedwood zone is dominated by forest stands that are young in comparison to many other forest regions in North America. This is because fire occurs frequently. In the boreal and mixedwood forests of the prairie provinces, Rowe (1961) never recorded any type of spruce stand that, in structure or condition of humus layer, would suggest a third- or fourth-generation spruce forest. Irregular-structured, hummocky-floored stands that indicate successive generations of white spruce can be observed in the more humid parts of the eastern Canadian boreal forest but are not present in the western parts of the boreal region. There probably are examples in the western boreal region of fireproof peninsulas in lakes or on islands in lakes where spruce climax occurs, but these examples are poorly documented. Second, boreal and mixedwood foresters often deal with young ecosystems because the main silvicultural challenge occurs in the first few years after disturbances. This is typified by dominant species such as fireweed, willow, alder, *Calamagrostis*, and a variety of other aggressive pioneer species that provide substantial interspecific competition. These young ecosystems are characterized by high growth rates, high production, and relative instability when contrasted with mature ecosystems. Fire relationships are inseparable from any consideration of successional relationships in aspen-dominated ecosystems.

A community type approach to classification is well-suited to stands that contain aspen because of the variety of successional stages. A recently prepared field guide for identification and interpretation of aspen ecosystems in various stages of succession in a portion of the Prince George Forest Region, British Columbia (DeLong 1988), emphasizes the importance of a site classification system that is not tied solely to mature or climax phases of each ecosystem. Foresters are often required to make management decisions on landscape units that are at an early stage of development following harvest or fire. During early successional (seral) stages, the plant community that will be present 100 or more years later is not always evident. Forest managers, therefore, need to base management interpretations on a site classification system that is built around ecosystem differences recognizable at early stages of stand development. That is the purpose of the field guide for a portion of northeastern British Columbia, in which DeLong provided vegetation, soil, and site descriptions for seven different aspen ecosystems. A sample site description of the most common of these ecosystems (aspen–creamy peavine unit) is summarized on the following page.

A classification approach that requires prediction of potential or climax vegetation at a given site is not well-suited to ecosystems in which aspen is a component (DeLong 1988). This point was also emphasized in a recent compilation of aspen community types of the intermountain region, involving southern Idaho, western Wyoming, Utah, and Nevada (Mueggler 1988). For aspen ecosystems in that region, the United States Forest Service prefers to focus on community types. This is because community types are what managers see in the field, rather than habitat types, which require recognition of potential or climax vegetation. The reasons for this choice are considered to be applicable to other regions, including the prairie provinces, where aspen occupies a great diversity of varying successional stages.

In the intermountain region, a community type approach to classification was chosen in preference to a habitat type approach because of the ill-defined successional status of communities within the overall aspen ecosystem. Community types are aggregations of similar plant communities based upon existing floristics regardless of successional status. In contrast to habitat types, the existing vegetation also reflects the effects of past disturbances. Community types, therefore, may represent either climax or early-successional plant associations. Once community types are defined, effort can be directed toward establishing successional relationships and linking the community types to known or expected climax plant associations (placing them within habitat types). The community types can also be used as a basis for mapping, structuring information, and resource management planning (Mueggler 1988). Examples of vegetation classification, which focus on present vegetation types in the boreal region of the prairie provinces, have been developed by Corns and Annas (1986), Kabzems et al. (1986), and Knapik et al. (1988).

Sample Descriptions of Aspen-dominated Ecosystems

It would require a lengthy report to outline the entire range of site types in which aspen and balsam poplar occur in western Canada. The most practical way to review site relations of aspen-dominated ecosystems is to provide some sample descriptions for the most common site types in this region. Forest ecosystem classifications are now available for British Columbia, Alberta, Saskatchewan, and Ontario as outlined in the recent reviews by Corns (1989) and Burger and Pierpoint (1990).

In the portion of the Moist Warm Boreal White and Black Spruce biogeoclimate zone of northeastern British Columbia, the most common seral aspen ecosystem is the aspen–creamy peavine unit.

In west-central Alberta, the *Picea glauca/Viburnum/Aralia* (aspen facies) ecosystem is common. It is a nutritionally richer and moister site unit than the aspen–creamy peavine unit described by DeLong; it is similar to the aspen–black twinberry ecosystem described in northeastern British Columbia. The following Alberta aspen facies is based on Corns and Annas (1986), edited slightly to more closely match the format of the sample site description by DeLong (1988).

Aspen–Creamy Peavine Ecosystem
(Distribution: very common)

Vegetation

Tree layer: 45% cover
- *Populus tremuloides*

Shrub layer: 25% cover
- *Rosa acicularis*
- *Viburnum edule*
- *Amelanchier alnifolia*
- *Lonicera involucrata*
- *Populus tremuloides*

Herb layer: 45% cover
- *Lathyrus ochroleucus*
- *Epilobium angustifolim*
- *Cornus canadensis*
- *Pyrola asarifolia*
- *Aster conspicuus*
- *Linnaea borealis*
- *Rubus pubescens*
- *Petasites palmatus*
- *Vicia americana*
- *Fragaria viginiana*
- *Galium boreale*
- *Calamagrostis canadensis*
- *Maianthemum canadense*
- *Mertensia paniculata*
- *Arnica cordifolia*

Moss layer: 5% cover
- *Eurhynchium pulchellum*

Soil and site

Moisture regime: (Submesic–) mesic
Nutrient regime: Medium–rich
Slope gradient (%): 0–60 (usually less than 20)
Slope position: Upper–lower or level
Parent material: (Glacio)fluvial, morainal, occasionally lacustrine
Soil texture: Fine–coarse
Coarse fragments (%): 0–50 (usually less than 20)
Site index (mean and range height, m, at age 100):
Aspen 24 (range 10–32)
black cottonwood 21 (range 15–27)

Picea glauca/Viburnum/Aralia Aspen Facies Ecosystem (Distribution: common)

Vegetation

Characteristic species; with % cover

Tree layer:
- *Populus tremuloides* (47)
- *Picea glauca* (11)

Shrub layer:
- *Viburnum edule* (16)
- *Rosa acicularis* (6)
- *Lonicera involucrata* (5)
- *Amelanchier alnifolia* (1)
- *Ribes lacustre* (1)

Herb layer:
- *Aralia nudicaulis* (9)
- *Cornus canadensis* (8)
- *Calamagrostis canadensis* (8)
- *Linnaea borealis* (7)
- *Lathyrus ochroleucus* (4)
- *Mertensia paniculata* (3)
- *Mitella nuda* (3)
- *Epilobium angustifolium* (2)
- *Pyrola asarifolia* (2)
- *Petasites palmatus* (1)
- *Maianthemum canadense* (1)
- *Aster ciliolatus* (1)
- *Smilacina racemosa* (1)
- *Galium boreale* (1)
- *Actaea rubra* (+)[a]
- *Streptopus amplexifolius* (+)

Moss layer:
- *Hylocomium splendens* (13)
- *Pleurozium schreberi* (9)
- *Ptilium crista-castrensis* (5)

Soil and site

Moisture regime (modal): Mesic (4)
pH regime (mean): Humus: 4.0–6.5 (5.3)
Mineral: 4.1–6.0 (5.2)
Elevation range (mean): 520–1050 (880) m
Percent slope gradient (mean): 0–25 (5)
Aspect: Variable
Soil subgroups: Orthic, Gleyed, Brunisolic, and Dark Gray Luvisols, Orthic Luvic Gleysols
Soil drainage: Imperfectly to well
Landform: Morainal, lacustrine
Site index (mean and range of height, m, at age 70):
Aspen 23 (range 21–29); white spruce 21 (range 17–29); lodgepole pine 25 (range 22–29)
Productivity, average, and range of mean annual increment: 5.6 m^3 ha^{-1} $year^{-1}$ (range 4.0–6.4)

[a] + indicates less than 5% cover.

Three aspen-dominated ecosystems were described by Kabzems et al. (1986) for mixedwood stands in Saskatchewan. The sample ecosystem description below is for the unit in which aspen productivity is highest.

***Populus–Aralia/Linnaea* Ecosystem**
(Distribution: common)

Vegetation

Tree layer:
Populus tremuloides

Shrub layer:
Rosa acicularis
Viburnum edule
Ribes triste

Herb layer:
Linnaea borealis
Cornus canadensis
Aralia nudicaulis
Lathyrus ochroleucus
Calamagrostis canadensis
Rubus pubescens
Epilobium angustifolium
Petasites palmatus
Mitella nuda
Vaccinium vitis-idaea
Fragaria virginiana

Soil and site

Soil drainage: Moderately well drained sites
Landform: Glacial till on hummocky topography
Productivity, average, and range of mean annual increment: 3.7 m^3 ha^{-1} $year^{-1}$ (range 3.5 to 3.8) at rotation age of 60 years; at 60–70 years, gross yields range from 210 to 315 m^3/ha

Influence of Tree Root Systems on Boreal Mixedwood Succession

From studies near Lesser Slave Lake, Alberta, Strong and La Roi (1983b) suggested an important role of roots in aspen succession to white spruce. As white spruce grows beneath the aspen canopy, the forest litter slowly changes from nutrient-rich deciduous broadleaf to nutrient-poor needle-litter, which is slower to decompose. Year-round shade as well as nonsmothering needle litter encourage an increase in terrestrial moss cover. As moss cover expands, a vertical partitioning of roots occurs, with white spruce roots growing in the moss carpet above the aspen roots. The moss carpet itself intercepts water and nutrients, further restricting the downward extension of aspen roots. Under these conditions white spruce is further encouraged. Strong and La Roi (1985) concluded from their Alberta root studies that white spruce is either less nutrient-demanding or has more efficient mechanisms for nutrient absorption than aspen.

Gale and Grigal (1987) also noted relationships between the successional status and vertical root distributions of northern tree species. Early successional species such as aspen had a significantly greater proportion of roots occurring deeper than did late successional or shade tolerant species. Differences in vertical root distributions were presumed by Gale and Grigal to be related to the inherent genetic potential of early successional species for deep exploitation of nutrients and water. Early successional species are also able to adapt to sites limited in water and nutrients because of their ability to exploit larger volumes of soil. Late successional or shallow-rooted species are better adapted to sites where resources are concentrated near the soil surface as the result of nutrient cycling and soil development.

Aspen's Reputation as a "Nurse Crop"

Field foresters familiar with boreal mixedwoods appear to relate to the concept of aspen as a nurse crop for conifers in the ecosystem. Although there is a general appreciation that aspen and spruce complement each other when they coexist in boreal mixedwood stands, the nurse crop concept is not well explained in the literature. Shepperd and Jones (1985) defined a nurse crop as any stand of trees or shrubs that fosters development of another tree species, usually by protecting the second species during its youth from frost, insolation, or wind. Aspen is most commonly classed as a nurse crop because of the shade that it provides for understory species and other tree species that are not easily established in full sunlight. The description by Ebata (1989) of pest concerns during backlog reforestation in British Columbia provides another example of aspen's potential "nurse" role. Root rots are a concern for spruce regeneration on many backlog sites, but sites that contain pure aspen generally do not require treatment for *Tomentosus* root rot because aspen is not a known host for *Tomentosus* root rot.

One documented benefit of overstory aspen is the protection it offers to understory conifers; after the overstory aspen was removed, damage to understory conifers from white pine weevil increased in the Lake States (Graham et al. 1963). Aspen is also known to protect understory spruce from late spring frost. For aspen and white spruce there is remarkably little information on possible symbiotic relationships in which both species benefit by the association without the relations being obligatory for survival, or commensalism in which one species benefits by the association, and the other is not affected. Competition for nutrients, even on sites that are considered to be relatively nutrient-rich is also poorly documented for the trees, shrubs, grasses, and herbs that make up boreal mixedwood sites. The review by Hagglund and Peterson (1985) touched on some aspects of these subjects for Scandinavian boreal hardwood species. Based on his studies of aspen forests in the Lake States, Ruark (1990) noted that the extent to which inter- and intra-specific competition may limit the nutrition of crop trees over the length of a rotation is difficult to quantify. Indeed, there are few data upon which to evaluate whether nutritional limitations due to vegetative competition even occur. Where data are available nutritional effects are commonly confounded with moisture availability. The role of such ecological relationships in the long-term productivity of Canada's mixedwood ecosystems is a subject that requires further study.

Wildlife Relationships

Many foresters have made harvesting and silvicultural decisions based on the concept that good timber management is good wildlife management. There are many examples to indicate that management is not that simple (Bunnell and Armleder 1989; Walker 1989). Some silvicultural treatments designed for maximizing fiber production are counter productive for wildlife; others may be either harmful or beneficial depending on how they are implemented; and others may be entirely beneficial for certain wildlife species (McAninch et al. 1987). The following capsule statements made by Bunnell and Armleder (1989) indicate the challenge faced by the forest manager wishing to enhance or protect wildlife habitat: the best sites for timber harvesting are sometimes also the best sites for wildlife; some shrub species considered by foresters to be weeds are often important wildlife forage; spacing can be a problem for wildlife if prescriptions acknowledge only silvicultural objectives; and common forestry practices often fail to create the diversity needed for optimum wildlife habitat. It is not surprising that McDougall (1988), at a recent northern mixedwood symposium, called for new techniques to incorporate wildlife management criteria into silvicultural management of northern hardwood and mixedwood stands.

Recent handbooks on how to manage forested lands for wildlife (Thomas 1979; Gullion 1984; Green and Salter 1987a, b; Green et al. 1987; Hoover and Wills 1987) make it clear that wildlife habitat management needs to be specific for each animal species involved. For example, if a land manager is interested in maintaining black bear (*Ursus americanus* Pallas) habitat, the most important consideration is to maintain large enough blocks of diverse forested land with few enough permanent human residents that black bears can reproduce faster than they are killed (Rogers et al. 1988). For bear management, silvicultural prescriptions should try to increase the production and diversity of food species, as well as maintaining adequate space free of regular human intrusion. Black bears are adapted to use a wide diversity of foods, particularly in northern forests where fruit crops sometimes fail because of extreme weather. Wildlife habitat requirements and timber management strategies have been summarized by Davison et al. (1988) for the main wildlife species that use aspen-dominated forest types in Ontario. The suggestions by Davison and co-workers are summarized in the following text that deals with wildlife management, as are the suggestions by Green and Salter (1987a, b).

Some of Alberta's most detailed studies of effects of logging on wildlife have focused on lodgepole pine-dominated forests in the foothills region (Stelfox et al. 1973). Handbooks such as *Managing northern forests for wildlife* (Gullion 1984) and the report on *Impact on wildlife of short-rotation management of boreal aspen stands* (D.A. Westworth and Associates Ltd. 1984), however, focus on aspen-dominated forest types. Hunt (1976) reported on big game utilization of hardwood cuts in Saskatchewan; Telfer (1974) dealt with boreal forest types generally in his account of logging as a factor in wildlife ecology; and Welsh (1981) dealt specifically with bird populations in relation to harvesting boreal mixedwood stands. Some of the general principles developed for wildlife management in coniferous forests apply as well for boreal hardwoods or mixedwoods. For example, the common practice in Alberta of two-stage clear-cut harvesting results in a mosaic of cut blocks and leave blocks. This provides a variety of habitat types that are suitable for species such as deer (*Odocoileus* spp.) and elk that feed on early successional vegetation of cut blocks and use the adjacent older stands for shelter. Wildlife habitat is less suitable, however, when the second pass of clear-cutting occurs because trees in the original cut blocks may be only a few meters high when the remaining mature stands are harvested. The resulting habitat is of limited value for species such as woodland caribou (*Rangifer tarandus caribou* [Gmelin]), lynx (*Lynx lynx canadensis* Kerr), marten (*Martes americana* Turton), weasel (*Mustela* spp.), and squirrel (*Eutamias* spp.), all of which require mature forests (Renewable Resources Sub-Committee, Public Advisory Committees to the Environment Council of Alberta 1989).

Whether the land manager is dealing with softwood, mixedwood, or hardwood boreal forest types, there appears to be consensus among wildlife habitat specialists that long, narrow irregularly shaped cut blocks are generally better for wildlife than uniform square blocks.

There is also agreement that as many snags as possible should be left standing during harvesting operations because of their use by woodpeckers, hawks (*Accipiter* spp., *Buteo* spp.), owls (*Aegolius* spp., *Strix* spp.), goldeneye (*Bucephala clangula americana* Bonaparte), bufflehead (*Bucephala albeola* Linnaeus), a variety of other bird species, small mammals, and insects. Most wildlife managers, if given the choice, would likely opt for some form of selective logging because clear-cutting removes more of the smaller trees over more of the logged area and therefore has a more significant effect on regional wildlife habitat than selective logging does (Renewable Resources Sub-Committee, Public Advisory Committees to the Environment Council of Alberta 1989).

Wildlife biologists have pointed out that intensive fiber production in aspen-dominated forests is not incompatible with game ranching of boreal herbivores (Telfer and Scotter 1975). With the suckering ability of aspen, heavy browsing on regeneration is not likely to seriously retard regeneration over the large area of the boreal forest, although some areas would incur damage. Boreal aspen forests possess several valuable characteristics for game ranching, namely: a relatively shallow snow cover; relatively productive soils; the presence of several native ungulates (bison [*Bison bison athabascae* Rhoads], moose [*Alces alces andersoni* Peterson], elk, mule deer [*Odocoileus hemionus hemionus* (Rafinesque)], and white-tailed deer [*Odocoileus virginianus dacotensis* Goldman and Kellogg]); the landscape is an undulating plain with a diverse terrain of low hills, small lakes, and marshy areas; aspen forests possess well-developed understories of shrubs, forbs, grasses, and sedges palatable to wildlife; and aspen is often interspersed with willow, an excellent browse for boreal ungulates (Telfer and Scotter 1975). For moose, an optimal balance of browse production and cover occurs 12–15 years after cutting an aspen/balsam poplar forest (Usher 1978), and 25–30 years after cutting in spruce and mixedwood forests (Stelfox 1984). Willows are considered the most important browse species for moose (Green and Salter 1987a, b), but aspen can be a major dietary constituent where it comprises a large proportion of the browse available (Usher 1981). Throughout their range, moose are most strongly associated with areas where active processes (water or wind deposition of soil, wind action, avalanches, impeded drainage, fire, or logging) have set back or arrested forest succession (Rolley and Keith 1979; Thompson et al. 1980; Nietfield et al. 1984; Green and Salter 1987a, b). Moose also use cut-over areas provided browse species and escape cover, especially coniferous cover, are available (Usher 1978, 1981; Telfer 1978; Stelfox 1981).

Boreal hardwoods are of particular interest to wildlife managers because of their nutritional content relative to their associated conifers. Comparative studies of aspen, white birch, white spruce, red pine, and white pine (*Pinus strobus* L.) near Chalk River, Ontario, revealed that aspen and birch had consistently higher wood and bark N concentrations in branches than the conifers. In general, total branch nutrient contents were higher in the hardwoods than in the conifers. The large amounts of nutrients in hardwood bark offset their lack of foliage available for browse in fall and winter. Aspen, in particular, has a high proportion of its total branch nutrients in the bark (Hendrickson 1987). Sampling by Hendrickson in Ontario revealed that although aspen bark made up only 40% of branch biomass, the bark contained 76% of branch N, 71% of branch Mg, 75% of branch K, and 81% of branch Ca. Aspen's exceptionally high amount of branch nutrients in its bark is a result of nutrient storage in phloem parenchyma, which are thin-walled cells that do not function in vertical support but do provide an active storage role.

Several herbivores typical of boreal mixedwood ecosystems, such as ruffed grouse (*Bonasa umbellus* spp.), snowshoe hare (*Lepus americanus* Erxleben), and moose, do not select their winter forage on the basis of its nutrient content. The preferred forage of these herbivores are the mature-growth-form twigs of fire-adapted trees such as willow, aspen, and balsam poplar. These are competitive species that allocate a relatively large amount of their carbon to height growth and to defense against browsing, at the expense of lateral crown development. Their defense takes the form of higher resin content in tissues that serve as forage, at least for a part of their life cycle. Resins protect these tree species in the juvenile state and to a lesser extent when they are mature. In less competitive species, such as black spruce or green alder, there is a smaller difference in resin content, and therefore palatability, between juvenile and adult stages than there is in competitive species such as aspen, balsam poplar, and willow (Bryant and Kuropat 1980).

In terms of wildlife influences upon aspen, it is well known that cattle, sheep, bison, deer and elk can all impede the growth and survival of aspen suckers through browsing and trampling. Aspen's relationship with wildlife has been documented for a great variety of species because of its wide geographic range in North America. The following examples illustrate this well.

- In Minnesota, as soon as black bears emerged from their dens in late spring, they were observed to feed on catkins and expanding leaves of aspen (Rogers et al. 1988). Similar use of aspen buds and catkins is known in Colorado (DeByle 1985d).

- In Arizona, pocket gophers (*Thomomys bottae* [Hoffmeister 1986]) regulate the expansion of aspen clones into meadows through underground herbivory of roots (Cantor and Whitham 1989). This influence is so strong that in a sample of 32 aspen–meadow associations the distributions of aspen and pocket gophers were nonoverlapping 93% of the time. There is evidence in the Arizona study site that pocket gophers actually limit the distribution of aspen to rock outcrops that are inaccessible to the gophers.

- Beaver (*Castor canadensis canadensis* Kuhl) use aspen both as construction material for dams and lodges, and as a preferred food (Novakowski 1967; Heeney et al. 1980; Skinner 1984). From 1 to 2 kg of aspen bark is eaten each day by a mature beaver, and although beaver will cut any size of aspen stem, they seem to prefer the 5-cm size class (DeByle 1985d). About 200 aspen trees would support one beaver for one year (Banfield 1974).

- Where streamside management is of particular concern for the forest manager, beaver can create problems by hampering aspen regeneration. Stable stream banks with growing vegetation are essential for good fish habitat. Wildlife managers have found that in some cases beaver colonies need to be managed to ensure that streamside aspen is regenerated after aspen trees are harvested by beaver (Greenway 1990).

- Porcupine (*Erethizon dorsatum* Linnaeus) feed on aspen leaves and twigs in spring and summer, and feed on the bark of branches and trunks in winter, sometimes causing extensive damage (Graham et al. 1963; Banfield 1974).

- Both snowshoe hare and cottontail rabbits (*Sylvilagus nuttallii* Bachman) feed on young aspen and may girdle small trees by eating bark (Graham et al. 1963; Banfield 1974).

- The large insect populations characteristic of aspen forests make this forest type attractive to such mammalian insectivores as bats (Winternitz 1980; DeByle 1985d).

- Fallen poplar leaves form a significant part of the autumn and winter diet of elk in central Alberta forests (Nietfield and Hudson 1984).

- Aspen is one of several browse species used by mule deer (Thomas 1979).

- Small mammals, such as mice, voles, shrews, and chipmunks, are the most abundant group of mammals inhabiting aspen forests and are important as the basis of the food web of many species of carnivorous birds and mammals (D.A. Westworth and Associates Ltd. 1984).

- A relatively great variety of predacious birds inhabit aspen–conifer mixedwoods, including raptores, owls, and eagles, all of which are effective predators of such small game as grouse and hares (DeByle 1985d).

- In winter, elk rely heavily on browse, of which aspen suckers are an important component (Banfield 1974).

- In the winter following the severe 1988 fires in Yellowstone National Park, elk were observed in early winter to be feeding from the bark of downed, burned, but still-green aspen stems (Singer et al. 1989).

Domestic Livestock

Most of the experience with aspen responses to livestock grazing is from the aspen parkland zone of the prairie provinces and the Rocky Mountain region of the western United States, rather than from the Mixedwood Section of the Boreal Forest Region. This means that much of the available information is derived from areas where aspen tends to occur in groves instead of continuous stands. It is not surprising, therefore, that the health of aspen groves has been watched by range managers for a long time (Greenway 1990). In particular, the presence or absence of aspen reproduction is used as an indicator of range condition. If aspen reproduction is present, range is considered to be in good condition; if absent, range condition is thought to be unsatisfactory (Houston 1954).

Influence of Intensity and Timing of Livestock Grazing on Aspen Suckers

A decade ago, Bailey (1981) predicted a bright future for increased beef cattle production using forage from southern portions of the boreal forest. This optimism was based, in part, on the assumption that escalating costs of bulldozers and other heavy equipment used for clearing would make brush species more attractive as potential forage. Instead of bulldozing brush, which in many cases includes young aspen stands, prescribed burning is a less expensive way to reduce woody vegetation. Forage can be seeded in burned areas and grazing can be used to control the suckers of palatable species, thus reducing competition for the established forage seedlings. Bailey (1981) suggested that palatable brush species should not be eliminated from grazing lands in forested areas. A better approach is to manage brush so that it can be used by livestock. Bailey stressed that grazing animals have been overlooked as an integral part of brush management, and brush has been overlooked as a source of forage for grazing animals. In northeastern British Columbia and across the mixedwood portion of the prairie provinces, aspen figures prominently as a component of the brush referred to by Bailey.

The effects of grazing by domestic livestock on an aspen community were evaluated near Rochester, Alberta, by Weatherill and Keith (1969). In general, trees were not influenced significantly by grazing. There was no significant difference in aspen communities sampled for three levels of grazing intensity (ungrazed, light, and heavy grazing). These researchers, however, predicted that grazing effects on these stands would become more apparent in time, as most of the grazed stands were in early stages of successional development at the time of the study. Herbs that decreased with grazing in the aspen community included: *Anemone, Apocynum, Aralia, Fragaria, Lathyrus, Prenanthes, Rubus pubescens* Raf., *Sanicula, Thalictrum*, and *Vicia*. Herbs that increased with grazing included *Achillea millefolium* L., *Agropyron repens* (L.) Beauv., *Cerastium* spp., *Poa pratensis* L., *Polygonum* spp., *Taraxacum officinale* Weber, and *Trifolium* spp.

Shrubs that decreased with grazing included: *Rosa* spp., *Viburnum edule* (Michx.) Raf., *Viburnum trilobum* (Marsh) Clausen, *Symphoricarpos occidentalis* Hook., *Amelanchier alnifolia* Nutt., *Rubus strigosus* Michx., *Corylus cornuta* Marsh., and *Cornus stolonifera* Michx. No significant change with grazing intensity was evident with *Prunus pensylvanica* L.f. and *Prunus virginiana* L. *Salix* spp., *Lonicera glaucescens* Rydb. Butters, and *Lonicera involucrata* (Richards.) Banks increased with grazing based on cover response, but their heights did not increase with greater grazing intensity. Currants (*Ribes* spp.) were classified as both increasers and invaders in response to grazing. Both species of alder (*Alnus crispa* [Ait.] Pursh and *Alnus rugosa* [Du Roi] Spreng.) were strong invaders after grazing. In general, tall densely growing shrubs such as hazel, willow, and alder were less vulnerable to grazing than weak-stemmed shrubs such as *Rosa* spp. and *R. strigosus* (Weatherill and Keith 1969).

In the Rochester area, as grazing intensity by domestic livestock increased, there were indications that light grazing was beneficial to ruffed grouse and that heavy grazing was harmful. An adverse impact of grazing on snowshoe hare populations was readily apparent. The factor most likely limiting hares in grazed aspen woodlands was thought to be a lack of suitable summer cover due to the decrease of tall herbaceous cover. Probably for the same reason, there were also fewer white-footed mice (*Peromyscus leucopus* Rafinesque) in grazed areas than in ungrazed aspen communities. There was a slight tendency for white-throated sparrows (*Zonotrichia albicollis* Gmelin) to decrease with increased grazing but grazing within aspen communities apparently had no effect on three other songbirds studied: ovenbirds (*Seiurus aurocapillus aurocapillus* Linnaeus), least flycatchers (*Empidonax minimus* Baird and Baird), and red-eyed vireos (*Vireo olivaceus* Linnaeus) (Weatherill and Keith 1969).

Wild Ungulates

Of the large boreal herbivores, moose has received the most attention in relation to its habitat needs provided by the aspen forests of the mixedwood section in western Canada. Mule deer, white-tailed deer and, in a few locations, elk and bison are also users of aspen and mixedwood stands. Wildlife management programs in the mixedwood section have not given as much attention to deer as has occurred in the Lake States in the past 20 years; in that region deer management has been largely based on management of the aspen ecosystem (Gullion 1986).

There is abundant information on the diets of moose and the relationship of this species to aspen-dominated forests (McTaggart-Cowan et al. 1950; Telfer 1970; LeResche and Davis 1973; Peek 1974; Cushwa and Coady 1976; Peek et al. 1976; Oldemeyer et al. 1977; Telfer 1978, 1984; Telfer and Cairns 1978; Irwin 1985; Timmerman and McNicol 1988). Although moose diets and moose habitat requirements in aspen-dominated forests are well understood, management to maximize moose populations is still a balancing act that involves quality and quantity of browse on summer and winter range. It is never an easy decision for a manager interested in moose habitat management to decide whether summer or winter range enhancement is the most appropriate course of action.

Depending on other browse species available, aspen appears to be relatively more important as moose browse in winter than in summer. For example, for the moose population on the Kenai Peninsula, Alaska, Oldemeyer et al. (1977) found that alder and willow species ranked as the best summer browse plants for moose and mountain cranberry (*Vaccinium vitis-idaea* L.) as the poorest. In contrast, in winter aspen and mountain cranberry ranked as the best moose browse and white birch as the poorest. Such observations, however, need to be extrapolated with caution. A review by Peek (1974) covered

41 studies of moose food habits and revealed that local variations in moose forage preferences were very important. Peek stressed that generalizations about preferred food species without confirming data for any given area was risky. Although a generalized picture of moose forage preferences in North America can be obtained from the available data, Peek suggested that there is not enough information to compare the annual, seasonal, or habitat-type use patterns between different areas.

Several authors have noted that postfire regeneration of young vigorous stands of aspen, willow, and other shrubs associated with these species improves moose habitat and results in a moose population increase (LeResche et al. 1974; Irwin 1975; Gullion 1977; Gruell 1980; Irwin 1985). Numbers of moose decrease after browse grows out of their reach, which is about 2.4 m high, although Telfer and Cairns (1978) reported that moose will break down saplings up to 10 cm in diameter to obtain browse that would otherwise be above their reach. If the choice is available, moose usually select willow first and then aspen. The associated understory forbs and shrubs are also favorite moose forage. Aspen stands less than 10 m tall are the preferred habitat for moose in Alberta (Rolley and Keith 1980), and the best overall combination of habitats for moose consists of an interspersion of young deciduous stands, muskeg, and conifer forest (Alberta Fish and Wildlife Division 1984), which provide a mix of foraging areas, cover, and shelter.

Logging increases the amount of browse available for moose. Data gathered by Zasada et al. (1981) on natural regeneration of balsam poplar following logging in Alaska indicated that this species produced 5.3 kg/ha of available moose browse 2 years after harvesting, 9.0 kg/ha in the third year and 13.7 kg/ha in the fourth year. There was no available balsam poplar browse in the adjacent uncut stand and no moose browsing was recorded for the scattered alder and high-bush cranberry (*Viburnum edule* [Michx.] Raf.) that occurred in the uncut area. The density of balsam poplar stumps was only 104 stems/ha but each stump had a mean of 37 twigs per stump 4 years after harvest. By the fourth year, alder, willow, and high-bush cranberry were tall enough (over 1 m) to be included in the browse survey.

Moose require young aspen stands for browse as well as mature stands for cover. In the Absaroka Range of western Montana, where Gordon (1976) documented changes to moose winter range after prescribed burning of aspen, it was found that 16 ha was actually a bigger burn than necessary for benefit to moose. In the second winter after the spring 1972 burn, use of aspen and shrubs by moose was heaviest adjacent to central areas where unburned cover was dense. Aside from the attraction of cover for moose, the lighter use of the center of the burn by moose may have been partly due to downed trees that had not been consumed by the burn. There is evidence that in the winter moose show a preference for habitats with cover over those that provide abundant browse. The ideal situation for moose wintering areas appears to be a mosaic of various age classes of aspen and associated shrubs. Such a mosaic of age classes provides both browse and cover in close proximity. Gordon (1976) recommended that depending upon the amount of natural openings, prescribed burns to improve moose habitat should be no larger than 20 ha in dense cover and should be less in more open forest areas.

In the summer months, when forage is highly digestible and homogeneous in boreal aspen stands, free-ranging moose show only moderate selectivity of species eaten, and they can meet their daily requirements in less than 10 hours of foraging. Moose respond to autumn senescence of forage plants by increasing foraging time and by feeding more selectively. In the winter months, however, as opportunities for selection decrease and as time required for rumination increases, moose must abandon the autumn tactic. During winter, moose diets in the boreal zone consist mostly of highly lignified woody stems and leaf litter (Renecker and Hudson 1986).

The similarity of moose and hare forage preferences has been described by Telfer (1974), Bryant and Kuropat (1980), and others. Forage selected by most moose populations (in descending order of importance) is willow, aspen, birch, jack pine and lodgepole pine, balsam fir, alder, and spruce. Moose, like hares, feed preferentially upon the crown twigs of mature (felled) trees and tall shrubs. Moose break the stems of moderately large saplings and tall shrubs to feed upon crown twigs even though younger plants of the same species are more available (Telfer and Cairns 1978). Based on observations in Minnesota (Peek et al. 1976) and Ontario (Thompson and Vukelich 1981), moose browse on balsam poplar only in the winter. In contrast, moose browse on aspen in the summer, autumn, and winter (Peek et al. 1976; McNicol et al. 1980; Cumming 1987). McNicol and co-workers suggested that mixedwood stands, when clear-cut, do not provide as desirable moose habitat as those resulting when only merchantable conifers are harvested, leaving residual hardwood cover and advanced conifer regeneration. These investigators recommended that when mixedwoods are harvested a residual basal area of about 2.5 m^2/ha each of hardwoods and softwoods provides the preferred winter habitat for moose. The best approach is to achieve this residual basal area by leaving distinct patches of unharvested mixedwood stands.

Seasonal Differences in Ungulate Use of Aspen Forests

In general, aspen forests are used by ungulates more in winter than in summer. In the boreal mixedwoods of Elk Island National Park, Alberta, where there is a unique occurrence of four species of native ungulates (moose, elk, white-tailed deer, and bison), Cairns and Telfer (1980) documented their relative use of five habitat types: sedge meadow; upland grass; shrub meadow; shrubland; and aspen forest. Moose moved around more in the forest than elsewhere, yet spent the most time, likely feeding and bedding, in shrub-dominated sites. Shrubby sites and shrub meadow were the most valuable year-round habitats for moose, although sedge meadows were used extensively in spring and summer, as were aspen forests in early winter. Of the four species studied, deer spent more time in aspen forests in the winter months than any of the other three ungulates. Although the shelter of conifers is usually considered a requirement for wintering deer, shrubby sites and aspen forests apparently are suitable substitutes for winter habitat in the prairie provinces (Kramer 1972; Cairns and Telfer 1980).

Bison were most active in the upland grass habitat, but spent more time in aspen forests. Bison showed the greatest habitat specificity of the species considered. In Wood Buffalo National Park, Alberta, they preferred mixedwoods and aspen and poplar stands interspersed with meadows for summer feeding, whereas in the winter months, upland meadows, flood plains, and delta marshes were most important. For elk in Elk Island National Park, upland grass is prime habitat, although they also frequent aspen groves in the winter.

In summary, aspen forests, the dominant habitat type in Elk Island National Park, received the major portion of animal use. Cairns and Telfer (1980), however, believed that its use was still less than its availability would warrant. Bison and elk in Elk Island National Park selected edges year-round, as did moose and deer to a lesser degree in the spring and summer. Deer showed less tendency than other species to use edges. Both moose and deer showed a slight but insignificant preference for more open and patchy habitat in spring and summer, and for larger and denser stands in winter (Cairns and Telfer 1980).

Influence of Protein Content on Browsing Intensity

In locations where aspen regeneration is hampered by continuous and severe browsing by elk, especially in mountain regions such as Banff National Park, Alberta or in the mountains of the western United States, there is evidence that the intensity of browsing is influenced by aspen's crude protein content (Bartos and Mueggler 1980; DeByle 1980; Olmsted 1980; Weinstein 1980). Recently, McNamara (1980) stressed clonal variation of nutrient availability as an important influence on intensity of elk browsing. In a Colorado study of 16 aspen clones, crude protein in stems of browsable size ranged from 3.3 to 4.9%. The two clones that had the lowest levels of browsing showed no significant differences in protein content; the clone with the highest level of protein had the highest level of browsing. McNamara (1980) suggested the encouragement of clones with high levels of protein and digestibility for wildlife use and clones with low protein and high fiber content for commercial pulp production.

Snowshoe Hare–Aspen Relationships

More attention has been given to aspen's relationship with snowshoe hare than with other nonungulate mammals. Snowshoe hares select forage in the following descending order of perference: willow, aspen, larch, dwarf birch, white birch, jack and lodgepole pine, balsam fir, white spruce, black spruce, and alder (Bryant and Kuropat 1980). Hare forage preferences are negatively correlated with the gross energy content of their browse; for example, their favored forage, willow and aspen, contain lower concentrations of soluble carbohydrate in their aboveground tissues than do birch and alder. Willow and aspen are, however, less resinous than birch, alder, and conifers and this appears to be an important factor in grouse's preference for these forage species.

Tests by Bryant (1981) in Alaska revealed that the adventitious shoots produced by aspen, balsam poplar, white birch, and green alder after browsing by snowshoe hares are extremely unpalatable to hares. These woody species, all of which have mature-growth-form twigs that are preferred food for hares, develop adventitious shoots that produce exceptionally large amounts of terpenes and phenolic resins. These compounds account for the low palatability of adventitious shoots to showshoe hares, although the mode of action of these compounds is unclear. Possible explanations are the presence of methylated flavonols in poplar resins that may lower protein digestibility and the presence of antibiotics in poplar resins that may upset vitamin production and digestion in the hares.

The fact that preferred browse species of the snowshoe hare, such as aspen and balsam poplar, produce a chemical defense after severe browsing by peak snowshoe hare populations may be related to the 10-year hare cycle. These tree species produce energy-rich resins after severe browsing, but allocate carbon to growth and other processes when there is little browsing. Bryant (1981) suggested that because the low palatability of the adventitious shoots is a consequence of a high terpene and phenolic resin content, these browsing-induced plant defenses may play a role in the 10-year hare population cycle.

Impact of Short-rotation Aspen Management on Wildlife

Studies by D.A. Westworth and Associates Ltd. (1984) were carried out in west-central Alberta to assess the potential effects of short-rotation harvesting of aspen on wildlife. The study involved a comparative evaluation of habitat conditions and wildlife use of aspen stands of different ages, including 1- and 2-year-old clear-cuts and 14-, 30-, 60-, and 80-year-old stands. Changes in habitat structure between different successional stages resulted in a successional replacement of bird species with stand age. Westworth suggests that overall densities of breeding birds would likely increase under short-rotation management; however, approximately one-third of the species common to aspen forests would undergo a significant decrease in abundance. The absence of large diameter snags in managed stands would result in a pronounced decrease in abundance of snag-dependent birds.

In Westworth's Alberta study, browse and grass production was highest in the 14-year-old stands while maximum production of forbs occurred in 30-year-old stands. As a result, short-rotation harvesting would be beneficial to ungulates as long as management programs include silvicultural options designed to meet the cover requirements of each species. Among the furbearing mammals, some species were expected to benefit from short-rotation management while others would be adversely affected. Snowshoe hares, beaver, lynx, coyotes (*Canis latrans* Say), and wolves (*Canis lupus* Linnaeus) would likely benefit while such species as marten, fisher (*Martes pennanti* Erxleben) and red squirrel (*Tamiasciurus hudsonicus* Erxleben), would be adversely affected by a reduction in the amount of aspen succeeding to mixedwood or coniferous forest under short-rotation management (D.A. Westworth and Associates Ltd. 1984).

Ruffed Grouse–Aspen Relationships

The work carried out by Gullion (1984, 1986, 1990) and others in the Lake States deals with aspen's role in habitat management for a number of wildlife species. The focus of this work, however, is overwhelmingly on aspen–ruffed grouse relationships. Although much of Gullion's work deals with ecosystems in which aspen is succeeded by shade tolerant eastern hardwoods, applicable information is summarized below. Grouse studies from the aspen parkland of western Canada are not summarized because the closed aspen forests of the Lake States region were considered to be more similar to Canada's boreal mixedwood than to aspen parkland stands.

Of all the wildlife species that benefit from appropriate aspen management, ruffed grouse are second only to beaver in their dependence upon this forest type. In terms of their need for proper aspen age class interspersion, grouse are more demanding than beaver. Grouse are among the last species to begin using newly regenerated sucker stands. For example, deer, beaver, snowshoe hare, and several songbirds use sucker stands in their first or second year, but such stands have to go through one or two natural thinnings before ruffed grouse make heavy use of them. In general, aspen sapling stands need to have reached one-quarter to one-half their initial sucker density before grouse will use them. This normally involves a 6- to 12-year delay (Gullion 1987).

Aspen is the basic food source for the ruffed grouse in 95% of grouse's continental distribution across the northern United States (Gullion 1987), Canada, and Alaska (McGowan 1973). Where different successional stages of aspen are present in close proximity grouse densities can be as high as 24 breeding pairs per 100 ha. The ecosystem most valuable to ruffed grouse is one that has diversity as a result of succession following severe disturbance from fire, windstorms, or harvesting. Selection of sites by male ruffed grouse for logs on which to drum indicates that they prefer moderately dense shrub or sapling vegetation within 100 m of mature aspen that provides winter-long food. In Minnesota, Gullion (1987) found that ruffed grouse are most abundant on those sites where aspen makes up the highest proportion of the sapling vegetation.

Data gathered by Doerr et al. (1974) near Rochester, Alberta, indicated that ruffed grouse selected those aspen and willow buds that had the highest protein and K contents. It is not clear how grouse identify buds with higher than average protein content. The most likely explanation is that ruffed grouse feeding occurs mainly in the upper branches of aspen, and it is in that part of the crown that buds with the highest energy content are found (Doerr et al. 1974). In the Rochester study, male aspen buds made up 35% (by volume) of winter ruffed grouse diet and willow buds made up 29%. Willow buds contained significantly more protein (14.0%) than aspen (11.7 and 12.9% in two samples). Doerr et al. (1974) suggested that ruffed grouse did not preferentially select the higher protein willow because aspen buds are stouter and more easily obtained than those of willow. By feeding on aspen, grouse can fill their crops quite rapidly; the amount of vegetation ingested in a short time may be as important as its nutrient content because if nutrients are present in lower concentrations this can be compensated for by ingesting larger quantities of food quickly.

Ruffed grouse preferentially feed in male aspen clones of the 30–50 year age class. These preferred clones are at an age where insects, diseases or other physiological stresses are more common than in juvenile stands. It has also been noted that ruffed grouse feed preferentially in the upper crowns of preferred aspen trees (Svoboda and Gullion 1972), which some observers suggest is the physiologically most stressed part of the tree crown (Kozlowski 1971; Zimmermann and Brown 1971). Staminate buds produced by preferred aspen clones contain slightly more N than staminate buds on rejected clones (Doerr et al. 1974). Ruffed grouse, however, do not selectively feed upon nitrogen-rich staminate buds within a selected clone, nor do they differentiate between willow and aspen on the basis of tissue N content.

Nutritional quality of forage has long been considered to be of prime importance in herbivore selection patterns, but there is mounting evidence that forage selection is the result of avoidance of plant secondary constituents that are antagonistic to vertebrates (Bryant and Kuropat 1980). For example, in the Lake States, ruffed grouse feed preferentially on the overwintering staminate buds of aspen and cottonwoods (Bryant and Kuropat 1980). Balsam poplar staminate buds are eaten only in late winter after their resinous bud scales have been shed (Svoboda and Gullion 1972).

These observations suggest that ruffed grouse do not select winter browse because of energy or nutrient content (Bryant and Kuropat 1980). They do, however, selectively avoid browse high in resins. In Alberta, aspen clones preferred by grouse have staminate buds less resinous than those in rejected clones. Furthermore, ingested aspen buds sampled from the crops of Alberta ruffed grouse are less resinous than those collected at random from preferred clones (Doerr et al. 1974). Aspen foliar buds are not eaten by ruffed grouse probably because they are more resinous than staminate buds. Resins of *Populus* species contain several methylated flavonols (Wollenweber 1973), which are suspected of inhibiting protein digestion. Balsam poplar produces the greatest quantity of bud resins of any of the cottonwoods (Bryant and Kuropat 1980).

Snags as Bird Habitat

Each forest community supports a distinct group of bird species that serve as primary excavators or secondary cavity-users, and each bird species has distinct requirements for minimum diameter and height of snags used for excavation, nesting, and shelter (Thomas 1979). These requirements are better known for coniferous than for aspen ecosystems. Data are available on the number of snags required per species pair/100 ha for several woodpecker species that have a primary association with snags in aspen forests of the Blue Mountains of Oregon and Washington. The minimum snag diameter to attract the common flicker (*Colaptes auratus borealis* Ridgway), the yellow-bellied sapsucker (*Sphyrapicus varius varius* Linnaeus), and the downy woodpecker (*Dendrocopos pubescens nelsoni* Oberholser) are 30.5, 25.4, and 15.2 cm, respectively (Table 33).

In the study area documented by Thomas (1979), aspen was the preferred species for cavity excavation for the three species listed above. In Alberta, the downy woodpecker is also found in aspen and balsam poplar stands more commonly than in mixedwood or coniferous stands and the common flicker prefers relatively open woodland where aspen, balsam poplar, and other deciduous trees predominate. In deciduous and mixedwood stands, flickers frequent the edges of clearings because they commonly feed on the ground as well as in trees (Salt and Salt 1976).

The yellow-bellied sapsucker does not appear to be as strongly attracted to aspen in Alberta as reported for the Blue Mountain area of Washington and Oregon.

Table 33. Snags required to support percentages of woodpecker populations in aspen forests (based on Thomas 1979)

Species	% maximum population									
	100	90	80	70	60	50	40	30	20	10
	No. snags needed/100 ha									
Common flicker	93	84	74	65	56	47	37	28	19	9
Yellow-bellied sapsucker	371	333	296	259	222	185	148	111	74	37
Downy woodpecker	741	667	593	519	445	371	296	222	148	74

Unlike the flicker, which drills holes to remove wood-boring insects, the yellow-bellied sapsucker drills orderly square pits in the smooth bark of young deciduous trees and then returns repeatedly to feed on sap and insects that collect in the pits. In Alberta, this sapsucker taps birch and large willows more commonly than aspen. The holes created by the yellow-bellied sapsucker serve as entry points for fungi (Salt and Salt 1976).

A study near Hinton, Alberta revealed that at least 38 cavity-dependent species rely on snags (McCallum 1984; Stelfox 1988). Large poplar snags, in particular, were essential for maintaining populations of woodpeckers (pileated [*Dryocopus pileatus abieticola* (Bangs)], hairy [*Dendrocopos villosus septentrionalis* (Nuttall)], downy, northern three-toed [*Picoides tridactylus fasciatus* Baird], yellow-bellied sapsucker, and flicker), red-breasted (*Sitta canadensis* Linnaeus) and white-breasted nuthatches (*Sitta carolinensis* Oberholser), boreal (*Parus hudsonicus* Godfrey) and black-capped chickadees (*Parus atricapillus* Harris), mountain bluebirds (*Siala currocoides* Bechstein), starlings (*Sturnus vulgaris vulgaris* Linnaeus), tree (*Iridoprocne bicolor* [Vieillot]) and violet-green swallows (*Tachycineta thalassina lepida* Mearns), house wrens (*Troglodytes aedon parkmanii* Audubon), kestrels (*Falco sparverius sparverius* Linnaeus), saw-whet owls (*Aegolius acadicus aeadicus* [Gmelin]), buffleheads, goldeneyes, and hooded mergansers (*Lophodytes cucullatus* Linnaeus), as well as flying squirrels (*Glaucomys sabrinus* [Shaw]) and big brown bats (*Eptesicus fuscus* [Palisot de Beauvois]). After logging, numbers of remaining standing trees with cavities were much higher on mixedwood sites than on pure spruce sites and were lowest of all on pine clear-cuts. Correspondingly, 84% of woodpecker and 79% of chickadee sightings were in the nonscarified mixedwood clear-cut during the first 27 years after logging. Almost 75% of snags on mixedwood nonscarified clear-cuts contained cavities compared with only 32% on spruce sites and 16% on nonscarified pine clear-cuts (Stelfox 1988).

Stelfox predicted that under a timber management rotation cycle of 80-90 years, decadent and dead snags with diameters greater than 30 cm dbh will be virtually nonexistent. That would result in a major decline in the 13 bird and mammal species that use decadent and dead trees with diameters over 30 cm (Table 34). The exception could be the red squirrel and marten, which probably could exist without snags. The Hinton, Alberta, observations by Stelfox (1988) are consistent with the findings of Welsh (1981), who concluded that population density and diversity of bird populations was greater within boreal mixedwood than within pine and spruce forests. The abundance and diversity of resources for birds are further enhanced in nonscarified clear-cuts, especially those containing unmerchantable trees such as aspen and balsam poplar of various sizes. Stelfox (1988) concluded that tree cavity-dwelling wildlife will not live in clear-cuts unless some old dead trees, especially aspen, are left standing following logging. About 24 snags per hectare are considered to be enough to sustain a variety of cavity-dwelling wildlife species in west-central Alberta. The Hinton study indicated that patches of mature aspen within coniferous forests are especially important to many wildlife species; however, Stelfox (1988) called for more detailed quantitative information on the role of mature aspen for bird and mammal species.

Soil Invertebrates

Soil organisms (worms, mites, springtails, nematodes, beetles, and insect larvae) and microorganisms (bacteria and fungi) are intimately associated with nutrient cycling and decomposition. The major contribution of soil organisms to litter decomposition is physical breakdown of organic material, grazing on microflora, and dispersal of microbial propagules within litter and the surface soils (Hassall et al. 1986). Soil organisms are affected by temperature, moisture, pH, nutrients, aeration, as well as the composition and quality of litter.

Role of Invertebrates in Decomposition of Aspen Soils

From studies in several locations, it is evident that soils developed under aspen are particularly favorable for

Table 34. Bird and mammal species in western Alberta that use decadent and dead trees (snags) over 30 cm diameter (Stelfox 1988)

	Snag diameter (cm)		
Species using snags	30–35	35–50	over 50
Kestrel	x		
Saw-whet owl	x		
Northern three-toed woodpecker	x		
White nuthatch	x		
Red-breasted nuthatch	x		
Red squirrel	x		
Flying squirrel	x		
Big brown bat	x		
Bufflehead duck		x	
Hooded merganser		x	
Marten		x	
Goldeneye duck			x
Pileated woodpecker			x

invertebrates. Hoff (1957) found in the Rocky Mountains of northern Colorado that invertebrate populations inhabiting the organic and upper mineral layers under aspen were greater than under adjacent coniferous forest. Similarly, enchytraeid worm populations were found to be much more numerous in soils of an aspen site in southwest Alberta than in a nearby fen (Dash 1970). In north-central Minnesota, the surface mineral soil beneath an aspen stand contained 10 times as many bacteria and 30–50% more fungi than did soil beneath two conifer stands (Kienzler et al. 1986). These organisms were also 10–1000 times more abundant in the surface 10 cm than in the subsequent 15 cm depth. The reason for the greater microbial abundance under aspen was not apparent; however, it was evident that soil pH was not an influential factor. It measured 5.6 under aspen with the most bacteria and 5.4 under spruce with the least bacteria. Decomposition rates of leaf litter in an aspen woodland in the foothills of Alberta were found to vary with leaf species, site, aspect, age of litter, and position of the litter in the soil profile (Parkinson 1971; Krauter 1976).

In an Ontario study, Bird et al. (1987) found that skeletonization of aspen leaves from the previous season's leaf fall was significantly greater on harvested plots than on uncut plots. This was believed to be the result of increased feeding by soil invertebrates. Based on the leaf litter consumed, invertebrate feeding on harvested plots suggested selective feeding on younger litter. Of the two harvesting methods, conventional and whole-tree, conventional harvesting had a lesser impact on soil microarthropods, implying that long-term site productivity would be greater following conventional rather than whole-tree harvesting (Bird and Chatarpaul 1986).

Fire in Ecosystems Dominated by Aspen or Balsam Poplar

As the recent reviews by Van Wagner (1990) and Hawkes et al. (1990) make clear, much of the Canadian forest, in its natural state, is dependent on periodic fire for its cyclic renewal and long-term existence; this circumstance applies to nearly all the pines and spruces, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), white birch, and aspen. This means, as Van Wagner pointed out, that much of Canada's present forest management is a process of intervening in a natural fire-cycled system. A key concern of the forest manager is how to retain, and ultimately harvest, the increment normally lost to fire while at the same time matching or improving on fire's role in forest renewal.

Aspen and balsam poplar are often grouped with white birch under the term, fire species *par excellence.* One common characteristic is the abundant production of wind-transported light-weight seeds, although birch is more successful at seedling establishment than are species of the genus *Populus.* The other common characteristic of those boreal pioneer species is their reliable regeneration by vegetative means—birches by way of stump sprouts and *Populus* by root suckers, root collar sprouts, and stump sprouts. Some authors have suggested that the abundance of aspen, balsam poplar, and birch is a direct measure of the severity and frequency of past forest fires (Spurr and Barnes 1973).

Fire has had such a vital role in the natural regeneration of aspen forests in the past that in certain areas today the perpetuation of aspen is threatened by a lack of fire. An example of this can be seen near the east entrance of Banff National Park where an absence of tree harvesting, vigilant with fire suppression, and wildlife browsing that removes any aspen suckers that do emerge, have combined to produce even-aged overmature aspen stands with no apparent prospect of new aspen stands. Circumstances such as this provide a strong incentive for prescribed burning. Aspen is well-adapted to regenerate itself after fire, and that is because its clonal root system is *not* temporary. The tenacity and longevity of aspen's root system are key factors in aspen's adaptation to fire. Even in stands that are predominantly coniferous, with only a few scattered residual aspen, root suckers commonly dominate the regeneration after fire. The ability of aspen's roots to be sustained only by transient suckers beneath a coniferous canopy is an adaptive feature of importance for aspen's prominence after logging or fire.

Fire can kill the cambium, buds and leaves of aspen trees. Instantaneous exposure to about 64°C is generally considered to be lethal for living tissue (Brown and Davis 1973). Death of tissue, however, is a function of both temperature and time, and death can occur at temperatures less than 64°C if exposed long enough. Fire damage can be quite injurious to juvenile and pole-sized aspen stems because, compared to conifers, they have relatively thin and succulent bark. Basal wounds caused by low-intensity wildfires are a common entry point for canker disease organisms (Hinds and Krebill 1975). Severity of fire injury to aspen stems varies with the type and amount of fuel available to burn (Brown and Simmerman 1986). Charring is the most obvious injury but wind-blown hot air can also sear aspen bark. Brown and DeByle (1987) noted in Idaho and Wyoming that aspen stems killed by fire had over 75% of the stem circumference charred; those that survived averaged less than 50% charred stem circumference. They noted that charring of the bark was not actually necessary to kill an aspen stem; some trees that had only browned or blistered bark, with no charring, died within 2 years.

Existing information on aspen–fire relationships does not provide much detail on the responses of young sucker stands to fire. Although fuel is often not very abundant in young aspen stands (Brown and Simmerman 1986), fire can kill aspen saplings (Kiil 1970). Zalasky (1970) also discussed fire damage to juvenile aspen, without specifying the age of stems involved. If there is sufficient fuel for a fire to pass through a young sucker stand, fire intensity will be great enough for the thin and succulent bark of aspen to be injured. Zalasky noted droplets of gum oozing from injured aspen bark several days after a fire. These pinhead openings can develop into sites of bark collapse, and eventually serve as entry points for fungi. From these examples it is evident that even if fire does not kill aspen, it can still have several secondary effects. Not only are trees weakened by fire more vulnerable to insect or disease attack and to frost crack injury, but growth rates may also be retarded and stand breakup may be accelerated (Fig. 20).

Rapid development of suckers after a burn is a well-known phenomenon. To give one recent example, Oswald and Brown (1990) documented aspen regeneration for 5 years after the 1982 Low Fire near Lower Post in northern British Columbia. About 4400 suckers/ha had sprouted by 1 year after the fire. This increased to 23 000 stems/ha at 5 years after the fire, with heights up to 2.5 m. The greatest increase in sucker density occurred in the second year after the fire. Burning is a stimulus to suckering for several reasons. First, the hormonal inhibition of sucker production imposed by live overstory aspen is removed if fire kills the stems in the clone. Second, charred and darkened soil surfaces absorb more heat and the resulting higher temperatures stimulate sucker formation. In addition, the increased light resulting from fire removal of aboveground vegetation encourages development of shade intolerant suckers (Schier 1976; Schier et al. 1985). Although the long-term effect of fire on sucker growth is unknown (Perala 1974a), in the short term burning appears to reduce the vigor of resulting aspen suckers, perhaps because of the loss of N during burning or because of the heat damage to the shallow sucker-producing parent roots (Horton and Hopkins 1965; Van Cleve 1973; Perala 1974b). Repeated spring burning reduces the abundance and vigor of aspen suckers (Smith and James 1978a, b; Bailey 1986b).

Some fire specialists have suggested that on repeatedly burned areas plant communities may have evolved to be more flammable than plant communities on less frequently burned areas (Mutch 1970; Rouse 1986). This may not, however, be true for aspen because it is not very flammable when young. Overall, aspen-dominated forests are low in flammability unless there is substantial slash on the ground (Perala and Russell 1983). In fact, some foresters view aspen stands as natural fire breaks (Fechner and Barrows 1976); however, fuel conditions and flammability of aspen vary greatly among stands and they also change from year to year (Barrows et al. 1976; Brown and Simmerman 1986).

Aspen stands that are breaking up, contributing to available dead fuel, do burn readily, but in general low intensity surface fires are characteristic of aspen stands (Horton and Hopkins 1965). Although root tissue is more susceptible to heat-induced mortality than aboveground tissue (Kayll 1968), insulation by the soil generally allows aspen roots to survive fires. Exceptions occur beneath slash piles, which may burn so intensely that sucker production is locally impossible because of root mortality (Perala 1974a).

Unlike areas farther north in the boreal zone of northern Alberta and the Northwest Territories where fires may be very large, burned areas in Alberta's mixedwood forests tend to be comparatively small. The fire maps prepared by Delisle and Hall (1987) show that most fires in the Calling Lake–Lac La Biche–Cold Lake region of Alberta between 1931 and 1983 were in the range of 10 to 30 km in the direction of their maximum extent, in contrast to the Lake Athabasca region of northeastern Alberta where many fires in that same time period burned for 50 km or more in their direction of advance. The other important feature that has been stressed by all researchers who have studied boreal fire ecology is the relatively short interval between repeat fires on the same area. Delisle and Hall (1987) showed a number of areas in the Lac La Biche region where at least three successive burns had occurred in the 50-year period from 1931 to the early 1980s.

Prescribed Burning in Aspen Management

The long-term effect of prescribed burning on aspen productivity has not yet been determined, and a complete clear-cut without burning is still commonly suggested as the best silviculture for aspen stands (Perala 1974a). In cases where complete clear-cutting or other means of overstory removal are not possible, control of hardwood overstories with fire will result in a much better stand of aspen than those stands where no cultural treatment is used. There is current research in this subject area. For example, Weber (1990b) recently reported on ecosystem conditions after 20-year-old stands in eastern Ontario were burned or harvested before and after spring leaf flushing. Three years after treatment the greatest density of suckers resulted from harvesting before leaf flush (11 000 stems/ha), followed by harvesting after leaf flush (9000 stems/ha), burning after leaf flush (4000 stems/ha), and burning before leaf flush (2000 stems/ha).

A moderate fire will stimulate suckering, and high intensity fires may reduce sucker density and height growth (Perala 1977; Rouse 1986; Brown and DeByle 1987; Doucet 1989). Fire relationships are complex, however. Following a severe fire both aspen and white spruce generally regenerate at about the same time, producing a more or less even-aged stand (Kabzems et al. 1986). In contrast, light surface fires that do not burn all of the humus on the forest floor, and that do not expose mineral soil, stimulate aspen regeneration but not spruce regeneration. Aspen will often sprout the same year after a light fire in spring, while white spruce seedlings gradually establish over many years. These variable responses, depending on fire intensity, emphasize the fact that the precise outcome of perscribed burning is difficult to predict in aspen or mixedwood stands (McRae 1985; Doucet 1989). Others have also noted this difficulty. For example, Horton and Hopkins (1965) observed that sucker response was related to fire severity, but Brown and DeByle (1987) could not detect a significant quantitative relationship between sucker density and fire severity. They found that sucker densities varied considerably both between and within individual burns. Brown and DeByle suggested that for good sucker production, a fire of moderate severity was best; this severity of fire is one in which litter and fine woody material is consumed, duff is deeply charred or consumed, shrubs are killed, and aspen stems are charred by flame heights of at least 45 cm.

Research by Brown and DeByle (1987) in Idaho and Wyoming revealed that sucker production following fire peaks in the first year and declines each year thereafter. Most suckers appear during the first 2 years after fire. If fire, or clear-cutting, occurs in the first half of the growing season, there is often a flush of suckers later in the same season followed by a second flush during the next year. This occurred following the large burn in May 1968 near Lesser Slave Lake, Alberta. If fire occurs late in the season, in the dormant period, suckers appear in the next growing season.

One of the most recent reviews of the effects of prescribed fire on biomass and plant succession is that by Brown and DeByle (1989), based on data from Idaho and Wyoming. From observations in three prescribed fires in aspen and aspen--conifer stands, these researchers found that over 4 postburn years, production of grasses and forbs averaged 1.5–3.3 times that in unburned areas. Maximum production was 2240 kg/ha, five times that of the associated control. High-severity fire resulted in a higher production of biomass from forbs than from grasses. After 5 years, shrub biomass was 21–100% of preburn biomass. The proportion of shrub biomass less than 0.5 cm in diameter peaked after 2 years. Aspen sucker densities peaked during the first 2 postburn years and ranged from one-half to fivefold their preburn densities. Suckering was most prolific following fire of moderate-to-high severity. Brown and DeByle suggested that sucker response to low-intensity fire was poor because too few aspen were killed by fire, and because competition and shading from overstory aspen and conifers remained.

Most researchers who have worked on prescribed burning of aspen have stressed that this is a difficult forest type to burn (Fechner and Barrows 1976; Bailey and Anderson 1980; Brown 1985; Brown and Simmerman 1986; Brown and DeByle 1987). Prescribed burns of the intensity needed to stimulate aspen suckering require some dead woody fuels less than 2 cm in diameter to help ignite larger woody fuels and to provide adequate flame residence time to kill aspen. Shrubs also contribute significantly to good burning opportunities. Brown and DeByle (1989) suggested that aspen managers should expect varied responses in suckers, shrubs, and herbaceous vegetation during early postfire years.

Intervals between Fires in Northern Mixedwood Forests

Estimates of the average interval between successive fires in northern mixedwood forests vary considerably. For example, some analysts have estimated that in much of the boreal region there is an average life expectancy of only 50 years between stand-killing fires (Yarie 1981). Recent analyses in Wood Buffalo National Park, Alberta, indicated that an additional indicator of fire occurrence is the pollen record (Larsen 1989). After each fire the pollen record is characterized by substantial increases of grasses, shrubs, aspen, and poplar, and eventually spruce. In the Wood Buffalo National Park study sites, the pollen record indicated the occurrence of eight major fires in a 1000-year period. The first fire removed a stand of white spruce. Aspen then dominated through the next three burns, which spanned about 400 years. During the following 600-year period, white spruce remained the dominant tree species except for one interfire period when jack pine dominated. Larsen (1989) concluded that the pollen record indicated an average interval of 120 years between local fires, but suggested that this may be an overestimate because pollen profiles would not reveal the presence of small fires nor those that recur at very short time intervals.

In the present century, fire control measures have had a marked influence on the average interval between fires. In 1909 the fire cycle was 38 years in Alberta's mixedwood region. By 1929 the fire cycle had increased to 48 years, and by 1969 it had become 90 years, based on averages. In the 1950 to 1969 interval, specifically, the fire cycle had increased to 384 years (Murphy 1988).

The lengthening fire cycles referred to above indicate that fire is no longer playing its historic role of killing and renewing aspen stands. Where clear-cut harvesting or top-killing with aerial application of herbicides are not acceptable practices for renewal of aspen stands, wildfires or prescribed fires are the only other alternatives available. For the western United States, DeByle et al. (1987) recommended burning as the most acceptable management tool for maintaining that region's aspen resource.

There have also been suggestions that burning may be particularly important in regions where sucker development is inhibited by low soil temperatures. Zasada and Schier (1973) found that low soil temperatures inhibit sucker development. This may explain the absence of aspen on cooler sites in Alaska and their presence chiefly on southern exposures in that region. These investigators also indicated that diurnal change rather than maximum temperature may influence suckering, and that low minimum temperatures may suppress suckering regardless of the maximum temperatures. Soil temperatures may be marginal for suckering in some northern aspen stands and some researchers suggest that in such circumstances burning could increase soil temperatures sufficiently to enhance suckering. For example, in a prescribed burn in an Idaho aspen stand, soil temperatures one year after the burn were as much as 13°C warmer than on an unburned control site at a 30-cm depth, from June through August. By September, however, the differences were not significant, and by the second summer new aspen suckers shaded the soil enough that temperatures were comparable in the burned and unburned control aspen sites (Hungerford 1988).

Aspen and Balsam Poplar in Relation to Climatic Change and Global Carbon Dioxide Concerns

The recent work of several Canadian researchers (Jozsa et al. 1984; Williams 1985; Singh and Powell 1986; Harrington 1987; Jozsa and Powell 1987; Singh and Higginbotham 1988) has focused attention on potential responses of boreal forests to various assumed climatic changes. In North America, an increasing number of conference proceedings focus solely on this subject (Shands and Hoffman 1987; Wall and Sanderson 1990). Parallel estimates of sensitivity of boreal forests to possible climatic warming have also been made by Scandinavian researchers, as exemplified by the work of Kauppi and Posch (1985).

Zoltai (1988) predicted that conditions favorable for coniferous boreal forests could occur 300–450 km farther north than at present if atmospheric CO_2 doubles from its present concentrations. Boreal forest conditions could also be displaced along the southern boundary by a comparable south–north shift, with transitional grassland occupying what is presently southern boreal forest. Both agriculture and fire suppression strongly influence the location of the southern ecotone of the boreal forest, however, and will probably continue to do so under a changing climate (Michael J. Apps, pers. com., June 1990).

Singh (1988) stressed that climatic changes could influence forests in a wide variety of ways, including: displacement of ecosystems; changes in land use; increased forest fires (a key mechanism for a shift in ecosystem boundaries); shifts in tree line; changes in snow accumulation and snowmelt patterns; higher risks of drought and soil moisture stress; impacts on tree regeneration and survival as a result of growth and species composition changes; increased growth and yield in some areas and decreases in others; and increases in wood density and timber quality in northern areas of the boreal forest. Clark (1990) concluded from fire studies in mixed conifer–hardwood stands in Minnesota that had fire suppression not been instituted in 1910, fire frequency would have increased by as much as 40% in the 20th century because of warmer and drier conditions compared to the 19th century; however, the time required for buildup of fuels limits the extent to which increased moisture deficits increase fire frequency.

The current interest in adaptability of species and ecosystems to possible climatic warming or to more variable climates extends to all major ecosystems in the prairie provinces. This raises questions about adaptability of the boreal hardwoods to assumed or projected climatic changes. The 1989 *Greenprint for Canada* stressed the role that forests play in regulating the earth's climate. Forests grow by photosynthesis that absorbs CO_2 from the atmosphere. With man-made carbon emissions to the atmosphere continuing to increase, the forest's capacity for absorption and storage of carbon is more important than ever (Greenprint for Canada Committee 1989). This committee recommended a national carbon tax to fund reforestation of an additional 2 million ha in Canada by the year 2000. It is not clear what role aspen or balsam poplar would play in such an expanded reforestation program.

Paleoecological Reconstructions of Distribution of Boreal Mixedwood Ecosystems

One way to predict changes in the distribution and abundance of aspen under assumed climatic shifts is to assume that reconstruction of past events may tell us what could happen in the future. Delcourt and Delcourt (1987) have reconstructed tree population dynamics, including aspen, during the past 20 000 years. The pollen record reveals major shifts in the areal extent of aspen coverage at various locations and at various times since the last glaciation. For example, there is evidence that a once continuous aspen population around the Hudson Bay has progressively fragmented into smaller, isolated populations in the past few thousand years. By 2000 years ago the continuity between the Hudson Bay and the Great Lakes populations of aspen was broken. From 2000 to 500 years ago, aspen populations were widely distributed but at low dominance levels, making up 0 to 20% of the tree species composition, along the southern fringe of the boreal forest.

There is also evidence that in the past 20 000 years aspen has increased in importance only during times of major climatic change. Examples are at 12 000 years before present (BP) when there was widespread ice stagnation and at 8000 years BP when major retreat of continental glaciers provided new terrain suitable for aspen colonization. It appears that aspen populations reached their peak distribution of $22.1 \times 10^5 km^2$ about 4000 years ago and by presettlement times (500 years ago) had diminished by about 12% to $19.1 \times 10^5 km^2$. During glacial times (20 000 years BP) aspen extended across 9° of latitude. By 4000 years ago its north–south distribution had tripled to 27° of latitude (Delcourt and Delcourt 1987). Pollen records can be used to infer past changes of species distribution but provide little or no information about changes in species abundance or productivity.

In relation to climatic change, aspen has been described as an advanced colonizer (Davis and Jacobson 1985), showing high rates of advance in comparison to other tree species. When the northward advance of aspen reached its maximum rate, it was averaging about 550 m/year. The rate of advance decreased to 185 m/year between 6000 and 4000 years ago as aspen reached its northernmost extent along the shores of the Hudson Bay (Delcourt and Delcourt 1987).

Although reconstructions of past distributions indicate a marked resilience of aspen to major climatic changes, none of the evidence from past shifts in aspen's distribution can be tied to specific climatic changes such as a 1 or 2°C cooling or warming. That makes it difficult to predict what aspen's response might be if future decades brought some specific assumed increase or decrease in mean temperatures in the boreal zone of the prairie provinces. This difficulty has not prevented scientists from suggesting hypotheses and research needs to estimate the response of forest vegetation of western Canada to the climatic change expected from a doubling of atmospheric CO_2 (Singh and Higginbotham 1988). Little is known about how the economically important tree species of the western boreal forest respond to environmental factors under current atmospheric CO_2 concentrations; Singh and Higginbotham have acknowledged this as a significant weakness. The research challenge is not made any easier by the fact that today's main species in the boreal forest, including aspen and balsam poplar, have exceptionally large east–west and north–south distributions and most of them are also adapted to a relatively broad range of site classes. Despite the extreme difficulty of predicting the forestry effects of assumed climatic changes, scientists are making cautious suggestions of how the distribution of the boreal forest zone could respond to a predicted doubling of atmospheric CO_2. None of the hypotheses suggested to date, however, deal specifically with aspen or balsam poplar.

Reconstructions of past climatic changes need to be interpreted with caution. Some scientists believe that both the rate and magnitude of climatic change predicted under the enhanced greenhouse effect are much greater than have been recorded for past changes. Changes associated with the greenhouse effect are also predicted to occur in time scales shorter than the life spans of boreal tree species, so transient phenomena are expected to dominate and there may not be adequate past analogues for use in predicting ecological responses (Michael J. Apps, pers. com., June 1990). An alternative to prediction from historical analogues is to develop simulation models built on scientific understanding of the processes that are influenced by climatic changes.

Adaptablity of Native *Populus* Species to Large Climatic Changes

The fossil record indicates the widespread occurrence of many *Populus* species over long geological periods, during which climatic conditions have varied dramatically. Thirty species of *Populus* were widespread in North America during the Upper Cretaceous period. During the Eocene, *Populus* occupied all of the plains and mountains of western North America, extending northward to the present Beaufort Sea, and encircling the globe at high latitudes, when the climate farther south was too warm for *Populus*. It is difficult to reconstruct a complete post-Pleistocene profile of the genus because *Populus* pollen is poorly preserved. Data gathered by Ritchie and co-workers (Ritchie 1964; Ritchie and de Vries 1964), and summarized by Maini (1968), however, indicate that after glaciation the ancestral populations of *Populus* appear to have invaded the available growing surfaces from more than one direction. *Populus* *tremuloides* var. *aurea* in western Canada is thought to have evolved from the populations that survived in the Yukon River valley and in other refugia south of the ice sheet (Maini 1960).

The tenacity of aspen and its predecessors over long and varied geological periods indicates an adaptability that may serve the species well in eras of future climatic change. An important point is that this adaptability need not necessarily be attributed to the plasticity that comes with gradual evolutionary changes through sexual reproduction. For example, for the Rocky Mountain region of the western United States, Barnes (1967) emphasized that modern clones of aspen are apparently very old and in unglaciated parts of that region only a few sexual generations may separate today's clones from their Pliocene ancestors. Even though aspen regeneration from seed is more common in eastern North America and in Canada than it is in the southern Rocky Mountain region, gene flow between widely separated populations of aspen is thought to be slow and uncertain (Jones and DeByle 1985a). The apparent adaptability of aspen to changing ecological conditions is reflected by the wide range of sites and climates in which today's clones survive.

Effects of SO_4 and other atmospheric pollutants are often difficult to separate from climatic effects. Interactions between climate, acid deposition, and tree growth have been analyzed in Wisconsin, Michigan, and Minnesota (Holdaway 1988) using data from 2408 inventory plots. In that region, as in the prairie provinces, SO_4 deposition does not yet appear to be a major factor influencing tree growth. Pine species on the driest sites are considered to be the most susceptible to regional atmospheric pollutants, whereas deciduous species such as aspen and balsam poplar are less seriously damaged than conifers, mainly because they have new foliage each year.

Weingartner and Doucet (1990) speculated on the possible effects of increasing temperature and decreasing precipitation on aspen production in sites that are drier than the best sites. They pointed out that growth of aspen has been related to moisture availability in many studies (Wilde and Pronin 1949; Strothmann 1960; Fralish and Loucks 1975). Long-term warming and drying trends may require active management to maintain aspen production on sites that are becoming drier because there is evidence that moisture deficits and slower growth are equated with more defect in aspen. Weingartner and Doucet (1990) suggested that one way to achieve this may be thinning to redistribute growth to fewer numbers of crop trees.

Libby (1982) examined the question of what is a safe number of aspen clones per plantation. Potential gains and risks are an appropriate context in which to speculate about the adaptability of aspen and balsam poplar ecosystems to climatic change. The clonal nature of these trees is also relevant because speculations about responses to assumed climatic changes will be different for genetically diverse forests than for homogenous managed forests. There is already considerable experience in estimating trade offs between risk and gain in contexts other than climatic change (Perry and Maghembe 1989). For example, how resistant are diverse and homogenous forest ecosystems to pests and pathogens? How resilient are diverse and homogenous systems for maintenance of productive capacity through many rotations? And how productive are diverse versus homogenous ecosystems? These are questions that have not yet been addressed for aspen and balsam poplar in the prairie provinces and northeastern British Columbia.

Aspen and Balsam Poplar as Part of the Boreal Carbon Sink

The boreal forest, because of its vast circumboreal distribution, is regarded as a major carbon sink, along with tropical rainforests. There are, of course, important differences. In tropical rainforests, most carbon is stored in aboveground biomass, with forest floor detritus and soil carbon actively recycled due to rapid decomposition rates. In contrast, in boreal ecosystems, carbon in humus and soil is relatively more important, with recycling slower because of both slower decomposition and slower uptake through growth. Any changes in decomposition rates as a result of a warming and drying climate in the boreal region could have a significant influence on the net carbon flux from these northern ecosystems because the forest floor and soil are very important in sequestering carbon (Michael J. Apps, pers. com., June 1990). Current research on the carbon budget of the Canadian forest sector, headed up by the Northern Forestry Centre of Forestry Canada, is addressing these topics. There is also other current research addressing the role of aspen forests in the CO_2 cycle. For example, Weber (1990a) recently reported on forest soil respiration after burning or harvesting of 20-year-old aspen in eastern Ontario. In the study sites at Petawawa, Ontario, soil respiration levels varied seasonally from a midsummer high of about 7000 mg CO_2 m^{-2} d^{-1} to spring and autumn lows of about 2000 mg CO_2 m^{-2} d^{-1}. Harvested and burned plots in the 20-year-old stand showed temporary declines in CO_2 release for two growing seasons compared with an untreated control. During the third growing season, respiration rates had fully recovered to pretreatment levels.

In a world seeking to slow the rate of release of CO_2 to the atmosphere, increasing numbers of people may come to value boreal forest standing crop simply as a reservoir of captured carbon. To the extent that this viewpoint becomes socially or politically important, two features of aspen and balsam poplar should be kept in mind. The first is that neither of these boreal hardwoods are long-lived when compared with their companion conifers. Carbon stored in the form of mature aspen is not a very secure reservoir because respiratory losses associated with decaying wood, whether standing or on the ground, result in a significant release of carbon long before stands reach 200 years of age. Along with decay, insects and fires also contribute to carbon release.

The second important feature of these boreal hardwoods is their exceptionally rapid growth rate in the first one or two decades of stand development. High rates of standing crop accumulation and high amounts of standing crop packed into a unit volume of growing space, documented in Alberta and Saskatchewan by Peterson et al. (1982), indicate that in their early years these species are very effective at capturing atmospheric CO_2. Data from the prairie provinces indicate that within 10 years from the date of stand establishment most tree and shrub species that characteristically occupy disturbed sites can achieve standing crop densities (dry weight of above-ground standing crop/m^3 of stand space) at least equal to those of mature forest stands.

These two characteristics—rapid carbon fixation in the early phases of stand development and rapid release of carbon with stand breakup between 100 and 200 years of age—must be considered when estimating the relative merits of hardwoods and softwoods for the boreal carbon sink. If the high rate of carbon capture associated with the early rapid growth of hardwoods is converted to pulp and paper products the carbon is quickly returned to the atmosphere because these products have a relatively short life. If hardwood biomass goes into composition board or lumber that will remain in buildings for a century or more then the re-release to the atmosphere of carbon captured by boreal hardwoods can be slowed.

MANAGEMENT OF ASPEN AND BALSAM POPLAR

Some foresters, more so in British Columbia than in the prairie provinces, still confess to a difficulty in accepting aspen as a silviculturally managed species (Zak 1990). The traditional bias in favor of conifers indicates that as aspen and balsam poplar achieve a status comparable to that traditionally held by boreal conifers there is a need to rethink forest management objectives and to change silviculture research priorities. In order to progress, traditional views must be challenged, and past practices and values need to be examined. The subsections below indicate that management of aspen and balsam poplar must recognize how the clonal nature of these species influences silvicultural responses. For many foresters it will be a new experience to work with a species that differs from conifers in several import aspects. For example, aspen regulates its density without silvicultural intervention; if thinned, aspen may respond by increased sucker production, which can hamper the intended concentration of increment in residual crop trees. Aspen is easily wounded during thinning operations, with the prospect of increased decay losses as a result of the thinning. The need for management innovation is apparent now that technological progress has provided the opportunity to use aspen and balsam poplar for pulp, panelboards, and other value-added products.

This section is a synthesis of several other reviews that have been published recently on the subject of aspen and balsam poplar management in boreal hardwood and boreal mixedwood stands. The key recent reviews were prepared by Davison et al. (1988), Samoil (1988), Peterson et al. (1989a), Peterson, Kabzems, and Peterson (1989), Navratil, Bella, and Peterson (1990), and Shortreid (1991). Comprehensive earlier work was done in the prairie provinces by Jarvis (1968) and by Steneker (1967a, b; 1974a, b; 1976a, b). The main headings of this section reflect the management challenges and opportunities associated with aspen and balsam poplar in an era when these species are taking on increasing value, not only for industrial products but also for water, wildlife, and recreational land uses.

Magnitude of Western Canada's *Populus* Resource

Land area, volume, and biomass comparisons of the prairie provinces and northeastern British Columbia aspen/poplar resource relative to that in all of Canada are presented in this section. Canada has five times as much merchantable volume of aspen as the United States. This volume is dispersed in Canada over a broad area from central and northeastern British Columbia to Quebec. In the United States most aspen volume is in the Lake States, with a lesser amount in Colorado and the surrounding mountain states (Adams and Gephart 1990).

From 20 to 40% of Canada's aspen/poplar resource occurs in the prairie provinces. The Canadian Forest Resource Data System indicates that *Populus* is the dominant genus on about 20 million ha, or 9.2% of Canada's productive forest land. Within the 31.3 million ha of forests classified as hardwood in Canada, *Populus* is the predominant genus on about 11 million ha, and on Canada's 49.8 million ha of mixedwood stands this genus is the predominant one on about 9 million ha. On Canada's 136.9 million ha classified as softwood types, aspen and poplar are the predominant genus on less than 100 000 ha (Forestry Canada 1988). Singh and Micko (1984) estimated that of the total area occupied by aspen/poplar in Canada, about 18% of that area occurs in Alberta, Saskatchewan, and Manitoba.

On a volume basis, Canada has about 18 273 million m^3 of softwoods and 5647 million m^3 of hardwoods. Aspen makes up about 34% of Canada's hardwood volume, and other poplars contribute another 22% to the hardwood volume in the country (Forestry Canada 1988). These estimates indicate that aspen is a more prominent component of the Canadian boreal forest than *P. tremula* is in the European boreal forest. For example, aspen accounts for only 9% of the total standing volume of Norway's forests (Borset 1960). On an area basis, aspen is the principal species on only about 2% (19.1 million ha) of forests in the U.S.S.R. (Barr and Braden 1988). Based on data summarized by Ondro and Bella (1987) and Peterson, Kabzems, and Peterson (1989) the relative proportions of aspen and balsam poplar in western Canada are as follows:

	% of total *Populus* represented	
Province	Aspen	Balsam poplar
Manitoba	86.1	13.9
Saskatchewan	85.9	14.1
Alberta	83.2	16.8
Northeastern British Columbia	84.6	15.4

Of the 20 million ha in which *Populus* is the predominant genus about 14.3 million ha (71.5%) occurs within the main part of the boreal forest region. An additional 1.1 million ha of *Populus*-dominated forests occur in the transition zone between the boreal forest and the grassland region of the prairie provinces. Only about 15 000 ha of *Populus*-dominated forests occur in the transition zone between the boreal forest and the subarctic barrens.

On a volume basis, of Canada's estimated total 2484 million m^3 of *Populus* pulpwood on stocked, productive forest land predominated by this genus, 1849 million m^3 (about 65%) occurs within the main part of the boreal forest region, with another 83 million m^3 (3%) in the aspen parkland on the southern fringes of the boreal forest region in the prairie provinces.

Mature and overmature forests in which *Populus* is the predominant genus are provincially distributed as summarized in Table 35. Considering only the mature and overmature *Populus* volumes listed in Table 35, Alberta has about 12% of Canada's total of 1513 million m^3, Saskatchewan has about 10%, and Manitoba has about 6%. In the case of the prairie provinces, these *Populus* volumes include aspen and balsam poplar whereas the Canadian total includes not only these species but also substantial volumes of *P. trichocarpa* and *P. grandidentata.* Aspen and balsam poplar volumes, as compiled by Ondro and Bella (1987), are reproduced in Figure 47 to indicate the amounts of the *Populus* resource present in the prairie provinces and British Columbia relative to other areas. Other estimates of aspen growing stock volume for Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland have been assembled by Weingartner and Doucet (1990).

Bonnor (1985) compared Canada's provinces in terms of total ovendry *Populus* standing crop on all nonreserved forest land, not just mature and overmature stands. His data combines aspen and poplars and compares them to all Canadian spruces combined (Table 36). Based on this data, the prairie provinces contain about 40% of Canada's total *Populus* biomass, with 23% in Alberta alone. On a volume basis, considering all maturity classes, Navratil, Bella, and Peterson (1990) recorded a total aspen/poplar resource of 2981 million m^3 in Canada. From this total, the Canadian annual allowable cut (AAC) was estimated at about 45 million m^3. In the four western provinces, current AAC is slightly over 16 million m^3, with 3.5 million m^3 in British Columbia, 8.4 million m^3 in Alberta, 2.6 million m^3 in Saskatchewan, and 1.8 million m^3 in Manitoba. By comparison, current AAC for aspen is about 7.2 million m^3 in Minnesota. In the prairie provinces and northeastern British Columbia, about 30% of the present aspen AAC occurs in mixedwood stands (Navratil, Bella, and Peterson 1990), which are the most difficult and challenging areas to manage.

Based on biomass estimates assembled by Bonnor (1985), Canada has an estimated inventory of 2440 million t of *Populus*, which is about 10% of Canada's total forest biomass of 25 306 million t. By comparison, spruces comprise about 35% of Canada's total biomass, pines 17%, and true firs 12%. The distribution of Canada's aspen/poplar and spruce biomass, by aboveground components, was estimated by Singh and Micko (1984) as follows:

Distribution of biomass	% of total biomass in various components	
	Aspen/poplar	Spruce
Merchantable stem wood	53	45
Merchantable stem bark	11	5
Tops of merchantable trees	5	8
Stump wood	2	2
Branches	12	11
Foliage	2	6
Submerchantable trees	15	23
	100	100

Challenges for Inventory and Annual Allowable Cut Calculations

The most common problems associated with inventory of aspen and balsam poplar for the forest manager are: difficulties in accurate age determination of mature and immature stands; large errors in estimation of cull; difficulties in distinguishing aspen from balsam poplar when aerial photographs are the basis of the inventory; and difficulties in estimating the amount of understory conifers.

There is still room for improved inventory of the boreal hardwood resource. Recently, a committee in the British Columbia Ministry of Forests, which defined 12 current problems related to hardwood management in the northeastern part of that province, identified improved hardwood inventory as the highest priority goal. The need to refine calculations of AAC for hardwoods and softwoods has highlighted the fact that there are poor inventory data on the relative proportions of hardwoods and softwoods in a variety of mixedwood stands (Revel et al. 1986).

Most previous inventories failed to provide information on young hardwood stands because they were often simply mapped as not sufficiently restocked (NSR) or as noncommercial brush (NCBr). Today many areas

Table 35. Areas and pulpwood volume, by province, for mature and overmature, stocked, productive, and nonreserved forests in which *Populus* is the predominant genus (Forestry Canada 1988)

	Mature/overmature *Populus*-dominated forest			
	Area (100 000 ha)		Volume (1 000 000 m^3)	
Province[a]				
British Columbia	18.41	(22.8%)	415.09	(27.4%)
Alberta	10.45	(13.0%)	183.29	(12.1%)
Saskatchewan	9.27	(11.5%)	145.76	(9.6%)
Manitoba	7.64	(9.5%)	95.86	(6.3%)
Ontario	34.73	(43.1%)	673.41	(44.5%)
Newfoundland	0.03	(0.1%)	0.37	(0.1%)
Total	80.54	(100.0%)	1513.79	(100.0%)

[a] Unlisted provinces have no mature/overmature *Populus*-dominated forests.

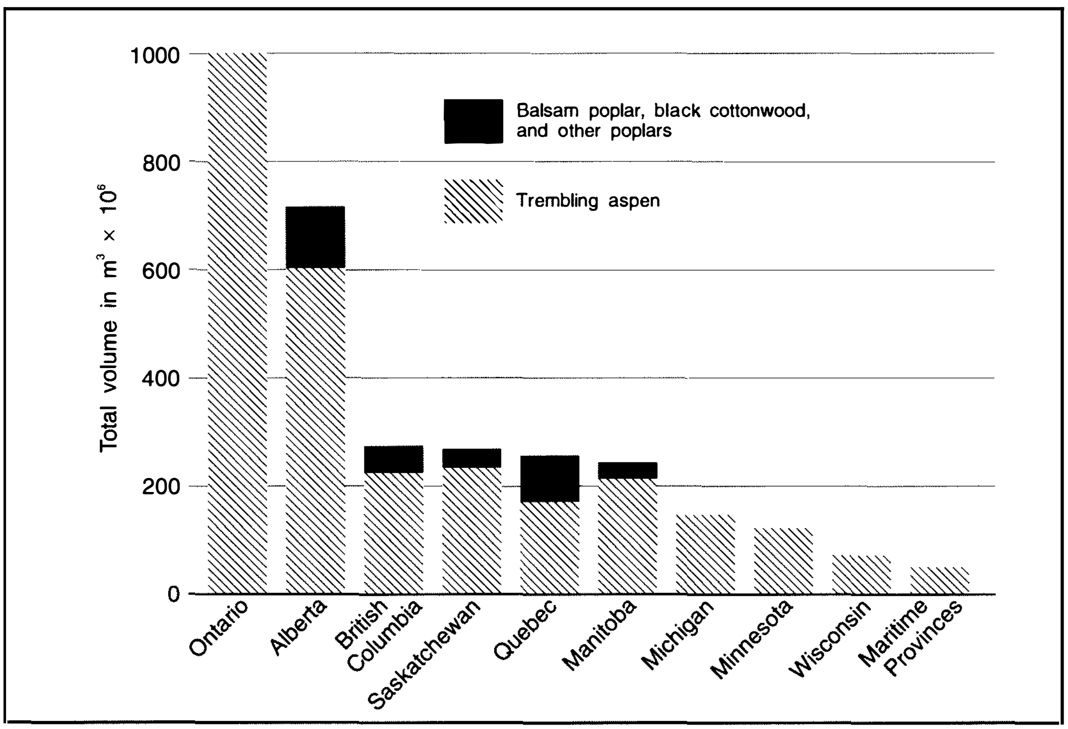

Figure 47. Aspen and poplar growing stock on Crown lands, state lands, and private lands in the major *Populus*-producing regions of Canada and the United States (Ondro and Bella 1987).

Table 36. Standing crop (in millions of ovendry tonnes) of aspen/poplar in comparison to spruce on unreserved forest land by province and territory in Canada, and the percentage of Canada's aspen/poplar standing crop that occurs in each jurisdiction (Bonnor 1985)

Province or territory	Spruce	Aspen/poplar	%
Newfoundland	512.05	2.02	0.1
Nova Scotia	96.76	7.02	0.3
Prince Edward Island	10.12	1.45	0.1
New Brunswick	142.49	30.75	1.3
Quebec	2171.52	166.51	6.8
Ontario	1899.11	628.29	25.7
Manitoba	548.15	251.64	10.3
Saskatchewan	405.43	170.24	7.0
Alberta	791.48	550.72	22.6
British Columbia	1915.36	592.07	24.2
Yukon Territory	100.15	13.11	0.5
Northwest Territories	257.00	25.88	1.0
Canada	8849.63	2439.69	100.0

mapped as NSR or NCBr support aspen-dominated stands that have potential value for harvesting. Furthermore, in mixedwood stands across western Canada there is a need for better data on size and age-class distribution of softwood regeneration beneath aspen overstories. This is considered by some mixedwood forest managers to be the single most important need for proper management of the conifer and aspen allowable annual cuts.

Earlier inventories often underestimated the balsam poplar component of aspen–balsam poplar stands. Recently, Minnesota and Alberta have been involved in a cooperative exchange of ideas on how to achieve better aerial photography for identification of hardwood species for inventory purposes (Westfield 1987). Additional testing is under way in Alberta to determine the best film emulsions, scales of photography, and season of photography for differentiation of balsam poplar from aspen (Morgan 1987).

Accurate age determination of aspen and balsam poplar stands remains a difficult problem, particularly in mature stands that have well-advanced stem decay. In Alberta, recent investigations that used laboratory equipment to obtain more accurate ages revealed that many stands originally classified as 120 years of age are only 80 years old, 80-year stands are really only 60, and 60-year stands are 50. For stands 40 years old or younger, previous age determinations have been relatively accurate. Similar ageing problems exist in northeastern British Columbia, where a recent audit of hardwood inventory data by D.R. Systems Inc. (1988) revealed not only overestimates of hardwood ages but underestimates of height classes and site classes in hardwood inventory groups.

When growth projections are to be tied to site types it is important to note that relationships between aspen growth and site characteristics are less evident in stands younger than 40 years than they are in older stands (Heeney et al. 1980). These possible differences, however, have not been quantified for mixedwood and hardwood stands of the prairie provinces. There is a need for greater use of ecological and other criteria to complement the traditional mensurational approaches for growth projections in young stands on sites of varying quality. There is also a need for better estimates of potential productivity of sites after fire or logging to replace the cover type emphasis of much of the hardwood inventory to date.

Aside from the inventory challenges previously mentioned, the large errors in estimation of cull in aspen and balsam poplar are well known. Other inventory problems relate to the clonal nature of aspen stands. As discussed in the following text, the clonal structure of aspen stands has a bearing on how sampling should be done for calculation of site index.

When aspen site index estimates are required, special sampling measures are necessary to ensure that a range of genetic diversity is assessed. For conifers, the usual sampling method is to select the tallest trees for height measurement. Zahner and Crawford (1965) outlined the problems that arise if this conventional practice is used in aspen site index studies. Should all clones on a site be sampled or should the shortest ones be omitted? What is the possible overestimate of site index if only the tallest trees of the tallest clone, or even the tallest three clones, are sampled?

Zahner and Crawford (1965) developed the following guidelines that are probably applicable to site index sampling requirements for aspen in the prairie provinces: i) a reliable estimate of productivity can probably be made if at least six clones are present on a given site, and a three-clone sample is selected to represent the stand; ii) selection of clones for measurement should not be random because obviously atypical clones should not be sampled; and iii) only two stems need to be sampled in each clone because individual trees do not deviate widely from the clone average. If only one or two clones are present, site quality can still be estimated but will be less reliable than if more than two clones are sampled.

The key rule for the inventory forester is to recognize that the greatest errors will occur if aspen site index measurements are limited to well-stocked, uniform portions of a stand, which in an aspen forest may be the center of one large, well-developed clone; measurement of a single clone is not a measure of site index for an aspen stand, regardless of how many trees are measured in that clone. Ideally, double sampling is needed—a sample of clone sizes and small samples of trees within clones. Strip cruising, instead of plot establishment, is probably the most appropriate sampling system for assessing clone size.

Information on aspen stand breakup is vital for management but is generally lacking. In particular, growth projections are hampered by uncertainty about aspen stand characteristics after age 60. For example, sample plots established by the British Columbia Ministry of Forests in pure aspen types in northeastern British Columbia revealed that on some mesic and subhygric sites there are two different patterns of diameter distribution and stand development after age 60. Breakup occurs in some stands, allowing new stems to come in and a multiaged stand to develop. Other stands remain intact and continue to add increment to at least age 90. It is not yet known whether there are clonal, ecological, or stand history reasons for these stand differences (Peterson, Kabzems, and Peterson 1989). Similar variability in stand mortality patterns is also known for aspen stands in the Rocky Mountain region of the United States.

Shields and Bockheim (1981) investigated aspen stand breakup in Ontario and the Lake States by comparing stand basal area at a given age to the maximum basal area, which is achieved in that region at approximately age 55 years for all site index classes. Maximum basal area for the highest site index class in that region was approximately 35 m^2/ha. Once it begins, stand breakup can occur in as little as 6 years as heavily decayed stems are prone to windbreak, which escalates the breakup process (Hambly 1985). This circumstance indicates that accurate age data are required to define the short interval between maturity and breakup in aspen stands (Denney 1987; Hiratsuka and Loman 1984).

As indicated previously, in both Alberta and northeastern British Columbia recent investigations revealed that aspen stands are often younger than existing inventories indicate. This circumstance has important implications for growth and yield projections and for AAC calculations. In northeastern British Columbia, forest inventory specialists have estimated that it will take as much as 20 years to develop a sound growth and yield data base for boreal hardwoods. Long-term empirical growth and yield studies are particularly needed in two general types of aspen stands: in recent aspen regeneration under 10 years of age, and in older stands 10–20 years of age; this would require permanent installations for long-term remeasurement. In young stands, the recommended approach is to sample a range of site classes and ecosystems; in older stands, the permanent installations should be located to sample a range of different levels of growing stock. The overall need is to assess, for all types of stands sampled, the following variables: growth and yield, piece size, wood quality, optimum rotation length, and harvest costs (Les Herring and Rick Nakatsu, pers. com., May 1988).

A common AAC problem is what to do with the present large inventory of mature aspen and balsam poplar. In some areas, such as in the Dawson Creek region of northeastern British Columbia, the largest proportion of aspen is in the 85–100 year age class. In such cases, for the resource to be used before there is too much decay, harvesting must be accelerated beyond that which occurs on a sustained yield basis. This circumstance is not unique to northeastern British Columbia or the prairie provinces. In the Rocky Mountain region of the United States there are also many aspen stands that are at or beyond rotation age (Jones and Shepperd 1985c).

In Alberta, the portion of hardwood AAC actually used has increased rapidly in recent years. In 1971 less than 2% of the hardwood AAC was used. In 1988, about 15% of Alberta's aspen AAC was being used, but this percentage was expected to increase very rapidly. By 1989, if all proposed developments for use of aspen in Alberta were to proceed, close to 80% of the AAC would be used (Karaim et al. 1990). In 1980–81, aspen and balsam poplar made up 2.4% of total volume cut in Alberta. By 1986–87, the hardwood harvest had increased to 15.4% of the province's total harvest (Ondro and Bella 1987), and by 1989 it had increased even further.

The main hardwood AAC challenge is to tie the current situation to longer-term timber supply (Denney 1988a). Supply levels and AAC in Alberta are based on a broad inventory and a number of criteria and assumptions. Attempts to apply this broad information to an operational situation are not always successful. For example, with a broad inventory base, certain stand types are dedicated to be cut for hardwoods. Some of these stands, however, contain merchantable quantities of softwood. This raises the question about which operator is responsible for such softwood and whether it should be charged to the softwood AAC. Denney believed that decisions need to be made either completely on the broad inventory or completely on the operational inventory; using a combination of the two inventories lead to confusion. If the emphasis is on operational information, at some point the decisions have to be tied back to the broad inventory. In Alberta, this has not been a major issue until now because there has been sufficient uncommitted timber to provide flexibility with operations, but it will be a problem as more of the boreal hardwood resource is allocated. At some point it is necessary to balance the AAC for hardwoods and softwoods. In pure stands this is commonly done every 5 years. If operations are in mixedwoods, however, the 5-year cuts may not balance with the overall long-term AAC for the management area.

Management of Aspen and Balsam Poplar in Stands Involving Conifers

Foresters involved with northern mixedwood management recognize that the coexistence of aspen and spruce on the same site represents a well-adapted ecological mix. They also know that these ecosystems present perplexing silvicultural problems. Most of these problems center around a desire for rapid and successful regeneration of spruce involving: competition from shrubs and grasses after clear-cutting; limitations in the use of herbicides to control competition; burial of natural spruce seedlings by aspen leaf litter; the need for exposed mineral soil or rotted stumps and logs as a germination medium for white spruce; the mismatch in early height growth of the two dominant tree species, with 1-year spruce seedlings 2–3 cm tall, 1-year aspen seedlings up to 20 cm tall, and 1-year aspen suckers up to 100 cm tall; and the substantial damage and mortality that snowshoe hares bring to coniferous seedlings.

The opportunities that go with northern mixedwood forestry are not as well publicized as those previously discussed. For example, Denney (1988a) pointed out that sometimes yields per hectare are doubled when both hardwoods and softwoods are harvested. This means that road building, felling, and skidding costs per unit area or per unit of raw material are reduced. Associated environmental impact per unit of harvested material is correspondingly reduced. If both hardwoods and softwoods are used, additional land base is opened that was previously uneconomical when only softwoods were harvested. Furthermore, use of both components of mixedwood stands adds stability to the forest industry because hardwoods and softwoods are associated with different products, different markets, and different market cycles. The 1989 National Survey of Canadian Public Opinion on Forestry Issues (Environics Research Group Limited 1989), commissioned by Forestry Canada, revealed strong public concern over the forest industry's wasteful utilization practices. On the other hand, there is very little public support for clear-cut areas. Therefore, the utilization improvements that could come with removal of all merchantable hardwoods and softwoods in the same harvest operation are not likely to be popular with the public.

There is limited experience to date on how to successfully remove hardwoods from lands allocated to softwood licencees. Forestry Canada, however, is continuing the research described by Brace and Bella (1988). Those studies have shown that disk trenching followed by application of the herbicide Pronone 10G, in granular form, effectively checked aspen, which resulted in increased diameter growth of spruce and pine within 3 years (Ascher 1990). Boreal mixedwood managers are becoming more aware of the opportunities for better management of the coniferous understory when aspen are harvested, and are realizing that an integrated approach to softwoods and hardwoods from the same land base offers certain advantages, especially where large leases are involved. For example, if hardwoods and softwoods are harvested in the same operation there are opportunities to reduce skidding costs and to reduce environmental impact. It is also good public relations to demonstrate higher levels of utilization. In addition, fluctuations of markets for coniferous products can be dampened by the availability of other marketable hardwood products (Denney 1988a).

Some foresters think there is not enough experience to effectively regenerate and manage mixedwood stands. They suggest a need for one land base for hardwoods and another for softwoods. In western Canada there are not yet well-defined criteria to determine when the hardwood or the softwood resource carries priority in circumstances of overlapping tenure. Similarly, there is no rigid standard for the amount of softwood that must be present for softwoods to carry priority in a given forest management area (C. Smith 1988). In the short term, the best method may be to reforest the area in proportion to the volumes of hardwood and softwood removed; this would allow a manager to choose the best sites for a particular species. Current regulations concerning reforestation responsibility would have to be modified, however, to give both hardwood and softwood operators reforestation responsibility for hardwoods and softwoods (Denney 1988a). Research is currently underway at the Northern Forestry Centre, Forestry Canada, to develop a silvicultural decision tool for predicting aspen regeneration and competition in mixedwood sites. Preliminary growth/competition models reported by Navratil, Phillips, and Morton (1990) suggest that an aspen cover of 10–20% can have a postitive effect on lodgepole pine seedling growth; higher levels of aspen cover have a negative effect on pine seedling growth.

Until very recently there were strong interests in methods to reduce the amount of hardwoods in boreal mixedwood stands. Mixedwood stands have anywhere from 20 to 60% lower net volumes of conifers than do pure coniferous stands on the same sites. These lower net volumes result in higher costs of access, harvesting, silviculture, and protection per unit of conifers available to the industry. In many mixedwood stands there is also significant damage to the leaders of conifers as they grow through the aspen canopy. This leader damage has the effect of reducing coniferous yield and extending the required length of rotation (Revel 1983).

Foresters with experience managing mixedwood stands recognize that, despite all treatments, some hardwoods will occur in most new stands in the boreal region. Therefore, control rather than eradication of hardwoods is the management goal. Experience has also shown that manual treatments alone are not effective as hardwood control measures; chemical control of hardwoods by aerial application is the only economic alternative in many cases.

Prescribed Burning in Boreal Mixedwoods

Fire is an integral part of boreal mixedwood management. Land managers can be interested in prescribed burning for a variety of reasons. For some foresters, prescribed burning is a way to remedy what some foresters call silvicultural slums. In the aspen parkland region of the prairie provinces, range enhancement often involves burning to remove aspen. Other benefits of prescribed burning include increased yield of herbage and increased forage use by livestock (Wright 1974; Wright and Bailey 1982). In other cases, land managers use prescribed burning to eliminate overmature aspen and to stimulate a new crop of vigorous aspen suckers. Fire is helpful for the latter purpose only if there is enough woody fuel to provide the heat needed to kill all aboveground stems. Prescribed fire would not normally be used in immature stands that are vigorous and decay-free unless the forest manager wishes to use fire to increase the diveristy of available wildlife habitat (Rouse 1986).

For the mixedwood manager interested in spruce regeneration, prescribed burning may be undesirable because of its stimulus to aspen suckering. This occurred near Lac La Biche, Alberta, where a burn in partially-cut spruce–aspen stands created suckers and herbaceous vegetation so dense that conditions were unfavorable for spruce seedling establishment (Kiil 1970). Spruce that did germinate were commonly covered with thick layers of leaves from aspen and other deciduous species. For herbaceous vegetation the greatest accumulation of leaves occurs a few months after a burn, and for aspen it is a few years after the burn. When the goal is to minimize aspen's potential inhibition of spruce regeneration, Kiil recommended that burning be applied shortly after logging when slash accumulations and lack of lush herbaceous growth would permit greater fire intensities.

Perala (1974a) recommended that the forest manager wishing to promote a new crop of aspen suckers should burn during the first dormant season following harvest and preferably before substantial suckering takes place to minimize growth loss attributed to reinitiation of suckering. Assuming good drying weather, aspen slash from summer harvesting can be ready to burn in the fall of that year or the following spring. Also, relatively little suckering will occur and sucker regrowth after burning would be least affected if fall burning is used.

Integration of Softwood and Hardwood Harvests from the Same Land Area

The early phase of Alberta's oriented strandboard (OSB) industry used only aspen as raw material, but there is now increasing interest in use of other species as well. Integrated use of hardwoods and softwoods from the same land base, and opportunities for innovative mixedwood management, will be enhanced as it becomes increasingly acceptable to mix some spruce, pine, and balsam poplar to the aspen raw material for OSB production. Management and harvesting of mixed-species stands will be simplified if all species from one area can be harvested at the same time for delivery to processing plants.

In cases where segregation of hardwoods and softwoods is essential because present operations use only one of these resources, difficult challenges remain. In western Canada, large operators have not found it easy to accept the idea of harvest removal by a disinterested third party who would parcel coniferous biomass to those who want it and hardwood raw materials to other processing facilities; however, some analysts have suggested just such an approach as a solution to the present problem (Murphy 1988). Beck et al. (1989) suggested additional solutions. For example, appropriate regulations and policies, harvesting technologies, and ethics about the future forest can be developed to allow partial harvesting of either conifers or hardwoods in a way that would cause minimal acceptable damage to the remaining species groups. Two of the important unanswered policy questions were concisely stated by Clark (1988) as follows: should land managers emulate nature by encouraging more mixedwood forest occurrence? Should land managers battle nature by discouraging mixedwood forest expansion?

The progression from agricultural land to aspen parkland to mixedwoods as one moves northwards in western Canada illustrates the notion that lands supporting relatively pure aspen/balsam poplar stands are in closer proximity to farming operations than is the case for mixedwood or coniferous stands. This imposes another level of land-use uncertainty, beyond the hardwood–softwood allocation question previously outlined. It suggests that forestry uses of the hardwood resource must be weighed against other land uses such as farming, grazing, wildlife habitat enhancement, or recreation. Use of boreal hardwoods as a crop represents a major shift in thinking in a region where aspen, until recently, was regarded as a weed. For a long time, piling and burning was the main form of aspen management on lands that had any agricultural potential. But now farm woodlots in the aspen parkland and mixedwood regions of western Canada are increasingly regarded as a source of hardwood crops to be managed as part of agricultural operations. New developments at the northern fringe of the agricultural zone in western Canada include industrial procurement of boreal hardwoods from small woodlot owners and temporary cattle grazing on forest land between the time of regeneration establishment and canopy closure (Vicars 1988).

Hardwood production from small private land holdings is not without its own particular challenges. Coordination of activities and improvement of utilization levels must be extended to these private lands as well. For long-term wood production, there are better alternatives than the present practice of some private landowners in Alberta who use aspen harvest sales to accelerate clearing for agricultural development. Furthermore, some landowners are not impressed with the state of their woodlots after the logging contractors have left. Special efforts are needed to enlist the enthusiastic involvement of woodlot owners as long-term, rather than marginal, suppliers of aspen and balsam poplar (Murphy 1988).

Protecting the Coniferous Understory when Overstory Aspen are Harvested

Protecting valuable white spruce understory is an important management decision because it is one step that ensures that one resource is not harvested at the expense of the other. Continuing research on this subject by Forestry Canada's Northern Forestry Centre (Brace and Bella 1988) and by the Forest Engineering Research Institute of Canada (Alex Sinclair, pers. com., September 1989) is building on techniques suggested by Froning (1980) to reduce damage to understory white spruce. Froning's pioneering work showed that careful logging of aspen can preserve a high percentage of the spruce understory. In an experimental area near Hudson Bay, Saskatchewan, 56% of the spruce were damaged in a 60-ha area where the logging contractor was given no particular guidance on methods to reduce damage to spruce. In contrast, in a nearby 16-ha trial area, where logging was planned and the skidder operator was supervised, there was only 12% damage and 7% total destruction of the white spruce understory after skidding.

This degree of protection to the spruce was achieved in the following way. Surveys were conducted prior to logging to map the spruce understory. Major skid trails were flagged, based on the stocking of white spruce, with sufficient flexibility to take advantage of gaps in the understory. Aspen logs were bunched in the direction of skidding. Over 75% of the hardwoods were logged; those remaining were often in dense clumps of spruce that would not have been removed under normal conditions. Other aspen were left standing to serve as "guard trees" for the deflection of skidded material around curves or turning points; some high stumps were also left for this purpose.

Froning (1980) made the point that vulnerability of spruce to windthrow is high when dense mixed stands are opened. Leaving some hardwoods will likely reduce wind damage to critically exposed spruce trees, an important consideration in the development of silvicultural guidelines for spruce release from aspen (Johnson 1986). Froning also warned against logging hardwoods when temperatures are very low because felling and skidding trees under those conditions increases mortality and damage to understory spruce.

There are some operational examples of other ways to reduce damage to spruce when overstory aspen is harvested from mixedwood stands. For example, during aspen harvesting by Pelican Spruce Mills Ltd., near Edson, Alberta, damage to understory spruce is decreased by using a mechanical harvester that cuts parallel swaths as it moves into the stand. Within reach of the boom, aspen are removed from both sides of the swath and placed lengthwise along the track created by the mechanical harvester as it backs into the stand. Trees are skidded out to landings along this same track. The result is a swath up to 6 m wide, in which there is substantial damage and loss of understory spruce, but between each disturbed swath there is a 9–12 m wide area in which aspen has been removed by the mechanical harvester with little or no disturbance to spruce (Nonnan Denney, pers. com., February 1988). Although added supervision of felling and skidding operations appears to be an extra cost, it can be offset by savings realized when designated skid trails are used instead of creating a new skid trail with each trip of the equipment.

Criteria for Deciding on the Balance between Hardwoods and Softwoods in the Next Rotation

A review of ecosystems with potential for aspen management confirmed that although aspen occurs over a wide range of site conditions it grows well in a much narrower range of sites (Corns 1989). Furthermore, its presence may be as much due to stand history as to site. The relative distribution of softwoods and hardwoods can be influenced not only by harvesting but also by fire history. Careful consideration should, therefore, be given to aspen's role in the next rotation. For example, in seral aspen ecosystems in northeastern British Columbia on subxeric, nutrient-poor aspen–kinnikinnick (*Arctostaphylos uva-ursi*) sites, lodgepole pine is the preferred species for forest production. In contrast, on productive, subhygric aspen–black twinberry (*Lonicera involucrata*) sites, aspen and balsam poplar are the preferred species for the next crop (DeLong 1988). Policy decisions about allocation of land to either white spruce or aspen production may be facilitated by considering the relative site potential for each species, rather than simply deciding on the basis of which species happens to presently occupy the site (Corns 1989).

In Alberta, the policy to date is that if a mixedwood stand contains merchantable conifers it should be regenerated to conifers, with the assumption that aspen will regenerate anyway. Some foresters currently involved with aspen harvesting and management prefer a more active approach for identifying a specific boreal hardwood land base. It may still be appropriate to regenerate the new crop in the proportions of softwoods and hardwoods now present, but within those proportions decide where it is best to regenerate hardwoods and where best to regenerate softwoods (Denney 1988b).

Mixedwood silviculture should involve two separate objectives as far as the spruce component is concerned: the first objective is to reestablish mixedwood stands in which the goal is to set an absolute minimum of spruce stems per hectare, as a maintenance measure, not a regeneration measure; the second objective is to create and maintain some pure coniferous stands. There is a perception that if these objectives are not met, present mixedwood stands will become hardwood stands and present coniferous stands will become mixedwood stands (Jack Wright, pers. com., April 1988).

Murphy (1988) stressed that administratively there are two very different situations in Alberta's mixedwood forests. In areas where hardwood harvesting commitments have already been made, the main concern is how to meet timber supply obligations. Will there be an adequate supply of the desired mixedwood species to meet the demands at any given time? In contrast, on lands where there are not yet commitments for hardwood harvests the main question is how to plan to ensure flexibility of future options. Even if the management goal is to keep softwoods and hardwoods in approximately equal proportions to give market flexibility and ecological diversity, effort will be required to maintain the desired proportion of softwood within the total mixedwood resource. The silviculture decision model currently under development by Navratil, Phillips, and Morton (1990) is expected to be an aid for designation of areas for hardwood and softwood production.

There is an increasing consensus that much of the boreal mixedwood should remain as mixedwood (Shortreid 1991). At a 1988 mixedwood symposium, several speakers dealt with the problems created when two operators held overlapping cutting rights in the same area—one for conifers and one for aspen–balsam poplar (Samoil 1988). In a review of these circumstances, Beck et al. (1989) noted that if either operator functions as if holding sole rights to the area, unacceptable waste of the other species group would probably occur. One possible approach is for each land unit to be analyzed and placed in either a conifer or hardwood land base. Once designated, priority would be given to the designated type and the other type would be harvested only in ways that are not detrimental to the species of prime designation.

Beck and co-workers noted that although there are large areas of essentially pure conifer or pure hardwood where this policy works, there is also a vast area of mixedwood in the boreal forest where significant volumes of both conifers and hardwoods are growing together. For such areas there are still unanswered questions. For example, to which land base would one assign a stand with 50 m^3/ha of conifer on a rotation of 120 years, and 210 m^3/ha of aspen on a rotation of 80 years? In some cases the most practical solution may be to manage for both softwoods and hardwoods, and in other cases it may be most practical to manage either one or the other.

A commitment to maintain mixedwoods has important implications for reforestation goals. On mixedwood areas both conifers and hardwoods must be regenerated. A possible solution may entail a single harvester of the existing mixedwood stands being responsible for regeneration of both species in a manner conducive to maintaining or enhancing the total allowable cut. Future policies must recognize that aspen and other hardwoods are not worthless and that joint production of conifers and hardwoods in certain proportions will be the goal.

Most foresters seem to agree that boreal hardwood management would be simpler in the absence of conifers. However, there can still be management problems if balsam poplar and white birch are not used concurrently with aspen. For example, for OSB operations that do not yet use balsam poplar as raw material, there are operational problems because current inventory maps do not indicate where balsam poplar and white birch are located within mapped hardwood forest types, or the proportion of these two species in various boreal hardwood stands (Denney 1988b).

Conversion of Aspen or Mixedwood Stands to Conifers

Boreal mixedwoods are difficult and expensive to manage. Forest managers who decide to remove aspen from a site generally do so for one of two reasons—to increase white spruce growth by eliminating competition from large aspen (Johnson 1986) or to remove aspen suckers that are hampering spruce regeneration. Responses of boreal hardwoods to various silvicultural treatments are summarized by Coates and Haeussler (1986) where aspen and balsam poplar are viewed as competitors to conifers. Steneker (1976b) stressed that elimination of aspen from mixedwood stands requires nothing less than the removal of all aspen root material. Herbicides kill aboveground portions of aspen, but most herbicides do not prevent suckering. Total removal of aspen probably requires a number of steps including girdling of aspen 2 years prior to clear-cutting them, intense scalping with a bulldozer blade or with plowing equipment to rip up aspen roots, and then applying herbicides to any suckers that do emerge in the first 2 or 3 years (Hambly 1985).

Girdling remains an economically and environmentally attractive alternative to chemical methods for aspen removal in mixedwood stands. This involves removal of a band of bark and cambium around the tree. By blocking the transport of photosynthate, girdling starves the roots and kills the tree. Effective girdling requires that the cambium be completely severed. Girdles that encircle the stem should be about 2 cm wide and 0.3 cm deep. Girdling should be done when root reserves are lowest, which is in early spring or summer when trees are growing actively, or just before bud break. Girdled aspens take from 1 to 4 years to die. Girdling can be performed with a number of tools, including hatchets, chainsaws, the Vredenburg girdler, and chain girdlers. The diameter of aspen stems determines which tool is most appropriate. More than one tool may be required for a stand if there is substantial variation in stem diameters (Bancroft 1989).

In mixedwood stands where establishment of conifers is the goal, site preparation has often included removal of residual hardwoods. If the density of residual hardwoods is high, access by mechanical site preparation equipment is hampered (Heikurinen 1981; Leblanc and Sutherland 1987; Puttock and Smith 1987). Simply knocking down residual trees during site preparation impedes the movement of tree planters. To overcome these difficulties, one approach is to use bulldozers equipped with Young's teeth to uproot and push residual hardwoods into windrows together with stumps and other slash. The cleared corridors between windrows improve access for tree planters and workers involved with subsequent silvicultural steps such as application of herbicides. In this context, recent site preparation trials in dense residual aspen stands near Ramsay, Ontario provide an example of the difficulties associated with removal of residual hardwoods (Puttock and Smith 1987). In these particular trials, Model 4A Young's teeth were mounted on the blade of a Caterpillar D7G bulldozer in an attempt to remove all residual aspen stems as well as stumps and slash in preparation for planting jack pine. Although 79–98% of the cleared corridors were plantable, windrowing actually resulted in a 20–37% loss of total area plantable. These Ontario trials illustrate the need for more information on: optimum corridor width in relation to stand density of residual aspen, and the desirability and implications of felling, and skidding and piling of hardwood stems during logging operations.

If aspen stands are to be discouraged in favor of conifers, preharvest treatment may be preferred to postharvest control. Where dense aspen suckers delay the establishment of conifers, the traditional approach has been to control aspen after the suckers have developed. Postharvest treatment can be expensive and is not always effective. There is therefore interest in an alternative, preharvest control that is cost effective and environmentally acceptable. Preharvest treatments are currently being tested in British Columbia mixedwood stands that contain aspen (Bancroft 1989).

One method being tested is the application of glyphosate after the growing season when transport of the chemical to the roots is greatest. The recommended rate is 1 mL of 100% glyphosate per 5 cm dbh, applied directly into an axe wound on the stem. A variation of this approach is to inject or directly screw into the target tree one capsule per 5 cm dbh, with each capsule containing 1 mL of glyphosate. The injection approach results in high rates of defoliation and death of target trees in 1–3 years. The chances of environmental contamination and worker contact are also low when capsules are used (Bancroft 1989). Bancroft did not indicate if this method of application will kill the clonal root system.

Another chemical control method involves injection of hexazinone (liquid Velpar) into the forest floor. Chances of soil contamination are high because hexazinone is soil-mobile, although it is degraded by microorganisms and light in 1--6 months. It should not be used on rocky, gravelly, sandy, or frozen soils, or on exposed subsoil. Deep organic layers and clay reduce the movement of hexazinone due to the high cation exchange capacities of these horizons. The manufacturer recommends that concentrated Velpar (0.75–1.5 mL per 1 cm dbh) be applied within 0.5 m of the root collar of the target tree. Application points should be at least 1.0 m from desired conifers to prevent possible damage to them. Best results occur if the soil is moist at the time of application, and if 0.6–1.2 cm of rain falls within 2 weeks. One to 4 years is needed to control aspen with hexazinone before crop harvest (Bancroft 1989).

At the time that Malik and Vanden Born (1986) prepared their review, the following herbicides were registered for forestry use in Canada:

Registered herbicides	Size of treatment area (ha)	Purpose
2,4,5-T; two formulations of 2,4-D; 2,4-D + 2,4,5-T; glyphosate	FMA[a] >500	Site preparation and conifer release by ground and aerial application
2,4-D + 2,4,5-T		Site preparation by aerial application
Two amine formulations of 2,4-D		Individual tree treatment (hack and squirt)
Hexazinone; asulam; amitrole; six formulations of simazine	FMA <500	Site preparation by ground application

[a] FMA = Forest management area.

If harvested aspen stands are made up of relatively old stems, root suckers are the predominant form of regeneration but harvesting of younger stands results in a significant proportion of root collar sprouts. If an aspen manager wishes to limit the number of root collar sprouts, the herbicide amitrol has successfully been used to limit sprout production (Horton 1984). In Horton's Ontario trials, however, the herbicidal reduction of root collar sprouts that was evident 1 year after application was expected to be offset by additional sucker production in later years. Horton suggested that if herbicides were to be applied to limit suckering of poor clones, basal spraying of trees before cutting or stump spraying following root suckering were probably the most reliable methods. Whether herbicidal treatment of aspen is for the purpose of stimulating sucker regeneration or for conifer site preparation, the most effective time of application is soon after aspen reaches the full-leaf stage.

From 1979 to 1986, there were attempts to convert about 35 000 ha of aspen and poplar stands to coniferous plantations in Alberta. The sites were cleared, windrowed, burned, often mechanically site-prepared, and then planted. On many of these sites the deciduous species have reestablished and provide serious competition for the young conifers. The forest manager has few options for controlling competing deciduous species because herbicide use is generally limited. Removal of aspen and balsam poplar suckers with clearing saws is costly and is only suitable when conifers are taller than 1.5 m. Where the goal is to reduce aspen competition in favor of coniferous regeneration there are several nonchemical methods that have given good results. For example, Ehrentraut and Branter (1990) indicated that in Alberta's boreal forests double disking of moist sites often controlled aspen regrowth for up to 5 years, by which time white spruce seedlings can reach a height of 1.5 m; on moist-to-wet sites, Marttiini plow scarification can reduce aspen suckering to one-third of its original density; and on wet sites that are accessible only in winter, aspen has been controlled for several years by use of a ripper plow.

Another alternative, involving mowing to reduce aspen competition in young spruce plantations was described by Holmsen (1989), based on two test blocks near Fort Vermilion, Alberta. Deciduous stems averaged 195 cm in height and 1.8 cm in diameter; spruce stems averaged 31.6 cm tall and 28.6 cm tall in the two blocks, with stem diamters averaging 0.4 cm. Mowing heights were 71 and 83 cm on the two test blocks. Deciduous stems were reduced from 39 500 to 5365 stems/ha on one block and from 32 600 to 2945 stems/ha on the other. Although the entire aspen cover was not removed, the mowing trials did clear swaths along the Bräcke mounds where spruce seedlings were located. The shade provided by residual aspen was thought to be beneficial in preventing sunscald to spruce seedlings. The tractor-mounted mowers did not significantly change the stocking of spruce seedlings on either test block. Where there was damage to spruce seedlings it was a result of burial by debris. There were 1055 spruce stems/ha on one block and 1100 stems/ha on the other; less than 1% of these planted spruce were physically damaged by the tractors or mowing units 2 years after the spruce were planted. Most of the damage to spruce seedlings occurred in turning areas. One year after mowing, most severed aspen stems supported new growth in the form of one or two shoots. The cut aspen stems had a high incidence of the fungi *Venturia* spp. and *Cytospora* spp. Holmsen expected the effects of mowing to be temporary.

A more recent report by Ehrentraut and Branter (1990) revealed that gyro-mowing of aspen in young Alberta spruce plantations costs an average of $70/ha and that one machine could mow about 17 ha/day. They observed that much of the resulting aspen mortality is caused by bark scraping and stem mutilation. Aspen stems that are not knocked down by the mowing develop enough apical dominance to prevent suckering.

For the mixedwood silviculturist, tractor-mounted mowers are an economically viable alternative to clearing saws. The use of mechanized vegetation control is limited, however, by several factors including size of the aspen, size of spruce seedlings, site and soil conditions, and site accessibility. As with clearing saws, mowing requires one or more repeat treatments to effectively control aspen competition.

Aspen–Balsam Poplar Management in the Absence of Conifers

In general, balsam poplar exceeds aspen in growth rates and maximum size (MacLeod and Blyth 1955; Slabaugh 1958), and also in longevity (Roe 1958). One of the earliest accounts of these species in Alberta indicated that balsam poplar lives longer than aspen and eventually dominates sites stocked by a mixture of the two species (Moss 1932). More recently, however, Morris and Farmer (1985) expressed the opinion that on most sites that are suitable for concurrent establishment of aspen and balsam poplar seedlings, aspen will dominate. These conflicting hypotheses require field verification in the prairie provinces and under a variety of site conditions.

Although balsam poplar is more exacting than aspen in its site requirements (Maini 1968), site preferences for these two species do not seem to be sufficiently different to warrant separate silvicultural treatments. Balsam poplar's prominence on some newly formed alluvial sites may be more related to flood tolerance than to its growth rate relative to aspen. In some cases, the relative success of aspen and balsam poplar may be influenced by the time that a suitably moist seedbed becomes available, since aspen disperses seeds earlier in the season than balsam poplar.

Until recently there was uncertainty about the use of balsam poplar as a profitable species (such as aspen) in the forest industry (Ondro and Bella 1987), but this problem is expected to diminish as balsam poplar is increasingly accepted by the forest industry. For example, two newly announced pulp mills in Alberta will be using both aspen and balsam poplar. With increased harvesting of balsam poplar, several other questions arise about its regeneration silviculture, treatments to encourage this species, and density and stocking requirements for optimal growth. There is little information on growth and yield in second-growth balsam poplar or in mixed stands of balsam poplar and aspen (Navratil, Bella, and Peterson 1990).

There are examples of aspen stands in western Canada where most remaining trees are decadent because of previous removal of the best aspen. This is most prevalent where aspen has been harvested for veneer, such as near Hudson Bay, Saskatchewan, where many stands may now be beyond any utilization potential. About 182 000 ha of mixedwood and 265 000 ha of pure aspen stands in Saskatchewan have reached an overmature and decadent stage (Alfred Kabzems, pers. com., January 1988). Similar after-effects of high-graded aspen stands are also evident in the Lesser Slave Lake area of Alberta. In some cases, such stands have an understory of younger aspen, creating uneven-aged or two-aged stands.

High-grading as a cause of uneven-aged stands is not expected to be a long-term problem. This practice is less common than it once was, partly because aspen veneer production is greatly reduced. It is now also recognized that clear-cutting is the most suitable way to achieve aspen regeneration, and selective removal of individual aspen or balsam poplar trees may soon be a practice of the past. Lastly, there will be less incentive to high-grade as technological changes encourage the use of all species and all size classes in panelboard production. For example, recent studies into the use of juvenile hardwood species for OSB production, involving 2- to 3-year-old black locust and sycamore, suggest that use of branches and small stems is commercially viable (Russell 1988).

Sampling of woody species in the prairie provinces confirmed that unmanaged dense stands of shrubs or young trees can reach very high standing crop values in a short time (Peterson et al. 1982). As young stands take on a commercial value for panelboard or pulp production, high-grading will not be the problem; the ecological consequences of harvest removal of all size classes of all woody species will be of more concern.

Uneven-aged stands can develop from causes other than high-grading. Aspen stands that have escaped fire for 90 years or more may have an advanced understory of aspen, often in the range of 40–50 years, and there is also sometimes another very young layer of shrub-height aspen suckers. The circumstance under which these multistoried aspen stands occur have not been well-documented in western Canada. Experience in Alberta indicates that multiaged aspen stands are the most difficult of all to manage (Norman Denney, pers. com., February 1988). The most direct remedy would be conversion to single-aged stands.

In circumstances where deteriorating aspen stands cannot be harvested early enough to avoid stand breakup, it should be recognized that there are other ecosystem roles for these old stands such as wildlife habitat, retention and recycling of on-site nutrients, or simply as a carbon sink.

Compared to aspen, management of the balsam poplar component is poorly developed to date. This is significant because in many hardwood stands in Alberta as much as one-third of the basal area in stands identified as aspen is actually balsam poplar. As a wildlife browse species, aspen is considered to be superior to balsam poplar. For this reason, it is important to know if preferential removal of aspen (the present practice when aspen–balsam poplar mixed stands are harvested for some of Alberta's OSB plants) will lead to a long-term decrease in the amount of available aspen browse. For the next forest crop and for wildlife habitat management, is it more desirable to leave the residual balsam poplar standing? Long-lasting veterans of balsam poplar are important for cavity-nesting birds but probably provide no habitat advantage for ungulates (Edward Telfer, pers. com., February 1988). In cases where balsam poplar is felled but not used, there are not yet guidelines on how best to segment or handle the felled material for maximum benefit to wildlife.

What influences do the two alternatives of leaving or felling the residual balsam poplar have on the subsequent vegetative regeneration of aspen and of balsam poplar? Observations to date suggest that residual standing balsam poplar is not stimulated to sucker when aspen is harvested from aspen–balsam poplar stands. Shading from residual standing trees, of any species, however, can reduce the amount of suckers (Maini and Horton 1964). Some Alberta Forest Service foresters are concerned that shading from residual balsam poplar may need to be regulated to ensure adequate aspen suckering, but industrial foresters interviewed in 1988 (Peterson et al. 1989a) had not yet observed this as a deterrent to aspen regeneration. In Minnesota, residual white birch and balsam poplar have been observed to have little influence on aspen suckering as long as they are scattered; these species do, however, inhibit aspen suckering if the residual trees occur in dense groves (Donald Perala, pers. com., January 1990). Some foresters dislike standing residual balsam poplar because they are an obstacle to site preparation. For future operations where both aspen and balsam poplar are removed simultaneously for industrial uses, the previously outlined uncertainties will be relatively unimportant. Where there is interest in preferential encouragement of either aspen or balsam poplar in the next crop, however, much has yet to be learned.

The appearance of cutover areas is a matter of public concern. Where balsam poplar and scattered decadent aspen are left uncut, often in combination with residual understory spruce below usable size, harvested areas may appear wasteful and messy, particularly to urban observers. This is less of a problem if the understory spruce is fairly tall, and if it can be preserved during harvesting of the overstory, together with effective slash disposal practices. The public perception of wasteful and careless practice is a major problem for boreal mixedwood foresters because this forest zone is relatively close to large urban areas in western Canada.

Aspen's intolerance to shade is of fundamental importance to the forest manager because the one feature of the physical environment that a forest manager can influence markedly is the amount of light in a specific environment. This is particularly true for aspen, a species whose intolerance to shade and physiological requirements for suckering dictate even-aged management systems using clear-cutting to maintain the stand at full productivity (Perala and Russell 1983). Single tree or group selection silvicultural systems discriminate against long-term maintenance of aspen ecosystems. Shelterwood or seed-tree systems are not needed and, furthermore, shading by residual stems is detrimental to sucker growth. The review by Perala and Russell (1983) indicated that openings about 0.4 ha in size are the minimum size acceptable for conditions that will stimulate aspen suckering; however, clear-cuts of at least 16–20 ha are needed for efficient harvesting. Maximum clear-cut size has no silvicultural limit, but size is often constrained to openings in the range of 4 to 8 ha for other multiple resource considerations. Despite widespread public dislike for clear-cutting, aspen managers can not escape the constraints of aspen's requirement for full light in order to achieve acceptable regeneration and growth.

Aspen–Balsam Poplar Management to Minimize Disease and Insect Losses

Maclean (1990) gave estimates that place aspen's insect and decay losses in perspective relative to total losses from these causes in all of Canada's forests. From 1977 to 1981, an estimated 107 million m^3 of timber were lost in Canada to insects and diseases each year; spruce budworms caused 41% of this loss, wood decays 23%, *Hypoxylon* cankers 10%, aspen defoliators 7%, mountain pine beetles 5%, and miscellaneous defoliators, bark beetles, and diseases caused the remaining 14%. To date, insect losses have not been of commercial importance for the aspen and balsam poplar resource of the prairie provinces and northeastern British Columbia. Although research is underway to develop expert systems to aid insect pest management in boreal mixedwood ecosystems (Volney 1990), currently artificial control of major insect pests on aspen is not recommended except in special instances where registered insecticides may be applied to stands or individual trees. Natural controls of insects include unfavorable weather, parasites, predators, and diseases (Davison et al. 1988).

Unlike the case with insects, diseases are of major importance to foresters managing aspen and balsam poplar. As described by Navratil, Bella, and Peterson (1990), decay estimates and cull prediction in aspen and balsam poplar remain as problems, partly because of the biological complexity of tree–decay relationships and partly due to inconsistency among the decay studies (Basham 1987; Navratil 1987; Hiratsuka and Loman 1984). Both of these tree species are extremely variable and unpredictable in wood quality because of stem decay (Fig. 48). There are strong economic incentives for more accurate estimates of cull in aspen and balsam poplar and several studies are in progress. The Alberta Forest Service is searching for criteria that would aid identification of rot-free aspen stands, and Forestry Canada's Northern Forestry Centre has recently published a guide for classification and measurement of aspen decay and stain (Hiratsuka et al. 1990).

Alberta studies indicate that white heart rot (*P. tremulae*) is the most common decay organism in boreal hardwoods; it is more prevalent in aspen than in balsam poplar (Woodbridge, Reed and Associates Ltd. 1985).

Figure 48. It is still difficult to predict cull without examination of the internal condition of aspen stems, even if there are no external indicators of decay (photo courtesy of Sask. Govt. Photo by Les Robinson).

Although the significance of decay to commercial use of aspen is well documented, one remaining problem is how to predict the extent of decay in existing or future hardwood stands. A major complication is that decay is unpredictably distributed throughout the tree. A review by Hiratsuka and Loman (1984) confirmed that decay and stain are two major factors limiting utilization of aspen and balsam poplar in Alberta, and this is corroborated by representatives of the pulp and paper industry (Breck 1987) and the OSB industry (Anderson 1987; Denney 1987). Decay and stain influences on aspen utilization continue to create uncertainty among those who produce, manage, and use this resource.

Although there have been dozens of aspen decay studies, a problem remains because aspen decay estimates from different studies are rarely comparable. Loman (1987) recognized three reasons for these inconsistencies. First, existing tables to show age–decay relationships have been assembled using data from wide-ranging study sites to ensure that all age classes are sampled. Such sampling introduces complexities as a result of different site qualities and stand histories. Second, there are inconsistencies among investigators in their classification of mineral stain, incipient decay, and advanced decay. Third, different investigators use different criteria for the percentage of decay required for an entire log to be rejected. The classification and measurement guide prepared by Hiratsuka et al. (1990) will provide a standard method for decay and stain sampling.

Present forest inventories indicate that many aspen stands in the prairie provinces and northeastern British Columbia are too old to use, and many others are too young to use. With present utilization standards there is actually a relatively narrow range of age classes in which the trees are of suitable size and still without severe decay. Fortunately, kraft pulping and OSB production are more tolerant of aspen stem decay than are other uses such as lumber, veneer, or specialty products.

Cull from decay is important for utilization standards for certain forest products, but a sustainable supply of aspen raw material for the wood-using industry is also influenced by other variables such as stand breakup. To give one example, during several years of aspen-harvesting operations, foresters for Pelican Spruce Mills Ltd. in Alberta have not encountered aspen that was too decayed to use in the manufacture of OSB. In this case, the operation is not faced with cull problems; a greater concern is the reduction of total yield when there is natural thinning and stand breakup to the point that there are sometimes as few as 120 large aspen trees/ha (Norman Denney, pers. com., February 1988).

The influences of aspen stand management practices upon the incidence of *Hypoxylon* infection is of concern to managers. There is now some evidence that previous observations of higher *Hypoxylon* incidence in thinned aspen stands may not be applicable in all regions where aspen occurs. Forestry Canada researchers have observed sample plots on the south end of the Porcupine Hills, near Hudson Bay, Saskatchewan, where there was a very high incidence of *Hypoxylon* on heavily thinned aspen plots. These were in 50 year stands that had been thinned at age 13. In some thinned plots there were hardly any trees left. Another set of plots in which aspen, 40 years old at the time of observation, had been thinned and pruned at age 25 also had high incidences of *Hypoxylon.* Circumstances may be different, however, in the part of aspen's range where its growth is optimal. For example, researchers in Ontario did not observe greater *Hypoxylon* incidence, 10 years subsequent to thinning, as one progresses northward within aspen's range in that province (Navratil and Bella 1988). Relationships between *Hypoxylon* incidence and thinning intensity have not yet been documented for northeastern British Columbia and the western part of aspen's range in the prairie provinces. There are indications that in Minnesota the incidence of *Hypoxylon* varies more by clone than it does by stand density (Donald Perala, pers. com., January 1990).

Foresters do not normally attempt to control population levels of forest tent caterpillar; outbreaks are simply allowed to run their own course. Ornamental trees or shrubs and high value aspen stands in parks or residential areas may, however, be high priorities for foliage protection through use of insecticides. Chemical sprays will also reduce the nuisance of wandering caterpillars in resort areas, towns, and around farmyards (Hildahl and Campbell 1975).

In circumstances where chemical control of this insect is contemplated, Hildahl and Campbell recommended that a manager should first know whether caterpillar populations are going to remain high. This is done by examining the abundance of newly-laid egg bands on aspen trees (Fig. 35C). A commonly used procedure is to fell three representative aspen trees at each sample location, examine the branches to ascertain the average number of egg bands per tree, and relate the number found to the diameter of the tree at breast height as indicated in the following table. If insecticides are used, they should be applied in late May or early June while the larvae are still small and before defoliation becomes advanced.

Dbh cm	No. of egg bands that will cause complete defoliation
2.5	2
5.0	5
7.5	9
10.0	11
12.5	14
15.0	19

There are indications that the bacterium *Bacillus thuringiensis* (Bt) is the best prospect among several biological ways to control forest tent caterpillar (Ives 1984). Commercial applications of Bt are economically competitive with chemical insecticides and applications are environmentally safe. Two applications seem to work best, spaced about 1 week apart, and timed for the first application to coincide with larvae at the second instar stage, a stage that lasts only a few days. *Bacillus thuringiensis* has also been tested in Alaska for control of defoliation by the large aspen tortrix (Holsten and Hard 1985). Use in urban settings may have more interest as the current potential impact of the large aspen tortrix is on high-value trees in urban or residential areas. Hulme (1988) considered Bt as one of the success stories of applied biological control in relation to 21 forest insect pests reviewed.

Aspen–Balsam Poplar Management to Meet Product Standards

There are several variables that the forest manager can control to meet certain product standards. For decay-prone species, such as aspen and balsam poplar, management to achieve an appropriate age-class structure is the most important step. Some products require stem dimensions of a certain minimum size and most present-day products require stems to be harvested before significant decay occurs. Aside from size and age-class manipulation, the manager has some flexibility in the mix of species harvested, subject to requirements of the manufacturing process. Although not yet practical, genetic selection of traits desirable for certain products is a third variable of potential interest to the forest manager. Since each clone apparently has its own distinct decay pattern (Hiratsuka and Loman 1984), a search for minimum decay will probably be a high priority criteria when genetic programs for aspen are expanded.

As a wider range of products tolerate the incorporation of aspen bark, specific product standards will become less important. Even if bark must be removed, there are now debarkers available to handle 10–15 aspen stems at once, including stems down to 10 cm in diameter. With equipment and manufacturing processes capable of handling such small pieces, a forest manager can concentrate on how to maximize total volume at any particular diameter desired above 10 cm.

The traditional forestry concept that large trees are inherently more desirable is outdated. Forest managers and developers of forest harvesting equipment now recognize that neither large trees nor extensive monocultures are required for efficient logging and delivery systems. In fact, large trees may raise costs substantially. Stand densities that capture a site's yield capacity quickly in medium-sized trees are considered by some managers to be a practical compromise to minimize production costs (Garner 1988).

Producers of OSB have developed methods to adapt to varying amounts of decay in aspen stems. During waferizing, stained or rotten wood does not cut cleanly; poor thickness control during waferizing occurs because the strand geometry is not as closely controlled as in sound wood. Furthermore, in summer the rot in logs tends to soak up water more rapidly than surrounding wood, creating additional energy requirements to dry the rotted material. Rotted ends of logs also harbor more sand and stones than normal wood, and these impurities shorten the life of the waferizing knife. In the blending phases of OSB production, the fines that result from rotted wood require more resin than normal; in particular, wafers of rotted wood soak up resin rather than keeping it on the surface to create a bond. The reduced surface bonding is accompanied by lower bending strengths in boards that contain rotted wood (Norman Denney, pers. com., February 1988).

For OSB production, logs with up to 50% incipient or advanced decay can be used, not because the finished product can accept that amount of inferior wood but because the manufacturing process effectively separates the lower quality wood. When the flaker knife hits rot, the rotted wood is broken into relatively small pieces that move with the flakes to the driers. Driers are operated near the flash point of the flake wood and much of the crumbled wood ignites. Any pieces of rotted wood that do not ignite are screened and then hammered in a mill, with the resulting material used as an energy source for heaters (Denney 1988b).

There are other disadvantages of decayed wood. Aspen wood for Alberta's OSB industry is bought on a firm net wood basis, which poses economic hardship on a logging contractor who harvests wood with a lot of cull. An advantage of short-wood harvesting is earlier and more accurate detection of cull in the bucked material, with the opportunity to reduce transportation costs by leaving cull logs at the harvest site (Denney 1988b).

Industries currently involved with aspen pulp production are aiming for a high quality pulp, a goal that is bound to influence aspen stand management. For example, Barr (1987) cautioned that if aspen is managed under the traditional "cut-the-oldest-first" policy, the aspen industry will be stifled just as it is getting off the ground. Generally, since aspen pulp commands lower prices than coniferous pulp, the delivered cost of aspen is critical. There is a need to achieve the highest yields possible from the aspen that is delivered to the mill. The ideal would be to deliver only logs with little or no rot. This ideal is not yet achievable because of difficulties in differentiation of decayed and sound trees in the field.

Aspen's appeal as raw material for pulp is a result of its distinctive wood chemistry and physical properties (MacLeod 1987), rather than a result of any silvicultural steps carried out to date. Aspen's low lignin content and high carbohydrate content are conducive to both chemical and mechanical pulping (Breck 1987; Law et al. 1987). In addition, aspen's small-diameter, thin-walled fibers are well suited for production of high-density paper with a smooth surface (Wong 1987).

Recent trends in satellite chipping also indicate that there are no stringent silvicultural steps needed to produce boreal hardwoods for pulp production. For example, Alberta Newsprint Co. Ltd. in Whitecourt, Alberta, is the first mill in western Canada to delimb and debark small-diameter hardwoods and softwoods for pulp production. The long-term potential for satellite chipping lies in its opportunities to provide employment in communities a considerable distance from the site of pulp production (Sims 1989). It will also encourage use of presently unusable young stands without any special silvicultural expenditures.

Aspen genetics may have a future role in meeting certain product standards because distinct aspen clonal differences have been determined for both wood density and fiber length based on a study of clones from north-central Alberta (Yanchuk 1982; Yanchuk et al. 1983, 1984). In the Lake States, the effect of clones accounted for 35% of the variation of wood density and 43% of fiber length (van Buijtenen et al. 1959; Einspahr et al. 1963). An observation of practical importance is that 4-year-old suckers that exhibited long fibers also had long fibers at later ages, a characteristic that could aid early detection of preferred clones if fiber length were of interest to the users of the aspen resource. Kennedy (1968) suggested that the selection of clones possessing both fast growth and high wood density may be an important objective. As long as there is an abundant supply of natural, unmanaged stands, however, such selection criteria will have little bearing on aspen silviculture and management. Where there are circumstances to warrant future plantations of superior clones, genetic encouragement of desirable features to meet product standards should be an integral part of the propagation program.

Wood quality is commonly a concern when growth is rapid, but this does not appear to be the case with aspen. Pronin and Lassen (1970), in reviewing and evaluating the relationship between site quality and specific gravity of Lake States aspen, found there was no consistent relationship and concluded that volume growth could be emphasized without concern for specific gravity variation associated with site quality. Although clones accounted for over 40% of the variation in fiber length, there was a positive correlation in young aspen between diameter growth and fiber length and between height growth and fiber length. These results suggest that measures taken, either genetically or environmentally, to improve growth rate will result in improved fiber length.

Recent advances in the manufacture of specialty products from polymerized aspen have also revealed that clonal differences may be important. In certain circumstances, there may be a preference for clones that have as small a heartwood core as possible. For example, the best raw materials for manufacture of specialty products, such as hard-surfaced table tops, from polymerized aspen are stems 20–30 cm in diameter with a small proportion of heartwood (H. Godwin, pers. com., July 1988).

Methods to Achieve Regeneration of Aspen and Balsam Poplar

There is not widespread public awareness that regeneration strategies are fundamentally different for the manager dealing with aspen and the manager dealing with conifers (Borset 1960). In the case of conifers, one method is to leave some of the best trees as seed sources for the next crop. For aspen this method is less reliable because the manager's regeneration strategy is normally not by seedlings. For aspen it is the stems that are cut, not the ones left behind, that produce the next crop through the production of suckers. To leave the best clones uncut could in fact contribute negatively to the characteristics of the next aspen crop. Where harvest removal is on a stem basis, instead of by whole clones, the selection of which stems to remove is less important since both residual and removed stems have the same genetic makeup. The significant point is that the idea of leaving what are thought to be genetically superior seed trees is not an important management tool for aspen.

The commonly vigorous suckering of aspen and balsam poplar after harvesting or fire, and the abundant literature on the subject of stand regeneration by suckering, have contributed to a complacency that forest renewal is not very difficult for these boreal hardwoods. Recent operational experience, however, such as that described by Smith (1989) for Weyerhaeuser's Saskatchewan harvesting area suggests that mixedwood regeneration may be more difficult than previously thought. Regeneration of boreal mixedwood species is increasingly viewed as an ecosystem management problem instead of a technical problem of how to get seedlings and suckers reestablished after harvesting. Wood volume can be reachieved by a monoculture approach, but there is increasing recognition that mixedwood ecosystems contain hundreds of other species of shrubs, herbs, mosses, lichens, large and small mammals, insects, and soil organisms. Therefore, in the long term regeneration methods need to address ecosystem quality as well as wood quality (J. Stan Rowe, pers. com., June 1990).

The rapid and dense growth of deciduous woody species after harvesting is often a mixture of aspen, balsam poplar, willow, alder, birch, red-osier dogwood, and hazel. Currently only the first two of these species are of industrial interest. Therefore, if aspen and balsam poplar are the desired hardwood species, silvicultural efforts may have to be altered to take these species into account. There are, of course, other factors to consider in the silvicultural manipulation of such mixes of early-succession deciduous woody species. For example, the wildlife value of willow, dogwood, or alder may in many places be more important than the goal of concentrating biomass accumulation in only aspen and balsam poplar.

As described by Navratil, Bella, and Peterson (1990), there are some circumstances where aspen regeneration is hampered; compaction of moist, fine-textured soils can limit aspen regeneration, as can shrub and grass competition. The most effective regeneration by suckering occurs on well-drained soils and, providing the prerequisite aspen root system is present throughout the harvested area, any steps that allow extra heat and light to reach the forest floor will maximize sucker density (Perala 1977). In general, the best silvicultural practices in aspen appear to be those that leave the parent root system intact. Root suckering is expected to remain as the most practical way for managers to regenerate aspen. Clear-cutting stimulates more aspen suckers than does partial cutting (Schier et al. 1985; Navratil, Bella, and Peterson 1990); however, under a broad range of harvesting conditions satisfactory stocking and density of aspen is usually achieved. Some foresters have suggested that aspen sucker production can be stimulated by disking, but trials to verify this on a variety of sites are needed in the prairie provinces and northeastern British Columbia, particularly since there is other evidence that site preparation by disking damages aspen root systems and deters sucker development (Perala 1972; Basham 1979, 1982b; Fletcher 1985). In most cases, particularly for stands over about 25 years of age, the aspen forest manager will be involved with suckers of root origin; however, if stands are harvested at ages younger than 25 years, there is a relatively higher proportion of sprouts clustered around stumps and root collars (Maini 1968). Sprouts of stump and root collar origin are shown in Figure 17.

Aspen Stocking Standards

Aspen stocking standards are still undergoing development. The thinking a decade ago is exemplified by the following excerpt from the 1980 version of Ontario's silvicultural guide for aspen (Heeney et al. 1980):

> ...6000 aspen stems per acre (14 800 stems per hectare) will give 90% stocking by mil-acre quadrats. Adequate stocking of 80% at 5 years of age can be obtained from as few as 1000 stems per acre (2500 stems per hectare), if they are uniformly spaced over the area. Very high density stands up to 60 000 stems per acre (148 000 stems per hectare) are sometimes encountered. This high stand density is reduced rapidly through natural mortality to: 5000 to 6000 stems per acre (12 350 to 14 800 stems per hectare) at 5 years of age and 1000 to 1200 stems per acre (2500 to 2960 stems per hectare) at age 20.
>
> Stocking standards
>
> i. Regeneration period: 5 years
> ii. Acceptable species:
>   - primary: aspen of good quality
>   - secondary: spruce, white pine, balsam fir, white birch, jack pine
> iii. Desirable stocking:
>   The following conditions should be met:
>   - more than 80% of stand should be aspen
> iv. Desirable trees per acre:
>   - more than 6000 aspen trees per acre (14 800 stems per hectare)
> v. Failure:
>   If any of the following conditions apply:
>   - less than 50% stocking of aspen
>   - poor quality aspen
> vi. Release: not required

An earlier version of *Silvicultural Guide to the Poplar Working Group* (Davison et al. 1988) recommended that forest renewal operations are not normally required for the successful establishment of a new forest of aspen. Clear-cutting followed by natural aspen regeneration will normally provide adequate stocking and growth. Nevertheless, free-to-grow standards for forest renewal of aspen in Ontario were suggested. The following free-to-grow benchmark standards have been specified by Davison and co-workers for aspen regeneration in northwestern Ontario:

Renewal treatment: natural
Free-to-grow minimum stocking: 60%
Objective stocking: 70%
Acceptable species: aspen
Minimum total height: 1.0 m
Recommended time of assessment: 3 years

For the prairie provinces, Steneker (1976b) suggested that a stocking of 6000 evenly-spaced suckers/ha during the third year after harvesting will be adequate for fiber production; for lumber production, there should be about 2500 stems/ha at age three. For Ontario, Hambly (1985) suggested that at age 5 a minimum of 2500 well-spaced stems/ha should give 80% stocking but the preferred goal is 15 000 well-spaced stems/ha for 80% stocking. The Ontario guidelines recognize that the density of natural aspen regeneration after clear-cutting is controlled mainly be aspen stocking of the parent stand. For Ontario conditions, a minimum of about 40 parent aspen stems/ha is considered enough to produce the minimum acceptable stocking, but about 120 parent stems are required to regenerate fully-stocked stands of aspen. The literature indicates that the age of the parent stand does not affect suckering capacity significantly. Table 37 summarizes an example from Alberta that

Table 37. Number of trees/ha, by age class, on good, medium, and poor sites, in fully-stocked stands of pure aspen in Alberta (MacLeod 1952)

Age	Grande Prairie to Lac La Biche, Alberta		
	Good	Medium	Poor
10	14 900	19 000	24 710
20	9 270	12 350	17 000
30	6 180	8 150	11 600
40	4 150	5 530	8 030
50	2 900	3 830	5 400
60	2 100	2 700	3 830
70	1 560	1 950	2 700
80	1 160	1 480	1 950
90	910	1 150	1 500
100	730	940	1 220
110	605	790	1 040
120	518	682	682

indicates the numbers of trees per hectare required for full stocking at various ages in pure aspen stands.

Juvenile stand surveys show that 50% of Alberta's cutover areas that were reforested to conifers have, after 10 years, reverted to stands with high densities of hardwoods, and another 14% have reverted to mixedwoods. Sampled hardwood densities commonly ranged from 2100 to 4500 stems/ha with some as high as 15 000 stems/ha (Henderson 1988a, b). The Alberta Forest Service is developing stocking standards for aspen and regeneration survey criteria for pure deciduous reforestation. Another area being reviewed is new reforestation standards for the mixedwood cutovers. Present stands provide for up to 10% deciduous stocking; however, the high regeneration capability of aspen is overshadowing the preferred coniferous species.

In Saskatchewan, former regeneration surveys focused only on the softwoods, although survey crews occasionally noted competition on the tally sheets. Some sites, previously considered understocked in terms of conifers can now be considered adequately stocked when the hardwoods, formerly termed competition, are counted. In essence, this means that the former concepts of productive and nonproductive forest types are being redefined because stocking standards are changing.

Minimum and target standards for hardwood stocking are not yet well defined. Free-to-grow standards for forest renewal of aspen have been drafted, but not published, in Ontario and northeastern British Columbia. In the Prince George Forest Region, aspen is a preferred species for stocking, along with white spruce and/or lodgepole pine, in some biogeoclimatic units. For those units, the draft guidelines for northeastern British Columbia specify 6 years as the earliest date at which aspen could be declared free-growing, and 9–12 years as the latest date. Target annual leader growth of free-growing crop trees on wetter sites is 80 cm for balsam poplar and black cottonwood, and 60 cm for aspen; on medium sites it is 60 cm for balsam poplar and black cottonwood, and 40 cm for aspen. On drier sites, target annual leader growth for free-growing aspen is 25 cm (Michael J. Connor, pers. com., May 1988). Alternative ways to define free-to-grow should be a subject of further study.

Part of the debate about stocking standards centers around the question of how many suckers are needed to ensure a fully stocked future crop. This question has been the subject of considerable debate (Perala 1972), but there is now a consensus that a wide range of early stand densities is acceptable for aspen management. One possible explanation is that there is a tendency to end up with a relatively similar stand density, in the range of 20 000 to 25 000 stems/ha, whether sucker density the first year after harvesting is as low as 44 000 or as high as 225 000 stems/ha (Table 6). For example, Bella (1986) noted that sucker density after the first growing season was twice as high after summer logging (exceeding 200 000 stems/ha) as after a winter cut. These large initial differences in stand density, however, diminished to 30% or less 5 years after harvesting (Fig. 19).

Brinkman and Roe (1975) suggested the following about early aspen stocking, based on work by Graham et al. (1963) and Sorensen (1968). Graham and co-workers had reported that 15 000–30 000 well-distributed suckers/ha are more likely to develop into a better stand than young stands with 85 000–100 000 stems/ha. Results of a thinning study in a 1-year-old stand of aspen suckers in Minnesota indicated that as few as 15 000 stems/ha may be more than enough. Sorensen's research indicated that areas stocked with from 2500 to 25 000 1-year-old aspen stems/ha will produce an adequate number of potential crop trees, and that lack of thinning will have little effect on their diameter. Later work by Perala (1979, 1984), however, suggests some qualifications for Sorensen's conclusion. First, crop trees cannot be identified until about 4 years of age. Second, there is also evidence that young suckers benefit from the protection of nearby neighbors. Perala (1979) also found that the continued removal of new suckers placed a stress on the root reserves and thus the young crop trees.

Influences of Parent Stand Density and Partial Cutting on Aspen Suckering

Sucker production is influenced by the stocking of the parent stand before cutting. Extremely poorly stocked aspen produce few suckers after logging because they do not have the necessary root densities. In Michigan, Graham et al. (1963) quantified the relationship between the basal area of parent stands and mean sucker production one year after clear-cutting as follows:

Original basal area of parent stand, m^2/ha	Mean no. of aspen suckers/ha 1 year after clear-cutting
<4.6	12 850
4.6–9.3	17 300
>9.3	24 450

Doucet (1989) suggested that in Quebec full aspen stocking can be achieved with a basal area of 5 m^2/ha in the parent stand as long as the aspen stems are no more than 8–10 m apart. When aspen stands are thinned immediately after establishment, additional suckering can be expected for at least 3 years (Strothmann and Heinselman 1957). Perala and Laidly (1989) cited several references that indicate that although very early thinning will promote more suckering, it is not a problem in stands 5 years or older. Perala and Laidly do not recommend thinning aspen at ages 5 or less.

In addition to the effects of original stand density on sucker production, the proportion of trees harvested also has an influence; partial rule cutting may hinder subsequent aspen suckering. A rule of thumb for the aspen silviculturist is that suckering is more or less proportional to the amount of overstory disturbance (Maini and Horton 1966; Shepperd 1986). Sucker formation is inhibited by substances called auxins, which are found in the growing tips of aspen. When trees are harvested or burned, this inhibition is removed and sucker formation is encouraged. What are the prospects for the next aspen crop if harvesting does not remove all aspen stems? Doucet (1989) reported that partial cutting may seriously inhibit suckering, involving two different processes. First, fewer suckers are produced because of the inhibition of suckering by auxins retained in the stems that are left standing. Second, shade from residual trees can reduce survival and growth of the highly shade intolerant young aspen in the understory. In some cases, postharvest slash can also hinder aspen sucker development (Shoup 1967, 1968; Bella 1986).

At least one recent analyst has challenged the preoccupation with clear-cutting for aspen regeneration (Ruark 1990). Based on his studies with Wisconsin aspen, Ruark suggested an alternative strategy for managing aspen, which he referred to as the reserve shelterwood system. This alternative is based on manipulation of ecosystem nutrient storage pools. It relies on leaving some dormant trees uncut to deliberately suppress the initial restocking levels, thereby directing more of the early rotation production into potential crop trees. For the Lake States region, Ruark (1990) recommended two steps: i) harvest the aspen stand at 32 years (the age at which mean annual increment for pulpwood is near its maximum) but leave 25–50 scattered residual dominant trees per hectare and reduce all logging slash to ground level; the residual trees are expected to transport enough auxin downward from the shoot and remove enough cytokinin from the roots so that density of aspen suckers will be reduced; ii) grow the regenerated stand for another 32 years, then harvest all of the 64-year-old stems that remain from the previous rotation along with all but some scattered 32-year-old dominants; reduce all logging slash to ground level.

Ruark believes that such a two-stage strategy would be better than a single-stage clear-cutting because the reduced number of aspen stems regenerated should result in a higher amount of production being placed onto crop trees at an early age. There may also be wildlife benefits because the two-aged stands would possess greater habitat diversity than single-aged stands. Ruark cautioned that such a reserve shelterwood system has not been widely tested yet, and he recommended it as a subject for further study.

The main stimuli for suckering—clear-cutting, brush removal, and soil disturbances—all result in higher soil temperatures. This raises the question of whether temperature-related stimuli for suckering are more readily achieved by logging in summer rather than winter. A general observation is that sucker density is usually adequate despite when logging is done (Doucet 1989); there are, however, recorded seasonal differences. In Saskatchewan, a greater sucker density after summer logging was attributed to increased soil temperature as a result of logging disturbance (Bella 1986). In contrast, in the Lake States and southern Rocky Mountains, sucker density was greater after winter logging because root carbohydrate reserves are greater in winter than in summer (Brinkman and Roe 1975; Schier 1981b). There is speculation that, in the southern part of aspen's geographic range, soil temperature may not be as critical to sucker formation as it is in cooler regions farther north (Schier 1976).

The additional shade created by slash can potentially lower soil surface temperature, which in turn can reduce sucker formation. Bella (1986) reported that following the harvest of aspen stands near Hudson Bay, Saskatchewan, sucker density was greatest where no slash cover occurred. Sucker density generally declined as the amount of slash increased from limbs only, to logs only, to limbs and logs. Average sucker density differed more, both relatively and absolutely, with slash condition after summer cutting than after winter cutting. Slash left by summer logging had the disadvantage of creating more shade than winter slash because of the foliage present; however, this effect appeared to be offset by the fact that summer logging disturbed the ground vegetation and humus more than winter logging did. As a result, areas logged in summer experienced warmer soil temperatures, which are known to promote root suckering. In terms of site differences, Steneker (1976b) reported that slash from clear-cutting was not a hindrance to sucker regeneration on fresh and moist sites, but on wet sites slash may keep temperatures below the optimum for suckering.

There are still some unknowns about aspen regeneration, particularly where harvesting results in drastic soil disturbances or very heavy shrub competition. For example, it has been observed in the Edson area of Alberta that summer logging with heavy equipment in wet conditions may compact the soil, damage aspen roots, and reduce suckering in localized areas (Imre Bella, pers. com., October 1988). Recognition of circumstances and site conditions in which this is a potential risk is a subject needing more documentation in the prairie provinces and northeastern British Columbia. The Expert Panel on Forest Management in Alberta (1990) also emphasized that there are some sites on which effective stocking of aspen should not be taken for granted. Sites where substantial amounts of balsam poplar or birch remain after cutting, especially if coupled with grass and shrub understory and possibly high water tables, may have poor natural regeneration of aspen. The Expert Panel singled out current surveys in Saskatchewan cutovers as old as 25 years, which indicate poor aspen regeneration where compaction or interrupted drainage exists on areas disturbed by skid trails and landings. In the prairie provinces the following conditions have been noted: multiaged patchy aspen regeneration after high-grading, unexplained differences in aspen density in response to site treatments, and insufficient stocking of aspen regeneration ascribed to soil compaction and root disturbance from logging (Navratil, Bella, and Peterson 1990).

Guidelines for Encouraging Aspen Regeneration

The guidelines developed by Steneker (1976b) are still the best available for the forester wishing to promote aspen regeneration. He suggested that, in general, complete removal of the original stand, together with harvesting methods that knock down much of the understory vegetation, will ensure a fully stocked stand of suckers, provided the root system of the original aspen stand fully occupied the site. In overmature stands, which are likely to have heavy shrub vegetation, the preferred time for harvesting is during the frost-free dormant season to encourage the destruction of shrub vegetation. Most of the shrub vegetation will be destroyed or uprooted if complete trees are brought to a landing; however, the area may subsequently have to be treated with anchor chains or other equipment that will destroy residual shrubs (Steneker 1976b).

Although Steneker (1976b) stressed that shading by shrubs can reduce the growth of aspen suckers, forest managers usually do not bother to control shrubs as a measure to encourage aspen regeneration. For example, in Saskatchewan the earlier concern about dense hazel understory as a deterrent to aspen suckering has turned out to be unfounded. In that province, instead of a shrub problem, the most difficult sites to regenerate to aspen are landings used in summer logging where there is extreme soil compaction. Such areas are more amenable to hardwood regeneration after ripper blade treatment (Little 1988a, b).

There have been recent trials in the western United States to search for less expensive ways to regenerate noncommercial aspen stands. The emphasis was on a comparison of clearing aspen by bulldozer pushing and by chainsaw felling. After five growing seasons, dozer-pushed areas contained more suckers than areas cleared by chainsaw. Removing the stumps apparently stimulated the remaining lateral roots to sucker more vigorously; however, there was a large variation in sucker density between replications, suggesting that site and clonal differences were more influential than the clearing method used (Shepperd 1987).

Site preparation for the regeneration of aspen is not a common practice, as it is for conifers (Weingartner and Doucet 1990), but reduced growth, reduced internal stem quality, and reduced root quality of suckers results where heavy scarification equipment is used in the presence of aspen suckers (Basham 1988). Basham observed that at 4, 6, and 10 years after 3-year-old aspen suckers had been scarified the reduced growth of surviving suckers was actually a result of damage to the parent root rather than direct injury to the stems of suckers. Normal height growth of treated suckers resumed after a 10-year period, but diameter growth was still slightly less than in unscarified stems. Scarification is thus expected to have an inhibitory effect on stem growth rate of survivors well beyond the 10-year period studied (Basham 1988) due to disruption of the parent root system on which young aspen suckers are almost completely dependent for several years (Zahner and DeByle 1965).

In the sites studied by Basham, scarification wounds were frequently associated with root and root-collar decay. Primary and secondary routes of entry for the principal fungi inhabiting the roots of suckers were scarification wounds, dead "companion" trees, and hepialid borer openings. Scarification wounds were the primary route of entry for five of the six basidiomycetes known to cause advanced root decay in mature Ontario aspen. The surviving aspen suckers were considered by Basham to be more susceptible to windthrow or breakage than those in unscarified areas.

Conditions for Aspen Reestablishment by Seedlings

The forestry literature provides little advice on what an aspen silviculturist can do to encourage aspen seedling regeneration, but it is known that exposed mineral soil and continuously moist soils during the seed germination period are optimum conditions. Circumstances under which natural seedling establishment is common in Alberta are currently under investigation at Forestry Canada's Northern Forestry Centre, but silvicultural prescriptions for establishment of seedling-origin aspen stands are not yet available for the mixedwood section. McDonough (1979) and most others who have documented aspen seedling production have stressed that abundant and continuous availability of moist soil is critical for establishment of seedlings. This sensitivity to even slight water deficits ranks aspen among the least drought-tolerant tree species in the seedling stage. Given the exacting germination and seedbed requirements of aspen, McDonough reported that there is not much a forest manager can do to promote seedling establishment over large areas. Gullion (1984) was more optimistic, however, and his suggested techniques to encourage seedlings are summarized in the following text.

Recommendations by Gullion on how to manage aspen to enhance ruffed grouse and deer habitat in Minnesota include advice on how to develop aspen stands from seeds. Based on sites where seedling aspen grow in Vermont, New York, Pennsylvania, Minnesota, Colorado, South Dakota, and Wyoming, it appears that success is most likely if a seedbed has been either scorched with a hot fire or scraped bare with a dozer blade. Gullion suggested that the seedbed should be bare mineral soil, fully exposed to the sun, and should be compacted. A rubber-tired skidder will create a tread mark that provides a trap for aspen seeds and moisture. In the Mille Lacs area, Minnesota, aspen seedbeds were established in pasture sod by a dozer blade that created cuts 4–6 m long, at intervals of about 10 m, with dozed strips about 10 m apart. If silviculturally prepared seedbeds do not coincide with a good seed-year for aspen, the seedbeds may need to be kept relatively bare until the desired seedling densities are achieved. In the Mille Lacs area, Gullion reported that after six growing seasons aspen seedlings had reached a height of 4 m, at densities exceeding 60 000 stems/ha. On some sites these aspen seedlings were as dense and within 0.6 m of the height of adjacent 6-year-old sucker-origin aspen.

Nursery Methods for Aspen Seedling Production

Some of the most detailed information on aspen seedling production is that provided by Barth (1942), Borset (1960), and Bärring (1988) for *P. tremula* in Norway. Methods suggested by Borset for European aspen are discussed in the following text.

The time of seed ripening must be closely watched because seed dispersal takes place as soon as seeds are mature, and dispersal lasts for only a very short time. Seed is most easily collected by cutting twigs with female catkins attached. If the capsules are completely mature the twigs are stored in a warm, dry place and the seeds with the seed-hair will be shed in a short time. If the capsules are collected a little too early, the twigs should be put in water to allow the seeds to reach full maturity. The germination capacity of newly harvested and well-ripened seeds is very high. The seeds lose germination potential relatively quickly when stored in warm areas because of the lack of endosperm. If the seeds are stored in cool areas and in vacuum, the germination power may be preserved for extended lengths of time. Best results from sowing are obtained by sowing the seeds as soon as possible after collection. Borset considered it unlikely that seed regeneration in nature is prevented directly by low temperatures. Sowing in greenhouses and nurseries has confirmed field observations that continuous moisture during the germination period is of greater importance than regulation of temperature.

European experience indicates that for seedling production, no other tree species requires as much attention as aspen. Seeds should be sown in a sandy medium that is weed-free, and sterilized soil is an advantage to avoid trouble from fungi and bacteria. The seed should not be covered, or at most it could be covered with a very thin layer of humus. Immediately after sowing, the seedbed should be irrigated. The seedbed may be covered with paper, sacking, or glass. Aspen seeds germinate rapidly; the hypocotyl breaks through in less than 12 hours. Development of the two cotyledons is finished in less than 24 hours. Then growth almost completely stagnates, and although root growth and shoot growth are minimized the cotyledons provide all the necessary assimilation for up to 3 weeks. In the field both germination and development of the seedlings take longer than in a greenhouse. More than 4 weeks may be required from germination to development of the first primary leaves, and beds must be irrigated up to three times daily for 2–3 weeks depending on temperature and evaporation.

If aspen seedlings are sown with adequate spacing they can remain in the seedbed the entire summer, during which time they can reach a height of 50 cm. They are usually too small to be planted the same season and require transplanting in the nursery the following spring. In Norway, most aspen seedling production takes place in greenhouses.

The best time for planting aspen is in the spring. If seedlings are lifted before new shoots develop and if placed in a cool environment, they can be stored for a long time before planting. Borset (1960) indicated that planting during July or August was least successful. Cutting back the plants at the time of planting generally does not affect either the success of the planting or the height growth.

The Institute of Paper Chemistry in Wisconsin developed an aspen seedling production system (Einspahr 1959; Benson and Einspahr 1962; Einspahr and Benson 1964), which was later tested on a commercial scale (Benson and Dubey 1972; Wann and Einspahr 1986). This nursery system was summarized by Wyckoff and Stewart (1977) and consists of the following eight steps:

1. Prepare a finely smoothed seedbed. Incorporate a nonburning granular fertilizer into the soil.

2. Fumigate the seedbed with methyl bromide. Aerate for 3 days before seeding.

3. Place a frame around the seedbeds. Sow seeds on a still day at a rate of approximately 215 seeds/m^2. After seeding, gently rake seedbed parallel to the slope rather than upslope or downslope.

4. To provide shade and protect seedlings from wind and splashing, cover the bed with muslin supported by 1.3-cm mesh hardware cloth (screen) on a lath frame, all of which is supported by the frame mentioned in step 3.

5. During the first 6 days, water the seedbed several times a day, keeping the surface constantly moist. Afterwards, water beds once a day. If necessary, use acid injection in the irrigation system to maintain the pH between 5.5 and 6.0.

6. Fertilize two more times before lifting. Follow a schedule for applying fungicides and insecticides.

7. Remove the muslin after 3 weeks, the screen after 7–8 weeks, and the framing boards after 10–12 weeks.

8. Lift trees in the fall, cut back to about 45 cm in height, prune roots if necessary, and bundle. Bundles are stored over the winter in an unheated building where they are heeled-in in sand, watered, and treated with a fungicide.

The usual losses from conventional nursery practice (rapid loss of seed viability in the seedbed, washing away of seed, drying of the soil surface in the first 2 weeks, and damping-off during the seedling stage) are eliminated or reduced by the procedures recommended by the Institute of Paper Chemistry (Fisher and Fancher 1984) and by using peat and sulfur as soil amendments.

For experimental purposes and only for small numbers of aspen seedlings, seeds can be started in moist sand in a greenhouse and transplanted to individual pots (Einspahr and Winton 1977). Schier (1978) used 6.4 × 25.5-cm tubes and a 1:1 vermiculite–peat medium to grow containerized aspen seedlings in a greenhouse with fertilizer application started 1 week after germination. Seedlings started in the spring grew 30–45 cm by the time they were ready to be set out in the fall. The greatest hazard for both natural regeneration and plantations of aspen are herbaceous plants and sod-forming grasses, which can seriously reduce growth and survival (Benson 1972; Bailey and Gupta 1973; Dickmann and Stuart 1983; Fisher and Neumann 1987).

Spacing during outplanting can vary from 1.5 × 1.5 m to as much as 3.0 × 3.0 m and depends on economics and the desired objective (Schier et al. 1985). Wide spacing can result in trees with many limbs and reduced quality for sawlogs or veneer. On the other hand, wide spacing may sometimes be desirable for reasons of aesthetics, wildlife habitat, or as a nurse crop for other tree species.

For vegetative propagation, experience with North American aspen indicates that sucker cuttings and transplanted wild suckers are not practical methods for propagation of aspen; if vegetative propagation is desired the most successful method is to use root cuttings (Schier et al. 1985). Commercial-scale vegetative propagation of aspen was recently described by Hall et al. (1990).

Rotations and Harvest Schedules for Aspen–Balsam Poplar Stands

There are several features that distinguish aspen from conifers when rotation lengths are being planned. Beyond a certain age there is too much decay in aspen to use the concept of cutting the oldest first, which is the traditional approach with conifers (Barr 1987; Beck et al. 1989). Compared to boreal conifers, aspen is well suited for short-rotation management, and there is already considerable literature on this subject (Bella and Jarvis 1967; Einspahr and Benson 1968; Person et al. 1971; Heilman et al. 1972; Hunt and Keays 1973; Berry 1973; Ek and Brodie 1975; Berry and Stiell 1978; Ohmann et al. 1978; Perala 1979; Isebrands et al. 1982; Stiell and Berry 1986). More recently, there has been renewed interest in short-rotation management of woody species in the context of mitigation of carbon dioxide buildup (Wright et al. 1990).

There is not much experience with different rotation lengths for aspen in the prairie provinces because many of the early aspen harvesting operations were high-grading. Navratil, Bella, and Peterson (1990) stated that uneven-aged stands caused by high-grading will not likely be a problem in the future. Technological changes and greater utilization of the aspen resource will encourage the use of all wood-quality grades and trees from all site classes. Similarly, the overmaturity problem will disappear as mature and overmature stands experience natural breakup or are harvested and renewed. There are strong economic and silvicultural reasons to rehabilitate the current large areas of decadent stands and bring them back to full production.

Aspen still tends to be harvested on relatively long rotations in western Canada. Near Hudson Bay, Saskatchewan, the forest industry currently plans on a 70-year rotation. For northern Alberta, MacLeod and Blyth (1955) suggested a rotation age of 115 years, if only the spruce component is considered; 75 years if both hardwoods and softwoods are used in mixedwood stands; and 30 years if only the aspen component is considered. Data gathered by Bella and De Franceschi (1980) reported that, in Alberta aspen stands, the maximum mean annual increment (MAI) for stem wood and bark occurs at about 30 years. On this basis, they suggested a rotation age of about 30 years for fully stocked, dense aspen stands, with slightly longer rotations on poor sites, and shorter rotations on good sites. This compares quite favorably with results by Perala (1973) that indicated a rotation age of about 25 years for aspen stands growing on relatively good sites (site index 21 m at 50 years) in north-central Minnesota.

These seemingly low rotation ages for aspen are based on the assumption that maximization of fiber production is the main objective. If managers think in terms of log production for lumber or veneer then longer rotations are required. For example, to produce aspen greater than 9 cm dbh in Saskatchewan, a rotation of 60 years is recommended for the best sites, 70 years for medium sites, and 85 years for poor sites (Kabzems et al. 1986). Northern Alberta volume yields presented by Woodbridge, Reed and Associates Ltd. (1985) indicated that, for a large roundwood utilization standard, culmination of MAI occurs at about 75 years on the basis of Alberta Forest Service data.

Experience in the United States indicates that most aspen can produce pulpwood with rotations of 35–45 years. On some of the best sites, however, sawtimber has been produced in 45 years when the stand was thinned at age 30. To avoid problems with stem decay, rotations of 50 years, or 60 years in decay-resistant stands, have been suggested as ideal for aspen lumber production (Perala and Russell 1983). Based on experience in Saskatchewan, Prince Albert Pulp Company (1983) also recommended 50–60 years as the optimum rotation for aspen. For the prairie provinces generally, Steneker (1976b) recommended rotations and stand-tending steps for aspen on different sites (Table 38).

During 1988 interviews by Peterson et al. (1989a), one respondent (Steve Ferdinand, pers. com., April 1988) described a circumstance in which aspen may in the future be harvested at younger ages than at present. The suggestion was that the goal of having aspen and white spruce harvestable at the same time could be encouraged by an intermediate treatment in young stands where aspen and spruce coexist by sacrificing the aspen at a relatively young age, about 25 or 30 years, leaving a spruce component that might be joined by a new aspen crop of sucker origin and of an age 20–25 years younger than the residual spruce. One uncertainty is the degree to which there would be suckering after initial removal of the aspen, because of the shading by residual spruce. It is also not clear if there could be a commercial return from aspen harvested at 25–30 years of age. Furthermore, there could be substantial logging damage to the understory spruce when the 25–30 year old aspen is removed. Despite these uncertainties, this suggestion should be tested in several types of mixedwood stands in the prairie provinces and northeastern British Columbia.

Rejuvenation of Overmature Boreal Aspen Stands

Boreal mixedwood managers are uncertain how to handle stands of pure, overmature aspen that are too decayed to harvest. Should overmature aspen be left

Table 38. Rotations and stand-tending steps for aspen (Steneker 1976b)

Site	Product	Stand tending	Rotation
Good	Sawlogs	Thin to increase tree increment (1600 trees/ha at age 15, with further thinning at age 30 to 1000 trees/ha)	50 years
	Fiber	Thin to salvage mortality (maintain stand basal area at 70% from normal, starting at age 15 or before)	30–40 years (less if total tree utilized)
Intermediate	Fiber	As for fiber on good sites, thin to salvage mortality	35–45 years (less if total tree utilized)
Poor	Fiber	No stand tending and possible conversion to other species	–[a]

[a] Not applicable.

standing until there is natural breakup? Should it be felled, windrowed, and burned, or felled and flattened mechanically? Should unusable old aspen be treated differently on diverse sites? If the timing of stand breakup could be predicted with more certainty, then preventative measures could be planned more accurately. In cases where there is a decision to replace overmature stands with a new crop, even if the overmature stands are commercially unsuitable, there are two remaining challenges. The first is to select the best silvicultural steps to reestablish vigorous hardwood stands. The second is to select the most optimal sites on which to spend silvicultural budgets for rejuvenation of overmature stands.

The first of these two challenges is not as difficult as the second. The criteria developed for the poplar working group in Ontario (Davison et al. 1988) are also considered to be applicable to western Canada, as confirmed by the work of Bella (1986) and Steneker (1976b). These criteria indicate that clear-cutting is the only silvicultural system that creates conditions suitable for vigorous aspen regeneration.

It is more difficult to decide which sites are the most optimal for encouragement of aspen. Aspen tends to grow best on the same sites as more valuable softwood species (Corns 1989), and often a choice needs to be made between hardwoods or softwoods as the object of silvicultural expenditures. Corns suggested that the choice of either white spruce or aspen production should consider the relative site potential of each species, rather than deciding on the basis of which species occupies the site now.

The move to greater hardwood use indirectly encourages prime site management. An example from the Weyerhaeuser Canada Ltd. operations in Saskatchewan demonstrates this point. Most of the mixedwood occurs in the southern half of their lease area, closest to the mill, and the softwoods are more prevalent farther north. Increased hardwood use has not occurred as an expansion of mill output; it is a replacement for softwood production. The net result is increased harvesting in areas closer to the mill. The reduced operating radius encourages prime site management, and the reduced hauling costs allow increased silviculture expenditures on hardwood, softwood, and mixedwood forest types close to the mill (Smith 1989).

Quality of Second-growth Stands

Aspen stand quality following harvesting is not yet well documented in western Canada, but the pathological quality of aspen suckers has been investigated in detail in northern Ontario by Basham and Navratil (1975), Kemperman et al. (1976), Gross and Basham (1981), and Basham (1982a, b). Of the cankers, *C. chrysosperma* was present in most stands sampled, but in no instance was it a cause of death. *Hypoxylon* canker was found to be relatively unimportant in aspen suckers or in young stands, in contrast to its severity in older stands. Aspen shoot blight (*V. macularis*) was one of the most important foliar diseases affecting sucker regeneration in the stands studied by the Ontario researchers. In years of severe blight, sucker stands with 100% terminal infection were common, and such stands tend to stagnate. The stubs of the terminals that remain following shoot blight infection become new infection sites for other canker and rot-causing agents (Gross and Basham 1981). Root rot and stain defect were also present in a large percentage of aspen suckers. With the frequent use of mechanical site preparation on mixedwood sites, root rot and stain defects, especially by *Armillaria* spp., are predicted to be relatively important in newly regenerated stands (Navratil, Bella, and Peterson 1990).

Despite the sucker diseases previously discussed, Kemperman et al. (1976) suggested that the development of second growth aspen stands will probably not be seriously limited by defect until they are between 40 and 60 years of age; however, the limitations imposed upon rotation ages by pathological factors cannot be fully assessed until second growth aspen stands approach a merchantable size.

It is not known how productivity might change from one rotation to the next if aspen were to be harvested on short rotation in western Canada. In Ontario, Berry and Stiell (1978) concluded that aspen productivity could not be sustained on rotations of 10 years or less. For example, their second 8-year rotation generated only 80% as much biomass as was produced in the first cycle. In Minnesota, Perala (1979) concluded that rotations of 15 years or more are unlikely to impair aspen's regenerative and productive capacity.

In some cases future stand quality may be influenced by changes in tree species composition as the next crop develops. For example, in the Hudson Bay area, Saskatchewan, foresters have observed a postharvesting increase in the proportion of balsam poplar, compared to aspen (Imre Bella, pers. com., May 1989). This may be a result of raised water tables on some sites after logging. If an increased proportion of balsam poplar is viewed by future users as a decrease in stand quality then the phenomenon observed in these Saskatchewan logging areas may be important. Aspen managers in Minnesota are also concerned about such stand composition changes, but no studies are underway yet to address this question (Donald A. Perala, pers. com., January 1990).

Short-log Harvesting of Aspen

The relative ease of reestablishing aspen after clear-cut logging, together with the use of short-log harvesting, make it an ideal crop for small-scale woodlots. Harvesting methods that can adapt to the scale of privately-owned woodlots allow many landowners to do their own harvesting with relatively low capital investment because regular farm equipment can be used. Virtually any method of harvesting can be used for production of short logs; in the prairie provinces and northeastern British Columbia, farm tractors, farm trucks, and horses are all used successfully. There is no need for farm woodlot owners to purchase any special licenses or insurance other than the normal farm Workers' Compensation Board coverage, farm insurance, and license plates for farm trucks because short logs are considered to be a farm product (Thorp 1988). For these reasons, boreal hardwood management is an ideal secondary endeavor in northeastern British Columbia and across the mixedwood and aspen parkland regions of the prairie provinces. Short-log harvesting does not necessarily imply short-rotation management; however, it is understandable that small private landowners will prefer short rotations rather than the 60 year or greater rotations typical of most forestry operations. Among silviculturists there is still some debate over the relative merits of short-log versus tree-length harvesting. For example, it has been suggested that short-log harvesting of aspen may not encourage sucker production as much as tree-length harvesting does because tree-length harvesting results in the destruction of more understory brush and also leaves fewer residual trees (Donald A. Perala, pers. com., January 1990). Adams and Gephart (1990) noted that fully mechanized operations result in a more complete clear-cut and also eliminate more of the residual trees than do conventional short wood systems. These differences are relevant for the forest manager intent on rapid sucker regeneration of the next aspen crop.

Use of Small-diameter Aspen

Some of the timber in the new operating areas of the prairie provinces is of relatively small diameter. This increases the interest in satellite whole-log debarking and chipping operations. Sauder and Sinclair (1989) tested flail multi-stem delimbing and debarking in several low-volume, small-diameter stands that were uneconomic to harvest and process with conventional single-stem equipment. The 160 aspen trees sampled near Hinton, Alberta, had an average volume of 0.547 m^3, average length of 14.7 m, average top diameter of 11 cm, and average bottom diameter of 29 cm. One hundred and fifty processed aspen stems generated 12 t of aspen debris and 54 t of aspen chips.

In the Hinton samples, aspen chips had an average bark content of 3.76% (percent green weight basis), compared to a range of 1.18 to 1.32% for white spruce and lodgepole pine debarked by this method. Aspen was the most difficult species to debark because of its thicker bark and because the sample stems were larger in diameter than the sample spruce and pine. These trials indicated that the tested satellite chipping operation was well suited to high production; however, the fast rate at which the flail and chipper equipment can process stems requires a stockpile of logs because a feller–buncher and skidder cannot supply the system without working more hours than the satellite chipping equipment.

Treatments to Improve Yields of Aspen and Balsam Poplar

The most common steps to improve forest yields are thinning and fertilization and, to a lesser extent, promotion of genetically superior growing stock. A recent opinion survey of industry and government foresters in the prairie provinces and northeastern British Columbia (Navratil, Bella, and Peterson 1990) revealed that rejuvenation of decadent stands, planting of genetically improved aspen and balsam poplar, and density management in hardwood stands ranked as the three top priorities for future management practices. These opinions are somewhat surprising in view of the literature, summarized in the following text, which question whether aspen requires much silvicultural attention.

Thinning

Perala and Laidly (1989) recently highlighted aspen's responses to thinning as follows:

- thinning first at about age 10–15 years accelerates diameter growth the most (Day 1958; Steneker 1966, 1969, 1974b; Perala 1978), although 5- to 7-year-old stands can also benefit (Hubbard 1972; Bella 1975);

- newly initiated stands (1–3 years old) may need more time to express dominance (Perala 1984) before they can respond (Sorensen 1968; Bella 1975);

- one or two more thinnings up to age 30 prolong rapid growth (Perala 1978);

- stands older than 30 years respond little to thinning (Perala 1978); and

- in general, thinning is most successful if it is initiated when aspen stems are about 10 years old or when the crop tree dbh is about 5 cm.

Aspen specialists who disfavor aspen thinning seem to outnumber those who recommend it; however, the arguments against thinning of aspen stands are by no means held by all aspen managers. For Ontario and Quebec, Weingartner and Doucet (1990) listed several reasons why thinning is an attractive future development for aspen managers:

- commercial thinning can increase yield by salvaging potential mortality and increasing the growth of residual trees;

- precommercial thinning can shorten rotation length;

- thinning can produce large diameters in less time than required in unthinned stands, thereby reducing the amount of cull that occurs if aspen is left standing to age 60 or more;

- defect in the harvested crop can also be reduced if thinning is directed at removal of trees in the lower crown classes because there is evidence of higher amounts of defect in those crown classes;

- in aspen stands with a few scattered conifers there is evidence that thinning of aspen can favor the establishment of coniferous regeneration; and

- thinning can increase browse production and add to the variety of habitats for game and nongame species.

Recently developed equipment for harvesting small diameter stems will also encourage thinning in aspen (Weingartner and Doucet 1990). Rotary brush cutters integrated with drum chippers, feller–bunchers, and chipper–forwarders are examples of equipment suited for handling small diameter stems. Jones et al. (1990) were also optimistic that aspen thinning may be an economically viable silvicultural tool on sites that command high stumpage prices, such as sites with good summer access. Jones and co-workers are continuing research in Minnesota on a variety of thinning methods to verify the biological and economic effectiveness of these treatments.

In summary, the primary objective of thinning is to concentrate growth on selected crop trees to increase yield of large-diameter products. Secondary objectives may include: increase of the total fiber yield by salvaging anticipated mortality; reduction in the cost of logging during the regeneration cut; improved regeneration conditions for aspen suckers; and upgrade of the genetic composition of a stand by removing undesirable clones in thinnings (Perala 1978).

The advantages and disadvantages of thinning aspen are outlined in more detail in the following text. If an aspen manager makes the decision to thin, the following guidelines by Perala (1978) are noteworthy. Thinnings should be done from below except to remove defective and risk trees. The first thinning may deviate from strictly regular spacing in order to keep the best trees. Occasional clumps of close-growing, vigorous trees can be left until a later commercial thinning to provide the widest latitude in crop tree selection. The final thinning, however, should be regularly spaced because of the long wait until the regeneration cut. Great care should be taken during thinning to avoid injury to crop trees. Aspen is extremely sensitive to wounds, which serve as entry points for defect and decay. The risk of wounding is highest during spring and early summer when the bark slips easily. Thinnings should be scheduled during the dormant season.

The literature dealing with pure aspen stands gives the impression that a hands-off approach may be the most appropriate form of silviculture for this species. For example, the *Silviculture Guide to the Aspen Working Group* in Ontario summed up a commonly held viewpoint about aspen stand tending as follows: "No cleaning, thinning or pruning of young aspen stands is recommended" (Heeney et al. 1980). A similar viewpoint is evident in the United States aspen literature, as cited below from DeByle (1976): "Little care is needed once a fully stocked, rapidly growing, even-aged aspen stand has been established. If too dense, the stand will thin itself with little loss in growth due to competition."

Thinning is generally not recommended if fiber production is the goal, but if the intent is to accelerate diameter growth to improve the value of aspen for sawlog and veneer production, then thinning may have a place. Work by Steneker (1964, 1969, 1974b) in the prairie provinces and by Zasada (1952) and Zehngraff (1949) in the Lake States gives ample evidence that thinning does stimulate the diameter increment of all tree sizes. Steneker (1976b) recommended that thinning should be considered, on good sites only, when the objective is to produce large trees for lumber or peeler logs in a shorter period of time. Jarvis (1968) also confirmed that growth of residual aspen after thinning was better on good sites than on poor sites. The exceptionally high stem density of many aspen stands of sucker origin is the obvious incentive for the interest in thinning (Jones 1976), although there are other reasons for thinning. For example, Navratil (1987) suggested that thinning could be used to remove decay-prone aspen trees and to manipulate clonal composition. Other authors who have identified circumstances where aspen thinning may be considered include: Graham et al. (1963); Steneker and Jarvis (1966); Schlaegel (1972); Brinkman and Roe (1975); Perala (1977, 1978); and Weingartner (1981).

Many other researchers have recommended against thinning in aspen (Bickerstaff 1946; Heinselman 1954; Anderson and Anderson 1968; Sorensen 1968; Schlaegel and Ringold 1971; Schlaegel 1972; Hocker 1982; Walters et al. 1982; Jones and Shepperd 1985a). Ultimately, however, aspen managers must use local criteria to determine whether thinning is justified under certain circumstances. If thinning trials are desired to fulfill some specific local or regional research need, the most defensible approach would be to incorporate the thinning trials into growth and yield studies.

Some foresters are concerned that thinning will stimulate new aspen suckers that could hamper redistribution of growth to the desired crop trees (Mowrer 1988). It is not yet clear whether this is a silviculturally or economically important phenomenon. In Minnesota, foresters have not noted many suckers after thinning stands that are 5 or more years old; the few suckers that did arise after thinning were generally short-lived (Donald A. Perala, pers. com., January 1990).

Follow-up observations of Saskatchewan and Alberta thinning trials (Bella 1975) indicated that thinning-induced suckers died as crown closure occurred in the residual canopy; however, even if these suckers eventually died they may have resulted in some decrease of potential growth to the intended crop trees. In any case, the vigor with which a clone suckers after disturbance will be a major factor in the extent to which increased growing space, after thinning, is reoccupied by new sprouts (Kemperman 1977). The ability of a particular clone to self-thin is thought to be another influence on how readily any suckers resulting from artificial thinning will be suppressed by the crop trees (Mowrer 1988).

Observations in the prairie provinces and in Quebec confirm that there can be extra infection by *Hypoxylon* after thinning (Fig. 34), but this phenomenon is not well quantified. Some of the most detailed documentation is from Minnesota where Anderson (1964), Anderson and Anderson (1968), and Ostry and Anderson (1990) demonstrated increased mortality and *Hypoxylon* infection in thinned stands. According to Jones (1976) the increased mortality from *Hypoxylon* and other cankers is a result of their introduction through bark wounds and increased insect activities. Similar results were recorded in thinned aspen in New Mexico (Walters et al. 1982) and in Colorado (Jones and Shepperd 1985a). Hiratsuka and Loman (1984) also recorded infection by *P. polygonia* as a result of damage to the bark of residual aspen trees during thinning operations (Fig. 49). If there is a decision to thin aspen, it is important to avoid wounding the residual crop trees (Hinds and Krebill 1975; Mowrer 1988). One way to lessen such wounds is to avoid operations during the growing season, especially prior to midsummer, when the cambium is active and the bark is most easily peeled (Jones and Shepperd 1985a).

For the prairie provinces, it has been suggested that if aspen is to be thinned, it is best done at about age 10 by which time there is an opportunity to select the best trees from the best clones as residuals. There is also evidence that aspen experiences less infection with *Hypoxylon* if trees are thinned before they are 15 m tall (Imre Bella, pers. com., October 1988; Donald A. Perala, pers. com., January 1990).

Figure 49. Damage to the bark of residual trees during thinning operations is of concern because such injuries serve as entry points for fungal species, in this case *Peniophora polygonia* (Hiratsuka and Loman 1984).

Technological changes are reinforcing the long-standing bias against thinning of aspen stands. For any tree species, the main reason to thin is to concentrate stem biomass on fewer stems of larger diameter. Now that panelboard production can accept aspen as small as 10 cm in diameter and can also use bark, there is no point in thinnings designed to increase average stand diameter. Furthermore, thinning remains costly, and it is particularly difficult to justify, economically, when dealing with a relatively low value raw material such as aspen.

The primary use for aspen in western Canada is for production of OSB and pulp, and there is no reason to expect any major shift in this priority. Thinning young aspen stands would not increase the supply of raw material for OSB or pulp production. Under these circumstances, if the costs are to be carried to the end of the rotation, thinning is not an economically viable option. In summary, thinning could increase total stand production if the thinnings could be commercially used (Perala 1978), but it is difficult to justify thinnings for fiber production.

In many forestry operations, pruning is an important stand tending activity but it is not recommended as a high priority for aspen stands because this species is self-pruned quite effectively. The manager's handbook for high-value hardwoods by Berry (1982) points out that pruning may inadvertently create entry courts for decay-causing fungi. Therefore, in species such as aspen or balsam poplar, where minimizing future decay losses is an important objective, pruning becomes a questionable stand tending activity.

Fertilization

Recent interviews with boreal mixedwood managers in the prairie provinces and northeastern British Columbia (Peterson et al. 1989a) revealed that nutritional status of sites and long-term nutrition management are not yet important concerns for boreal mixedwood managers. For example, respondents from Abitibi-Price Inc., Pine Falls, Manitoba, thought that nutrient problems were minimal on good sites. The dominant concern is how to achieve forest renewal on good sites rather than how to improve their present nutrient status. It was also pointed out that if rotations remain as long as the rotation time for conifers there is time for significant atmospheric replacement of nutrients lost by harvest removals.

In contrast, some researchers believe that even if many mixedwood sites now have good nutrient status, it does not prevent them from being improved nutritionally through management practices (Day and Bell 1988). Even on rich sites there is competition for nutrients where roots of grasses, herbs, shrubs, and trees coexist, and it is possible that this competition could be silviculturally altered.

The economics of fertilization is not encouraging. Doucet and Weetman (1990) determined that efficiency of fertilizer conversion in Canada ranges from 10 to 45 kg of N for each extra cubic meter of wood grown. At current application costs of about \$1/kg of N, the extra wood that is produced by fertilization costs from \$8 to \$45/m^{-3}. Current stumpage rates are usually lower than these values for pulpwood, thus eliminating fertilization for nearly all of Canada except on the west coast where fertilization of Douglas-fir can be economically justified. Jack pine responds to N fertilization in the boreal forest, but there is usually no financial incentive to fertilize that species (Doucet and Weetman 1990); this also applies to aspen and balsam poplar.

There is only a limited amount of information on the effects of fertilization in aspen stands of western Canada, but there are data from elsewhere (Van Cleve 1973; Coyne and Van Cleve 1977; Parkerson 1977; Van Cleve and Moore 1978; Czapowskyj and Safford 1979; Teachman et al. 1980; Van Cleve and Oliver 1982; Fisher and Fancher 1984; Jones and Shepperd 1985b; Chapin et al. 1986; Safford and Czapowskyj 1986; Berguson and Perala 1988; Perala and Laidly 1989; Rauscher et al.

1990; Wyckoff et al. 1990). Heinonen (1983) reported on fertilization results for *P. tremula*. Trials indicate that aspen generally did not respond well to added P, K, or Ca, but grew between 33 and 177% faster when fertilized with N (Perala and Liadly 1989). Nitrogen has been applied at rates ranging from 170 to 500 kg/ha, and responses have lasted anywhere from 3 to 10 years.

In Canada, interprovincial forest fertilization trials described by Weetman et al. (1987) revealed that there were notable 5-year responses to fertilization in a 35-year-old aspen stand in Saskatchewan. The results are summarized in the following table:

Treatment	5-year increment (m^3/ha)	Increase over control (%)
Control	33.5	0.0
N at 112 kg/ha	35.6	6.2
N at 224 kg/ha	49.6	48.0
N at 224 kg/ha and P at 112 kg/ha	50.1	49.6
N at 224 kg/ha and K at 112 kg/ha	59.4	77.3
N at 224 kg/ha and P and K at 112 kg/ha	70.8	111.3
Initial total volume in stand: 145 m^3/ha		

Although the examples above indicate that aspen will respond positively to fertilizer application on sites where nutrients are not in good supply, Steneker (1976b) stated that in the short growing season, where boreal mixedwood stands occur, fertilization would not greatly improve growth. Furthermore, because productive aspen sites are characterized by an abundant cover of understory vegetation, the added nutrients may be taken up by ground vegetation instead of by trees.

Data from Wisconsin aspen stands reveal that the amounts of P and K in understory plant tissue are similar to those in the aspen biomass at ages 8 and 14 (Ruark 1990). Most of the P and K tied up in the understory of aspen stands is in the root tissue. This is not surprising in view of findings by Ruark and Bockheim (1987) in their Wisconsin study site that reported the fine root biomass of understory plants was three times that of aspen. These findings are consistent with the suggestion by Steneker (1976b) that control of understory vegetation would be a greater stimulus to aspen growth than fertilization. It is also significant that the ground cover in many aspen stands is characterized by the presence of alder, Canadian buffalo-berry (*Shepherdia canadensis* Nutt.), and legumes (*Lathyrus* sp. and *Vicia* sp.), all of which fix N. There are, however, several unanswered questions about nutrition management in aspen stands (Philip G. Comeau, pers. com., July 1988). For example, how will nutrient availability change as intensity of utilization changes? Will the increased harvest removal of hardwoods increase the need for fertilizers in comparison to conifer-only harvesting systems?

The potential influence of fertilization on disease incidence is not known for aspen in the prairie provinces. On two study sites in Michigan, *Hypoxylon* infection and canker development increased with N fertilizer during the summer, but P and K treatments restricted canker incidence and development. Generally, canker incidence was higher and canker length was greater with combined fertilizer treatments than with single element treatments. Although susceptibility to *Hypoxylon* can be increased by fertilization, plant moisture stress in a specific year, clonal variation, and other factors were noted by Teachman et al. (1980) to negate fertilizer effects.

There is some information on the effects of combining fertilization with irrigation in aspen stands. Murphey and Bowier (1975) applied sewage effluent to an aspen stand that had stems from 6 to 20 years old. Over a 10-year period, each hectare received 1500 kg of N, 280 kg of K, 335 kg of P, 1075 kg of Ca, and 450 kg of Mg. At the end of 10 years, 12 harvested trees, ranging from 25 to 32 cm dbh, revealed that effluent irrigation and fertilization more than doubled the 10-year volume increment per tree, it increased the fiber length 20%, and did not change the specific gravity of the aspen wood.

Einspahr and Wyckoff (1978) irrigated and fertilized aspen stands growing on an unproductive site on fine sand. The irrigation was timed to keep the soil from dropping below 60% of field capacity. The fertilizer was given in two applications each of 1120 kg/ha of N_{20} P_5 K_{20} Ca_{20} Mg_{20}. Young aspen sucker stands growing on low quality upland sands and averaging about 3 $m^3 ha^{-1} yr^{-1}$ increased their growth about 35% from fertilization, 50–80% from irrigation, and 100–150% from irrigation and fertilization. Irrigation increased fiber length 10%, but had little effect on specific gravity. The response to irrigation appeared to be greater in aspen stands 7–13 years old than in stands 1–7 years old.

Silvicultural Encouragement of Superior Clones

The review by Navratil, Bella, and Peterson (1990) suggested that aspen growth characteristics and associated stem quality, as well as insect and disease resistance, generally have a strong genetic component and thus provide an opportunity to improve stand quality. Undesirable clones, whether because of poor growth habits or disease susceptibility, can be identified and removed. Such forms of "sanitary thinning" may be feasible in aspen stands where trees of different and easily identifiable clones are intermixed rather than grouped (Navratil 1987).

Although poplar hybrids are a different concept than selection of the best clones in naturally occurring aspen stands, some comparisons have been made between wood production in poplar hybrid plantations and in naturally regenerated aspen (Vallée 1979; Jones and Grant 1983). Such comparisons revealed that volume increment of hybrid poplar trees can be as much as four times that in natural aspen stands of comparable age; however, this production gain is offset by several advantages of natural stands. Naturally regenerated aspen avoids the high cost of plantations, poses no silvicultural difficulties, does not involve the costly selection of the best clones from natural aspen populations, and does not result in a monoculture. For all of these reasons, sucker encouragement in superior clones of natural stands is expected to remain the predominant form of aspen and balsam poplar silviculture in the foreseeable future in the prairie provinces. Current research at Lakehead University, Thunder Bay, Ontario, includes studies of genetic variation of balsam poplar (Fowler and Morgenstern 1990).

Silvicultural encouragement of certain clones is questionable unless exceptionally superior triploid genotypes are involved. Several studies have confirmed that aspen clones that exhibit exceptionally large stems in relation to neighboring clones on the same site may involve triploid genetic material. The largest individuals of aspen in a given region are likely to be triploids, as is the case for the largest recorded aspen in Wisconsin (Einspahr et al. 1963) and in Riding Mountain National Park, Manitoba (W. Jim Ball, pers. com., January 1988). Triploid aspen has been of considerable interest to the pulp and paper industry in Europe and in the Lake States (van Buijtenen et al. 1958; Einspahr et al. 1963; Winton 1968).

As much as 20 years ago Winton and Einspahr (1970) predicted mass production of triploid aspen in the Lake States. This optimism was based on data that show outstanding form and growth rates in triploids and triploid hybrid crosses. An example of triploid hybrid crosses is provided by Einspahr and Winton (1977) in which a 13-year-old plantation of *P. tremuloides* (2n) × *P. tremula* (4n), growing on a sandy site in northern Wisconsin, had an average height of 15.5 m and average dbh of 15.2 cm. By comparison, the best sites in Alberta (site index 24 m at 50 years) have a dominant height of 9.2 m at age 13 and an average dbh of 3.6 cm (Bella and De Franceschi 1980).

Selection of naturally-occurring superior parent trees is one of the first steps in most tree improvement programs. Selection standards for superior aspen include the following criteria: 1) maximum wood production through improved height and diameter growth, improved form (natural pruning, straightness of stem, fine branching, and narrow crown), and vigorous suckering; 2) juvenile wood with high specific gravity for greater pulp yield and improved tearing strength; 3) longer fiber length, which improves basic paper properties including tear, burst, and tensile strength; 4) improved insect and disease resistance with special emphasis on *Hypoxylon* canker and wood borers; and 5) improved response to intensive forestry practices (Einspahr and Winton 1977). Rudolph (1956) provided a specific selection criterion for growth rates for the Lake States region, suggesting growth targets of not less than 70 cm/yr in height and not more than 1.8 rings per radial centimetre. Recent genetic improvement work at the University of Minnesota (Anderson et al. 1990) has focused on the place of *Hypoxylon* in the search for superior aspen. This work has shown that the presence of many varieties of *Hypoxylon* requires that aspen genotypes selected for propagation should be screened for resistance to a number of varieties of this fungus, rather than just to one isolate.

Studies by Einspahr and Benson (1967) and Einspahr and Winton (1977) indicate that gains from selection and first generation intraspecific breeding are expected to be 20–30% in volume growth, 2–5% in specific gravity, 5–7% in fiber length and 40–50% in *Hypoxylon* resistance. Additional gains through the use of polyploidy and hybridization are expected to be nearly twice those obtained from selection and first generation breeding. Naturally occurring *P. tremuloides* triploids, for example, consistently have had 25–30% longer fibers and recent 10th-year observations had only 3% *Hypoxylon*, less than one-third the normal level of infection at age 10. Triploid hybrids involving crosses between *P. tremuloides* and *P. tremula* had a specific gravity of 0.42 at age 10 while comparable diploid *P. tremuloides* crosses had a specific gravity of 0.35.

Given the potential gains mentioned above, to what extent can today's silviculturist usefully incorporate clonal considerations into management decisions? Both Perala (1981) and Horton (1984) noted the potential for clonal expansion. For example, a clone 0.1 ha in size has been noted to expand in area by 200–300% at each rotation, and a large clone of 1 ha could increase by 50% during one rotation. Initial comments by Horton (1984) on the "root tree" method of regeneration of specific clones noted two practical issues: the danger of losing root trees to windfall, and the erratic distribution of superior clones. Heeney et al. (1980), citing a personal communication from J.S. Maini, described one possible method for promoting the best clones in a stand. Maini's suggestions are cited below:

> Before any logging takes place in the stand, identify and mark (blue paint) one or two stems as "root" trees in each good clone to keep at least some of the root system alive. Five to ten such trees per acre would be suitable. Log all the unmarked trees during mid-summer leaving as much slash and debris on the site as possible to inhibit sucker formation and growth. Leave the site for two to three years to exhaust the carbohydrate reserves of the poor clones. Finally, harvest the marked trees and treat the site to remove slash, debris and any existing aspen suckers. Subsequent sucker regeneration in the stand will be largely from the best clones whose vigour has been preserved by the "root" tree. This is considered experimental at this time and requires further testing before it can be recommended as a management technique.

Zahner and Crawford (1965) and Lehn and Higginbotham (1982) are among those who advocate the importance of managing aspen on a clonal rather than a stand basis, as a way to promote superior clones. This means that aspen silviculture must rely heavily on management of aspen root systems (Gifford 1966, 1967; Tappeiner 1982). Navratil (1987) suggested, however, that the concept of clone manipulation may have been oversold because clonal management in stands where clones are well separated is very unlikely; and also because yearly gains in expansion of promoted clones are too small to make the practice operationally worthwhile. The difficulty of recognizing clones within a stand is another deterrent. Navratil predicted that it may take five or six rotations before significant distribution of superior clones can be achieved.

If an aspen manager wishes to propagate a fast-growing or otherwise desirable clone, Steneker (1976b) suggested the following procedure. Root cuttings from 1.0 to 2.5 cm in diameter should be collected. These cuttings should be placed in sand flats in a greenhouse at about 25°C. Water should be supplied by overhead misting for 0.5 minutes every half hour. Once suckers have reached about 5 cm in height they can be detached and rooted in sand flats for later transplanting.

Conversion of Aspen or Balsam Poplar Stands to Other Forest Types or Land Uses

Until recently in the prairie provinces and northeastern British Columbia, the most common conversion activity involving aspen was cutting, piling, and burning it to make way for agricultural clearing. That activity is becoming less common as forested areas with soils of agricultural quality become more scarce, and because there are fewer policies favoring agricultural expansion. There is also increasing criticism of recent attempts to convert hardwood stands to conifer stands (Thorp 1989). The important question today is not how much boreal hardwood conversion is required but whether it is required at all. There remain, however, many active programs to limit the amount of aspen in pastureland (Bailey 1972; Pringle et al. 1973; Bailey and Wroe 1974; Hilton 1970; Hilton and Bailey 1972, 1974; Bowes 1975, 1976, 1982, 1983; FitzGerald and Bailey 1984; Bailey 1986a, b; Waddington and Bittman 1987). These programs have gradually evolved into a system of browse management, often involving prescribed burning. It is now recognized that browse is an inexpensive and underrated food resource for livestock in western Canada (Bailey 1986a; Bailey et al. 1990).

Prescribed burning to promote new browse of a height reachable by herbivores and postburn grazing are common practices in aspen-dominated agricultural areas. Burning, seeding of forage species, and short-duration heavy grazing have proven to be a financially attractive alternative to the traditional clear and break method for conversion of aspen woodland to grassland (Bailey 1986b). There is still no rapid and inexpensive way to turn aspen forest into permanent productive pasture. For example, trials by Pringle et al. (1973), using moldboard plow, Rome disk, rotovator, one-way disk, and tandem disk, all tended to enhance aspen establishment after the treatment. This is one reason why herbicide treatments are still in favor for brush control.

With aspen's increasing industrial use, interest in conversion of aspen stands to conifers is weakening. Boreal and mixedwood forest managers recognize that aspen and balsam poplar are permanent members of those ecosystems because they are not eliminated by either fire or logging (Navratil, Bella, and Peterson 1990). Not only will aspen persist, but further increases in its annual allowable cut can be expected. Much of the aspen growing stock is in agriculture fringe areas, dispersed among many small holdings. Demand for aspen wood from these privately-owned woodlots will benefit the local economy. Planting of improved aspen and poplar stock on abandoned farm land near manufacturing facilities may also become feasible in the future.

There are some circumstances where aspen stands will not be converted to a different type of vegetation but will simply be changed from one kind of stand structure to a more desirable structure. For example, thinning may have a role in opening the aspen canopy to increase light penetration which, in turn, can improve forage for wildlife or livestock. Aspen thinning may also be beneficial in recreational areas to improve aesthetics.

For many years, the main goal of aspen management was to convert aspen stands to more valuable coniferous species (Shirley 1941; Daly 1950; Heinselman 1954; Graham et al. 1963; Waldron 1961; Lees 1962, 1963, 1964; Steneker 1963, 1967a, b). In the prairie provinces and northeastern British Columbia, this meant primarily conversion to white spruce, lodgepole pine, or jack pine. Stand conversion is confounded by the highly variable proportions with which conifers and aspen intermix. Mixedwood stands in the prairie provinces are characterized by great variations in the relative proportions of hardwoods and softwoods. Any one area in this mixedwood region could contain: pure stands of softwoods surrounded by essentially pure hardwood stands, generally a result of fire boundaries; pure stands of aspen; and aspen overstory with spruce of various ages in the understory. The important point is that not all of the northern mixedwood section supports mixedwood stands; some of them are, in fact, pure stands of either hardwoods or softwoods. It may be difficult, because of this variability, to justify large-scale conversion aimed at either pure coniferous stands or pure hardwood stands.

Where aspen occurs on sites in which it is considered to be poorly suited in the boreal region, conversion to conifers requires careful consideration because the cost of establishing conifers is high, and the success rate for coniferous regeneration is often low (Hambly 1985; Johnson 1986). The conversion of good-site aspen to conifers may also be ecologically and silviculturally imprudent. In western Alberta and northeastern British Columbia, it is important to distinguish aspen–lodgepole pine types from aspen–spruce types because conversion to a pure conifer stand is silviculturally simpler and less costly in aspen–pine types than it is in the spruce sites where there is greater competition from grasses, herbs, and shrubs (Craig DeLong, pers. com., July 1988).

Management of Aspen and Balsam Poplar Stands for Water, Wildlife, or Recreational Uses

There is no reason to exempt boreal hardwoods from the objectives embodied in the recent discussion paper entitled *Sustainable development and the Canadian forestry sector* (Forestry Canada 1989). Those objectives are: to maintain the productive and renewal capacities and species diversity of forest ecosystems; to protect other forest environmental values; to maintain the quality of water, air, and soil; and to reduce pollutant deposits on forests from other production and consumption activities to levels that are within the assimilative capacity of the forest environment. For *Populus*-dominated ecosystems, the most common concerns within the context of these objectives involve water, wildlife, and recreational land uses.

Foresters who have experienced the transition from boreal forestry, with a coniferous focus, to forestry with a mixedwood or hardwood focus are aware that aspen and balsam poplar provide a greater variety of possible multiple uses than is possible with coniferous ecosystems. Thorp (1988) singled out several virtues of these boreal hardwoods that make them adaptable to multiple use: provision of wildlife habitat and range for livestock; value as a nurse crop for conifers; rapid regeneration of scarred landscapes; and rapid growth that opens the prospect of short rotations. Even more importantly, aspen stands can be successfully managed for several land uses simultaneously (Jones et al. 1985).

Management expectations for water, forage, wildlife, and recreation values are dependent on the successional stage of aspen—whether it is decadent, stable, or seral. Decadent stands have low expectations in terms of management returns, while those from seral aspen stands have high expectations (Harniss 1981). In general, succession to conifers reduces water yields and the variety of aesthetic values, although timber values increase.

Management for Water Yield

Most of the experience in aspen management for water yield is from foothills or mountainous areas of Alberta and the western United States, rather than from the Lake States and boreal portions of aspen's range. The degree to which this experience is applicable to aspen ecosystems in a boreal setting is unclear.

Clear-cutting aspen in the intermountain region of the western United States reduced soil moisture depletion by 7.5–10.0 cm in a 1.8 m profile over three seasons. Mean annual evapotranspiration losses were about 8 cm lower in clear-cut sites than in uncleared aspen stands (Johnston 1969). Clear-cutting entire small watersheds may temporarily increase streamflow by as much as 60%. Rapid sucker regrowth, however, enabled preharvest water yields to be reestablished in about 10 years. In Utah, Johnston et al. (1969) found that sucker stands used 1–13 cm less water from the surface 2 m of soil in a growing season than did mature aspen. Most of the savings to the soil moisture supply were in lower profiles. In the Utah study area, it took from 10 to 20 years for a sucker stand to reach a water consumption comparable to the preharvest parent stand.

In a region more akin to the boreal region than is the case with the Rocky Mountain watershed study sites, Wilde et al. (1953) found in Wisconsin sites with strongly podzolized morainic soils that clear-cutting of aspen stands produced an average water table rise of 35 cm and converted a reasonably well-drained soil into a semiswamp. Similiar changes have been observed in planting trials on logged areas in Saskatchewan (Harry J. Johnson, pers. com., July 1990). In Minnesota, increases in annual water yield occurred in each of the first 9 years and again at year 14. Maximum increases in the first 3 years of regrowth were 85, 117, and 88 mm/year. Increases in water yield resulted from the altered aboveground biomass. Increases became insignificant once aboveground biomass approached 57 t/ha. Once the initially-elevated slash settled onto the ground surface and decayed, it increased water storage and reduced streamflow volumes (Paul and Verry 1980; Bernath et al. 1982; Verry et al. 1983; Verry 1987).

As temperature and precipitation are both important factors governing water yield, changes in either or both of these factors as a result of climatic changes will determine the amount and regimen of water from forest watersheds. There could be modified precipitation patterns, changes in patterns of snow accumulation and snowmelt, and changes in frequency and intensity of droughts (Singh and Higginbotham 1988).

Aspen cover types offer several advantages over coniferous types for water management. Perala and Russell (1983) suggested that, compared to coniferous forests, aspen vegetation types allow greater groundwater recharge and streamflow due to lower seasonal use of water by aspen and smaller interception losses than with conifers. Some researchers also contend that aspen-dominated watersheds produce higher quality water than other kinds of forests. A suggested reason is that soils under aspen are typically porous, near neutral in pH, have a high organic matter content, and have high biological activity (DeByle 1985c).

Aspen forests transpire water throughout their growing season (Kramer and Kozlowski 1960; Tew 1967), but the amount of water lost annually by aspen forests is less than in coniferous forest types because of aspen's leafless period (Jaynes 1978; Gifford et al. 1983, 1984). Significant quantities of water are extracted by aspen at the time of vegetative bud burst and new leaf growth. Data from Utah (Tew 1967) indicated that 80% of the seasonal depletion of water by aspen occurred in the first 40% of the growing season.

The distribution of aspen in the prairie provinces and northeastern British Columbia coincides with areas that each year have winter snowpacks and subsequent spring runoff. Recharge of soil moisture from snowmelt in April to early June is a significant feature of the hydrologic cycle of these aspen ecosystems. In southern Alberta, it has been noted that isolated clumps of aspen and willow retained their snowpack longer than adjacent large open areas (Swanson and Stevenson 1971).

Management for Wildlife Enhancement

Wildlife concerns on forest land figured prominently in the 1989 survey of Canadian public opinion on forestry issues (Environics Research Group Limited 1989). For the question, "On what forestry issues should the public have more information?", the largest number of respondents (35%) gave environment/wildlife as an answer. When asked to list the most important use of Canada's forests, the most commonly listed use (27% of respondents) was wildlife protection. Other uses in decreasing order were wilderness preservation (25%), more than one use (23%), logging (12%), tourism and recreation (8%), do not know (4%), and mining (1%). In the prairie provinces, 60% of respondents thought that chemicals used in silviculture pose a major hazard to fish and wildlife.

These concerns are consistent with the principle put forward in the Forest Management Policy released by the Canadian Nature Federation (1990), namely that there must be no net loss of forested lands and natural biological diversity. The natural biological diversity is important because it implies that aspen forests should be managed to maintain and enhance the habitats of not only the main game species but for small mammals, songbirds, and other zoological components of the ecosystem. This requires specific steps to maintain a broad range of age classes in relatively near proximity to each other. For the wildlife manager there are important trade-offs between managing for short-rotation species such as aspen and longer-rotation conifers. Wildlife requirements for old-growth stands are also crucial in setting standards for maintenance of biological diversity, even if one is dealing with species amenable to short rotations.

Publicly expressed concerns about the wildlife implications of increased hardwood harvesting in western Canada usually focus on reduction of habitat diversity and habitat fragmentation. There are also uncertainties about the wildlife implications of a trend towards an increased hardwood component in the mixedwood region. There appears to be a public perception that pure aspen stands will be encouraged, perhaps on shorter rotations than used now, and that this trend will lead to the total loss of conifers, which provide essential habitat for some wildlife species, at least in certain parts of their life cycle.

The fundamental point for any mixedwood forest manager attempting to enhance wildlife for the native ungulates that inhabit the boreal region is that these grazing and browsing species have complementary food preferences that, collectively, make good use of the available forage resource: elk use browse and grasses, particularly from upland sites; moose use browse and vegetation from aquatic habitats; bison prefer grasses and sedges; and deer primarily use browse and forbs, although they may feed heavily on grasses and sedges during winters with moderate snow depth (Telfer and Scotter 1975). Aspen and balsam poplar are integral components of habitat maintenance for these boreal ungulates, except in seasons when they prefer open sedge and grass areas. The aspen type is particularly good habitat for wildlife associated with forest margins and openings, such as white-tailed deer, mule deer, ruffed grouse, snowshoe hare, and several songbird species (Ohmann et al. 1978; Perala and Russell 1983). If the land manager can maintain mixed aspen age classes with intermixed conifer stands the required diversity of wildlife for the above species, and also for moose and beaver, will be achieved.

Game ranching is considered to be well suited to boreal mixedwood ecosystems. In the three prairie provinces, about 40% of the existing game and bison farms are located in the transition zone between boreal forest and aspen parkland; a large portion of the remainder occur within the aspen parkland zone (Renecker 1988). This relatively new industry offers opportunities to Metis and native people provided they have priority to foundation stock that can complement facilities on community-owned land. An attraction of boreal game ranching is that it broadens the role of wildlife beyond sport hunting (Telfer and Scotter 1975; Hudson and Blyth 1986). As of April 1988 there were 193 game farms in Alberta, 49 in Saskatchewan, and 13 in Manitoba. Plains bison, elk, and fallow deer were the most common species raised (Renecker 1988). There is currently considerable opposition to game ranching, especially in Alberta, because of uncertainties about the effects of introducing exotic species, as well as the fear that poaching will increase (Harry J. Johnson, pers. com., July 1990).

For the land manager interested in forage production, one of the most effective ways to limit encroachment of aspen suckers is to encourage grazing by livestock and native ungulates (Pringle et al. 1973; Basile 1979; Jones 1983; FitzGerald and Bailey 1984; Bailey and Arthur 1985). For the land manager wishing to encourage aspen, cattle presents special challenges. Where browsing and trampling of aspen suckers by livestock is a threat, scattered slash from aspen logging can provide some protection for young sucker stands. Light browsing of stems has little effect on the eventual form or height growth of aspen because a single dominant shoot develops from the uppermost lateral bud after the terminal shoot is browsed (Graham et al. 1963; Maini 1966; Schier et al. 1985). Any livestock grazing during the first 3 years following logging is a strong deterrent to sucker regeneration (Jones 1975). Spring grazing, however, is less damaging to aspen suckers than is late-season grazing (DeByle 1985a). In some cases livestock grazing, browsing by wildlife species, and diseases may eliminate suckers as rapidly as they are produced (Shepperd 1986).

The recommendations by Green and Salter (1987a, b) for enhancement of wildlife habitat in Alberta's deciduous and mixedwood forests focused on three key species—beaver, mule deer, and sharp-tailed grouse. All of these species are adapted to shrub lands, forest edges, and forest openings of boreal mixedwood forests. Recommended objectives for mixedwood habitat enhancement for these wildlife species are summarized in Table 39. What is needed now is the development and application of expert systems, such as those described by Buech et al. (1990) for white-tailed deer, to help mixedwood managers make appropriate silvicultural decisions.

Mule deer require a mix of grasslands, shrublands, deciduous forest, and coniferous forest. One recommendation for the reclamation of habitat for mule deer (Green et al. 1987) specifies the establishment of deciduous forest communities on east, west, and north aspects, particularly using aspen as a dominant tree species. For optimal beaver habitat, the forest manager should encourage willow–aspen communities within 30–245 m of water. Although aspen and willow provide excellent food and building materials for beaver, balsam poplar, alder, and birch are also suitable. Beaver can be maintained on a site by ensuring that such food and construction materials are present, particularly during late summer and fall when food caching and construction activities are at a peak (Green et al. 1987).

In addition to the guidelines mentioned above, the boreal mixedwood manager can establish clear-cuts with irregular boundaries that blend with contours and landscape features. In this way, if the clear-cuts are not too large, they serve both amenity and wildlife purposes (Steneker 1976b). Slash management also has a bearing on wildlife habitat. For example, it is known that aspen logging slash provides excellent winter feed for certain ungulates and for hares (Steneker 1976b; Shepperd and Engelby 1983).

Table 39. Habitat requirements and vegetation management objectives for key wildlife species in the boreal mixedwood region (Green and Salter 1987b)

Selected species	Wildlife habitat	Vegetation management objectives
Beaver	Streams and lakes for year-round occupation with adjacent accessible deciduous trees and shrubs.	Encourage moderate-to-dense deciduous cover (preferably willow or aspen) within 30 m of shore.
Mule deer (and white-tailed deer in aspen parkland)	Browse- and forage-producing habitats for food; dense shrub or tree cover or steep, broken topography for thermal and escape cover.	Establish a mosaic of grasslands, croplands, shrublands, and forests (deciduous, mixed and coniferous woods) to maximize habitat edge. Plant a selection of browse species (chokecherry, Saskatoon, red-osier dogwood, aspen, willows, black alder, dwarf birch, snowberry, green alder, rose) for year-round use. Plant grasses and forbs in open meadow areas or establish small patches of cropland (cereal grains, legumes) to provide additional foraging opportunities. Grasslands established on south- and west-facing slopes will provide winter and spring habitat. Ensure that open areas are <200 m in width for optimum use.
		Maintain dense shrub and forest growth (at least 1.5 m in height and >75% crown closure) for use as thermal and escape cover; stands should be 1–2 ha (minimum width 92 m) for thermal cover and 3–10 ha (minimum width 183 m) for escape cover. Wherever possible, retain forest and shrub stand in blocks of 40 ha or more.
Sharp-tailed grouse	Grasslands or croplands interspersed with shrubs or aspen forest.	Intersperse shrub meadows, shrublands, and clumps of aspen forest throughout the remainder of the area; include several of juniper, silver-berry, snowberry, rose, bearberry, chokecherry, Saskatoon, pin cherry, buffalo-berry, willow, aspen, and balsam poplar in the planting mix.

Boreal silviculturists who wish to enhance wildlife habitat also need to consider the effects of fire in this context. From postfire studies in Alaska, MacCracken and Viereck (1990) noted that most nutrients made available by fire are quickly absorbed by resprouting plants, and that this benefit of fire is relatively short-lived compared to the increase in browse biomass. Schwartz et al. (1987) reported that moose need a minimum dietary crude protein content of 6.8%. Alaskan data indicate the postfire white birch browse generally exceeds 6.8% crude protein but aspen and willows do not; however, K and Ca levels are higher in aspen and willows than in birch. This suggests that moose need and use a variety of browse species to meet their nutritional needs. MacCracken and Viereck made the following suggestions for land managers who want to use fire to improve moose habitat. Burning should be done in early spring as soon as the area will carry a fire. A hot fire will expose a good seedbed, yet still allow sprouting of trees and shrubs. A planned mosaic of burned and unburned vegetation will allow moose to remain in the immediate area during the spring burn.

Short-rotation aspen management has important implications for wildlife. The Forest Management Policy prepared by the Canadian Nature Federation (1990) recommended that short rotations, along with whole-tree harvesting, should not be considered unless it can be demonstrated that these practices will not reduce the biological diversity and productivity of the forest. If a landowner wishes to manage aspen for enhancement of wildlife habitat, the most important variable is the successional stage of the stand. Total animal biomass can be as much as 8 times greater in a 10-year aspen stand than in a 40-year stand. The first 20 years of aspen stand development provide abundant natural browse needed to sustain a high biomass of deer, moose, beaver, and snowshoe hare. As the aspen grows taller, populations of larger mammals decline, but the numbers and diversity of bird species increases (Gullion 1986). Consistent with these data from the Lake States, D.A. Westworth and Associates Ltd. (1984) concluded that in Alberta overall densities of breeding birds would increase under short-rotation management and that the absence of large diameter snags in managed stands would result in a pronounced decrease in abundance of snag-dependent birds. Short-rotation harvesting was considered to be potentially beneficial to ungulates as long as management programs include silvicultural options designed to meet the cover requirements of each species.

Habitat changes caused by patch clear-cutting in aspen are usually temporary, but provide excellent successional stages for several bird species. DeByle (1981) suggested that block clear-cutting of aspen on an 80-year rotation would provide a mosaic of age and size classes, would increase edge, and should increase bird species diversity and total numbers of birds. Shorter rotations or cutting a greater portion of an aspen forest may cause a more serious decline in birds that depend on older forests (Scott and Crouch 1987).

Sizes and patterns of clear-cuts have long been of concern to wildlife managers. Their usual goal is to encourage as much edge as possible, with a mix of cutover areas to serve as feeding habitat and nearby uncut areas for shelter. In Saskatchewan, softwood clear-cut areas are currently limited to 40 ha and hardwood clear-cuts are limited to 120 ha (Little 1988b). In Alberta, hardwood clear-cuts currently average about 60 ha but may range up to 100 ha. In their suggested methods for reclamation of moose habitat in the prairie provinces, Green and Salter (1987a) recommended the maintenance of dense forest blocks at least 1 ha in size to provide escape and thermal cover within clear-cut areas. Recommendations on size and distribution of habitat units are provided by Green and Salter (1987b) for all of the large mammals that inhabit mixedwood and aspen parkland areas in Alberta, as well as for spruce grouse and sharp-tailed grouse.

The Silvicultural Guide for the Poplar Working Group in Ontario (Davison et al. 1988) also contains practical recommendations for timber management strategies to address specific wildlife concerns for the main mammal and bird species that use aspen forests (Table 40). The suggestions provided in Table 40 indicate that there is a good information base for effective wildlife management in boreal hardwood forests. The problem is that land managers and foresters generally do not apply the knowledge that is available for managing forests for uses other than fiber production (Dancik 1990).

Work by Perala (1977) and others indicates that, for moose, clear-cuts as large as 80 ha appear to be acceptable. In contrast, white-tailed deer prefer to remain within about 80 m of undisturbed cover; consequently, aspen clearings of 25 ha or less are best for deer. Deer rely on aspen forests particularly in spring and fall for herbaceous and shrubby growth. A good mix of stand composition for deer should include conifers, brushy openings, and aspen of varied age, particularly with some aspen stands 1–10 years old (Perala 1977). Snowshoe hares show a preference for regeneration on very small clear-cuts of 2–4 ha.

Work in the Lake States aspen indicates that ruffed grouse are the most demanding of the managed wildlife species for their requirements. Flower buds of male aspen clones are important winter food for grouse (Gullion 1987, 1990). Grouse populations are usually greatest in situations where sufficient mature male aspen trees are within about 100 m of 10- to 25-year-old aspen regeneration at densities of 5000–19 000 stems/ha. This means that when individual cutting blocks exceed about 4 ha in size the benefits to grouse diminish. Clear-cut blocks 8 ha in area produce about 70% of the grouse achievable with 4 ha clear-cuts (Gullion 1986). If clear-cuts are greater than 4 ha, Gullion recommended leaving 3050 trees from male clones to reduce the negative impact of harvest on grouse. The ideal aspen harvesting system for ruffed grouse habitat enchancement is to clear-cut blocks about 4 ha in size, at 10- to 12-year intervals, in a four-stage rotation around a central point. The total area cut is less important than the size and interspersion of individual cut blocks. Grazing and other causes of sucker loss is detrimental to ruffed grouse populations; virtually all sucker regeneration occurs in the first and second growing seasons after clear-cutting and any sucker loss during these first 2 years is usually not recovered.

When herbicides are used in mixedwood management, special steps can be taken to decrease impact on wildlife species that use aspen habitat. For example, Santillo et al. (1989) found on large clear-cuts in north-central Maine that leaving patches of vegetation untreated with herbicides and by staggering herbicide treatments to control competing hardwoods, including aspen, bird populations can be maintained similar to

Table 40. Timber management strategies for wildlife habitat maintenance and enhancement in aspen-dominated ecosystems (Davison et al. 1988)

Selected species	Wildlife habitat	Concern in timber management	Timber management strategies to maintain/enhance habitat
Moose	Pure conifer stands for winter shelter. Mature upland mixedwoods for food and shelter in early winter. Early successional areas for food during spring and summer.	Loss of winter shelter and security cover. Proximity of browse to late and early winter cover. Disturbance of aquatic feeding areas, mineral lick sites, calving sites.	Break up cuts. Shape cuts to limit cover-to-cover distance. Leave shelter patches within cutovers. Leave reserves.
Deer	Dense conifer as winter shelter in close proximity to browse. Early successional stages for year-round food supply.	Loss of current and potential winter shelter (yards). Maintenance of early successional forest adjacent to winter shelter.	Cut within winter yards to maintain or enhance shelter value. Produce a mosaic of small cuts and leave blocks to benefit foraging deer.
Black bear	Mixed habitat including riparian forests, mature upland mixedwoods for den sites and feeding, early successional areas for feeding. Largely vegetarian diet, carrion, some predation on moose calves.	Food supplies enhanced by cutting (early successional forest). Loss of den sites, mast crops.	Cuts that result in high edge/ area ratio will benefit bear. Protect known den sites. Retain some mature mast-producing trees.
Beaver, otter, mink	Riparian areas. Beaver preference for poplar stands.	Loss of cover including snags, stumps, woody debris, deciduous, and herbaceous vegetation.	Protect shoreland, depending on slope and soil texture. Some cutting to shore will enhance beaver habitat.
Marten, fisher	Immature and mature coniferous and mixedwood stands. Dens often in cavities in large trees.	Loss of dense, conifer-dominated stands will adversely affect fisher and marten	Modified cutting and strip cutting will contribute to maintenance of canopy. Retain snags and potential snags within cutovers as safety concerns allow.
Lynx, fox	Early successional areas, mixedwood stands of various ages.	Regeneration of deciduous and herbaceous vegetation in cutover will improve small-mammal populations and benefit their predators (lynx, fox).	Producing a mosaic of cut and uncut stands will maximize edge effect and provide mix of cover and early successional feeding areas.
Waterfowl	Riparian areas for nesting and feeding, cavitates in trees and upland areas used as nest site	Loss of nest sites. Disturbance during nesting. Alternation of water regimes and water quality of wetlands.	Limit cutting of shoreland, depending on slope and soil texture. Leave snags and some large trees as future snag as safety concerns allow.

Table 40. Continued

Selected species	Wildlife habitat	Concern in timber management	Timber management strategies to maintain/enhance habitat
Grouse	Upland mixedwoods for feeding, winter and escape cover (all grouse). Recent cutovers and burn sites (sharp-tailed grouse). Pure and mixed mature spruce stands for feeding and cover (spruce grouse).	Loss of nest sites, feeding areas, winter cover. Disturbance during nesting.	Maintain even-aged aspen in patches throughout the area. Create small openings. Maintain units of conifer as winter shelter.
Osprey	Riparian areas, nesting in dead or open-topped trees, prey on fish.	Loss of current and potential nest sites, trees, habitat disruption and loss near nest site. Disturbance during sensitive period: Osprey—approximately April 15 to September 1. Herons—approximately April 1 to August 15. Bald and golden eagles—approximately February 15 to September 1. Peregrine falcon—approximately March 15 to September 1.	No timber management activities in immediate vicinity of nest at any time. Modified cutting possible near nest during non-sensitive.
Herons	Riparian areas.		
Bald eagle (endangered species)	Riparian areas, nest in very tall trees.		
Golden eagle (endangered species)	Forested areas with large openings (burns, bogs, etc.). Nesting usually on cliff ledges but also in trees.		
Peregrine falcon (endangered species)	Nest of cliff ledges, especially near water. Prey on small birds.		
Other birds	All combinations of vegetation provide habitat for birds.	Loss of nest sites, feeding areas, shelter. Disturbance during nesting.	Maintain/create a range of stand types, ages, and sizes. Maintain riparian forests. Leave snags and potential snags according to timber/wildlife management objectives as safety concerns allow. Maintain several large blocks of mature conifer and/or mixedwoods within the management unit.

those on untreated clear-cuts. Vegetation complexity on a large clear-cut or on adjacent clear-cuts can also be maintained by staggering treatments 3 years apart and by leaving intentional skips of brushy habitat for insects and plant food.

Management for Recreational Uses

Aspen and balsam poplar, either alone or as mixed-wood forest, fit well into management for dispersed recreational activities. In mountainous areas, ski developments provide an excellent use of aspen areas (DeByle 1985b). In any kind of terrain, open aspen stands are particularly attractive for cross-country skiing. Aspen does not tolerate concentrated recreational use unless snow or frozen ground protects the soil surface from disturbance and compaction. Examination of the literature on compaction experience in recreational sites in forests with an aspen component (Peterson, Kabzems, and Peterson 1989) noted that intense recreational use resulted in the loss of surface organic horizons, soil compaction, and reduced infiltration rates. Damage to shallow roots of aspen can result in decay and dieback of stems, as well as winter drying of bark (Zalasky 1970). Campground deterioration in aspen ecosystems in the Rocky Mountain region (Hinds 1976; DeByle 1985b), in the Lake States (Brinkman and Roe 1975), and in Ontario (Mackintosh 1979; Monti and Mackintosh 1979) confirm aspen's relatively low tolerance to intense recreational use. Aspen works well as an aesthetic cover adjacent to heavily used areas. This review did not reveal any data to indicate whether balsam poplar was more or less able than aspen to withstand compaction in campgrounds and other recreational areas in the prairie provinces.

Small irregularly-shaped aspen clear-cuts that blend with the landscape are preferable for aesthetic and recreational uses. In the Lake States, Ohmann et al. (1978) and Perala (1977) suggested the following guidelines for aesthetic enhancement during aspen management: 1) provide vistas to expose and frame scenic features; 2) use clear-cuts to create variety by opening up dense and continuous stands, and by providing curved lines and irregular openings; 3) leave attractive or special interest trees; 4) provide diversity in forest types, species mixes, and age/size classes; 5) encourage transition vegetation along edges; 6) vary the sizes and shapes of cuts; and 7) sometimes convert from aspen to other vegetation types.

Important factors in aspen management for aesthetics are viewing distance, size and shape of openings, creation of diversity, softening of edges, and timing of clear-cuts (Perala 1977). Slash treatment is an integral part of aesthetic management in aspen areas that are used either for public hiking or viewing.

End uses for all species of harvested *Populus* in Canada were as follows in 1987: 47.8% of the harvested volume went into pulp and paper; 45.5% into panelboards and particleboards; 5.0% into plywood and special products (lathes, dowels, posts, and poles); 1.6% into lumber; and a fraction of a percent into roundwood exports (Ondro 1989). The steadily increasing commercial role of aspen and balsam poplar is exemplified by Alberta data Ondro assembled for the period 1980–81 to 1987–88 (Table 41). Within Alberta, for 1987–88, the consumption of *Populus* by various industries was distributed very differently than it was nationally because of the predominance of OSB use of aspen and its relatively limited use for pulp. Data compiled by Ondro on the use of aspen and balsam poplar by various industries in Alberta in 1987–88 are reproduced in Table 42. His analyses indicate that aspen is currently suitable as raw material for a broader range of products than balsam poplar or black cottonwood.

There is an impressive amount of recent literature on aspen and balsam poplar utilization (Maini and Cayford 1968; Bailey 1973; Keays et al. 1974; Neilson and McBride 1974; U.S. Department of Agriculture, Forest Service 1976; Brese 1977; McIntosh and Carroll 1980; Whitney and McClain 1981; Woodbridge, Reed and Associates Ltd. 1981, 1985; Alberta Research Council 1983; Carroll-Hatch (International) Ltd. 1983; Singh and Micko 1984; Arbokem Inc. 1986, 1987; H.A. Simons (International) Ltd. 1986; Lepper and Keenan 1986; Wengert 1986, 1988; Canadian Forestry Service and Alberta Forest Service 1987; Wong and Szabo 1987; Bryson 1989; Ondro 1989; Adams 1990). For northeastern British Columbia and the prairie provinces the most informative of these background reports are the Aspen Quality Workshop (Canadian Forestry Service and Alberta Forest Service 1987), the hardwood utilization review prepared for the Northern Alberta Development Council by Woodbridge, Reed and Associates Ltd. (1985), and the aspen utilization and marketing reviews carried out by Wengert (1988) and Ondro (1989).

Properties of Aspen and Balsam Poplar that Influence Their Use

The following sections focus on the anatomical, chemical, physical, and mechanical properties that determine the use and manufacture of aspen and balsam poplar for various primary and secondary forest products.

Table 41. Annual aspen/poplar harvest in Alberta[a] as a percentage of total volume cut, 1980–88 (Ondro [1989] based on data from Alberta Energy and Natural Resources, 1982–88)

Year	Total volume cut, all species (m^3)	Total volume cut, poplar (m^3)	Poplar as % of total
1980–81	5 433 301	131 777	2.4
1981–82	5 564 033	182 114	3.3
1982–83	5 560 131	172 107	3.1
1983–84	7 314 091	522 033	7.1
1984–85	6 600 271	472 301	7.2
1985–86	6 956 336	680 114[b]	9.8
1986–87[c]	8 229 874	1 285 877[b,d]	15.4
1987–88	8 345 694	1 436 050[b,d]	17.2

[a] Consists of 97% aspen, 2% balsam poplar, and 1% black cottonwood. Excludes poplar harvested and used for firewood.

[b] Includes 56 500 m^3 harvested for lumber and firewood on private lands and for firewood on Crown lands.

[c] Source: Personal communication to W.J. Ondro from R. Dunnigan, Alberta Forestry, Lands and Wildlife, Edmonton, Alberta, December 1988.

[d] Includes 400 000 m^3 of aspen harvested on Forest Management Agreement area and purchased from private lands in 1987–88 by Pelican Spruce Mills Ltd. at Drayton Valley, Alberta, which began OSB production in January 1987.

Table 42. Number of industries in Alberta using aspen/poplar and annual input of aspen–poplar logs as of 1987–88 (Ondro 1989)

Industry	No. plants	Aspen–poplar log input m³	Aspen–poplar log input %
OSB mills	3	1 083 133	75.4
Pulp and paper mills (1988 use)	2	220 632	15.4
Sawmill–planing mill complexes	117	58 155	4.0
Firewood producers	N/A[a]	41 500	2.9
Pallet mills	2	31 300	2.2
Container mill	1	N/A	0.0
Furniture mills	2	430	0.0
Cattle feed pelleting mill	1	900	0.0
Total	128	1 436 050	99.9

[a] N/A = not available.

Anatomical Features

Anatomical characteristics of aspen wood, based on more detailed descriptions by Panshin and de Zeeuw (1980), can be summarized as follows: sapwood whitish to creamy colored, generally merging gradually into heartwood and hence not clearly defined; heartwood whitish creamy to light grayish brown; wood with a characteristic disagreeable odor when wet, odorless when dry, without characteristic taste, with a pronounced silky luster, usually straight-grained; growth rings distinct because of darker latewood but not always conspicuous; pores numerous, small, not visible without a hand lens, more crowded in the earlywood, decreasing gradually in size through the latewood (wood semi-ring porous to porous), solitary or in multiples of two to several; parenchyma marginal, indistinct; rays very fine, essentially homocellular, scarcely visible with a hand lens; vessels very numerous; perforation plates simple; intervessel pits orbicular to oval or angular through crowding; pits leading to vessels confined to the marginal cells or occurring occasionally in rows in the body of the ray as well, simple to bordered.

The anatomical description of balsam poplar wood is almost identical to that of aspen. The most conspicuous differences are that the poplars are coarser in texture, somewhat darker in color (never creamy-colored) and are devoid of luster (Panshin and de Zeeuw 1980). The vessels in balsam poplar are wider than those in aspen, which is the reason for its coarser texture and slightly lower wood density than aspen. The fibers of balsam poplar are more gelatinous than those in aspen, making balsam poplar more difficult to process into wafers because its fibers wrap around knife edges, greatly reducing their effectiveness (Panning and Gertjejansen 1985).

Compared to other hardwoods, aspen and poplars are low-density woods. About one-quarter of their stemwood cross-section appears as pores under low magnification. The vessels are generally small enough to allow surface finishing without a filler treatment, a characteristic similar to birch or maple. About two-thirds of the wood volume is made up of fibers that, compared to vessel elements, are relatively long and thick walled (Table 43).

Fiber length is typically quite short near the pith, steadily increasing outwards from the pith (Yanchuk et al. 1984). Overall, fibers of aspen and poplars are much shorter than the fibers (tracheids) of softwoods. The amount of tracheids in softwoods is also considerably higher than the fiber content of hardwoods, generally exceeding 90% of the cellular structure of softwoods.

These fundamental differences in anatomy between poplars and softwoods explain significant differences in pulp strength between the two classes of wood. Pulps made from aspen or balsam poplar have about 70% of the tear strength of softwood pulps, 50% of their burst strength, and 70% of their breaking strength (Kennedy 1974). On the other hand, the vessel elements enhance smoothness and opacity, making poplars good species for the production of fine printing papers (Fig. 50).

Table 43. Fiber and vessel dimensions recorded for aspen and balsam poplar in Alberta

Variable	Aspen		Balsam poplar	
	Mean	Range	Mean	Range
Fiber				
Length (mm)	0.98[a]	0.4–1.9[b]	1.07[a]	0.73–1.30[a]
Width (μm)	–[c]	10–27[b]	–	26–30[d]
Wall thickness (μm)	–	2–3[b]	4[e]	–
Vessel elements				
Length (mm)	0.71[a], 0.50[b]	0.50–0.83[a]	0.61[a]	0.44–0.82[a]
Width (μm)	69[a]	40–95[a]	80[a]	52–110[a]

[a] Micko 1987; [b] Thomas 1987; [c] not available; [d] Pfaff 1988; [e] Wong 1987.

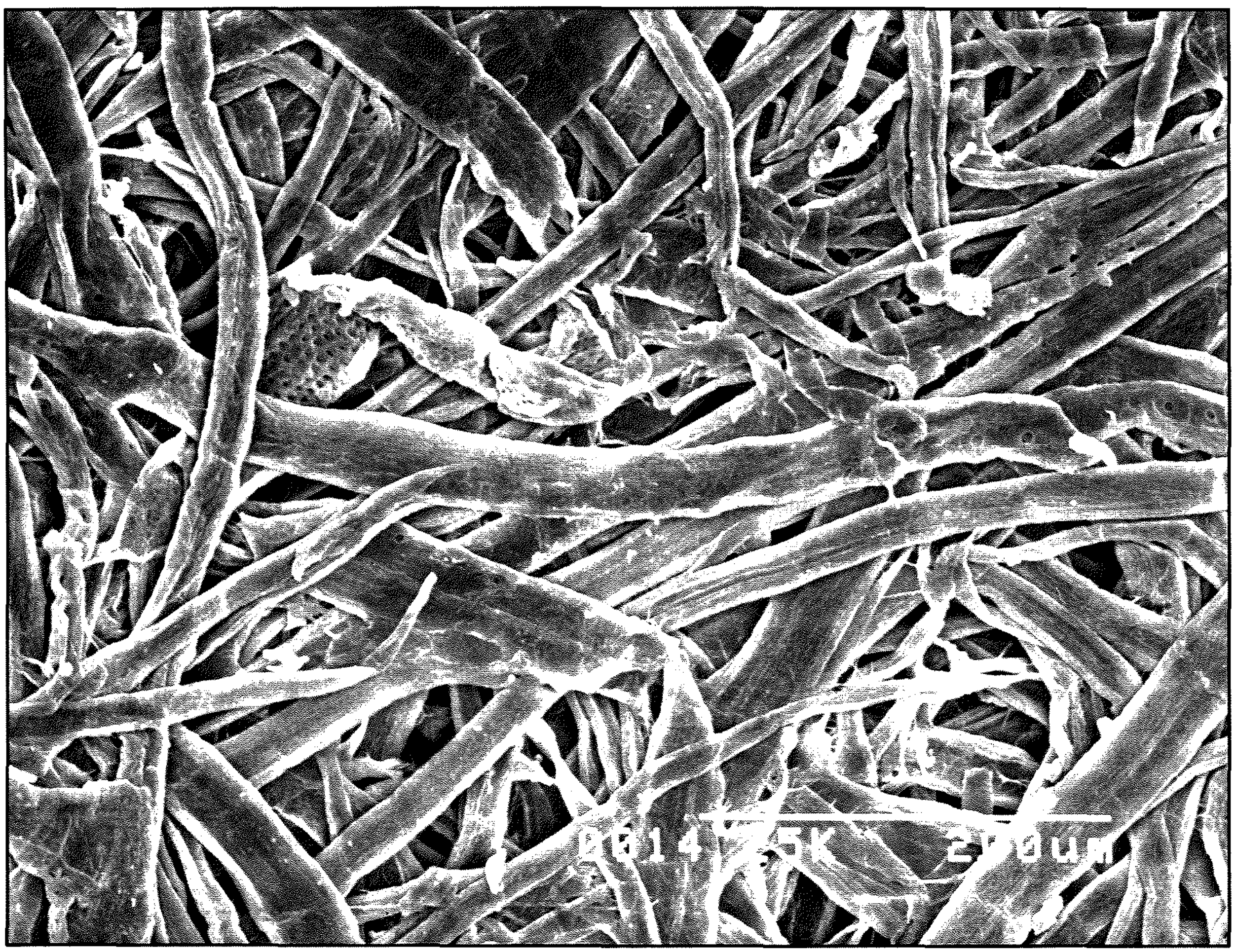

Figure 50. Surface of pulp made from aspen has a microstructure that reveals long slender fibers that provide the matrix with wide vessel elements blending into the fibers (photo courtesy of Y. Hiratsuka).

In aspen, as in other trees, the outer part of the stem is sapwood; however, the color difference between sapwood and heartwood is not as striking in aspen as in some species. Aspen heartwood has a much lower permeability than sapwood (Wengert 1988). This provides a way to distinguish heartwood from sapwood; when alcohol is brushed on the end grain of aspen wood it quickly disappears from the surface of the heartwood, whereas the sapwood remains wet for a short period of time (Wengert 1988). Heartwood, on average, has higher shrinkage/swelling values than sapwood for both aspen and balsam poplar and generally a higher moisture content than sapwood (Micko 1987).

Many of the vessels that are open for longitudinal conduction of fluids become blocked by tyloses when heartwood is formed. Tyloses are thin, membranous structures that proliferate from the neighboring parenchyma cells into the vessel cavities. Their presence in the vessels reduces the penetrability of the aspen by liquids during pulping processes or wood preservation treatment (Muhammad and Micko 1984; Côté 1985).

Chemical Properties

The carbohydrate contents of poplars is relatively high and the lignin contents are correspondingly low. Micko (1987) recorded a lignin content of 19.2% in aspen heartwood and 16.3% in aspen sapwood; these proportions are reversed in balsam poplar where heartwood is 17.2% lignin and sapwood is 20.4%. Other chemical constituents of aspen and balsam poplar wood are summarized in Table 44. Aspen-based sulfate pulp yields are in the range of 52 to 56% of the dry weight of wood because of aspen's carbohydrate/lignin ratios, compared with about 44% for most softwoods and 50 to 52% for several other hardwoods. The crushing strength of aspen and balsam poplar wood is low, however, for its specific gravity, presumably due to its relatively small amount of lignin (Kennedy 1974).

Aspen's low lignin content permits the wood to be softened and delignified more easily than the wood of spruce and other conifers. As a result, chemical pulping of aspen is fast and efficient, and mechanical pulping can be achieved with low levels of power consumption. The relatively high polysaccharide content of aspen wood leads to high pulp yields from chemical processes. Pulps made from aspen are light in color before any bleaching or brightening is done because sound, newly cut aspen wood is exceptionally white (MacLeod 1987).

A minor chemical component of aspen and balsam poplar wood is the group of compounds called extractives. These low-molecular-weight organic compounds can be dealt with effectively in most chemical pulping processes (MacLeod 1987). Based on samples from 13 aspen clones in central Alberta, sound aspen wood contained extractives that comprise 3.5–4.9% (mean 4.2%) of the wood mass (Yanchuk et al. 1988), a level not very different from that in many other Canadian woods. Based on data from Micko (1987), aspen and balsam poplar wood extractives are listed, as a percentage of wood mass, in Table 45. An unusual feature of aspen and balsam poplar is the extractives content of the inner bark, which is typically 4 to 5 times that in the wood. This is relevant because these species are relatively difficult to debark, except in spring when the bark–cambium interface is slippery (Berlyn 1965; Wengert 1988). Some aspen extractives, if they reach the chlorination stage of a bleach plant, can form very sticky pitch deposits; these deposits may later come loose and cause pulp contamination. To avoid some of these problems, aspen logs destined for pulp are often aged for a year before they are debarked and chipped (MacLeod 1987).

There is evidence of a correlation between aspen's rate of growth and its extractive content. Yanchuk et al.

Table 44. Chemical content of aspen and balsam poplar wood (Micko 1987)

Content	% of wood mass: Aspen	% of wood mass: Balsam poplar
Hollocellulose		
Bark	65.91	69.57
Sapwood	84.48	80.18
Heartwood	87.10	84.04
Cross and bevan cellulose content		
Bark	40.10	42.60
Sapwood	65.20	66.20
Heartwood	68.81	68.72
Lignin		
Bark	22.43	28.02
Sapwood	16.31	20.39
Heartwood	19.20	17.20
Ash content		
Bark	4.99	7.98
Sapwood	0.66	0.92
Heartwood	1.20	1.89
1% sodium hydroxide solubility		
Bark	23.27	30.63
Sapwood	13.28	14.99
Heartwood	9.58	10.29

Table 45. Extractives, as a percent of wood mass, removed by various solvents applied to bark, sapwood, and heartwood of aspen and balsam poplar (Micko 1987)

Solvent	% of wood mass removed as extractives	
	Aspen	Balsam poplar
Alcohol and benzene		
Bark	19.33	18.62
Sapwood	3.21	2.82
Heartwood	2.26	2.61
Petroleum ether		
Bark	1.27	3.14
Sapwood	0.87	1.43
Heartwood	1.07	1.79
Water		
Sapwood	2.07	2.87
Heartwood	2.25	2.25
PH water extracts		
Sapwood	7.3	7.0
Heartwood	8.2	7.0

(1988) found that faster-growing clones or trees exhibit a lower concentration of benzene–alcohol–water extractives than slow-growing clones. If this relationship is widespread, selection and propagation of faster-growing aspen clones could increase yield and also lower extractive content, a step that would have practical value for both forest management and the pulp and paper industry.

Physical and Mechanical Properties

In general, aspen and balsam poplar strength properties compare favorably with those of other low-density hardwoods and the pines, except that aspen has a relatively low bending strength. The natural decay resistance of aspen is low; untreated posts in contact with soil have a life span of only 2–4 years. Unfortunately, this disadvantage is hard to counteract because the heartwood is moderately difficult to penetrate with preservatives (Lamb 1967).

Aspen tends to crush or tear rather than cut cleanly when conventional machining methods are used because of its low-density properties. Machine settings suitable for higher density hardwoods will not produce a satisfactory finish on aspen. Based on tests of 50 samples, Cantin (1965) reported that only 58% of the pieces planed were defect-free; 66% of pieces shaped were good-to-excellent, 43% of turned pieces were good-to-excellent, and 67% of mortised pieces were fair-to-excellent.

The influence of *P. tremulae* decay upon strength of aspen wood was documented by Bach et al. (1983) and Wang and Micko (1985) from sample trees, 55–120 years of age, near Blue Ridge, Alberta. Tests included modulus of rupture (an index of toughness), modulus of elasticity (an index of stiffness), compression parallel to the grain, which indicates the load a post or column can support, and hardness, which indicates the resistance of wood to denting, as in flooring. Results of these tests performed on four classes of aspen wood (clear, stained, intermediate decay, and advanced decay) are summarized in Table 46.

Most strength properties of discolored wood ranged from 14 to 17% lower than those in clear wood, except ovendry side hardness, which showed a 30% reduction from clear to discolored conditions. Loss of strength when clear wood becomes discolored was not considered by Bach et al. (1983) and Wang and Micko (1985) to be sufficient to prevent its use in solid wood products, provided no impact load is expected. Clear aspen wood exhibited more than 8 times the strength of advanced decay wood. Intermediate decay wood retained about 60% of the original wood strength in the Alberta tests. Compared with other mechanical properties tested, hardness showed the most pronounced decrease in decayed wood. Stained aspen wood had only about 70% of the hardness of clear wood.

As with other species, wood density is one of aspen's most important wood properties because it is positively correlated with most strength properties of wood (Bach et al. 1983). Although sampling has revealed substantial variation in wood density of aspen and balsam poplar, in most cases the field forester or mill manager probably wants a single wood density value for calculation purposes. Mullins and McKnight (1981) give an average basic density for aspen, ovendry weight/green volume, of 0.37 g/cm^3. This is corroborated by several other references listed in Table 47 where the recorded mean values have an overall average of 0.369 g/cm^3. Aspen's wood density is higher when ovendry volume is used instead of green volume. For example, Mullins and McKnight recorded aspen's ovendry weight/ovendry volume as 0.41 g/cm^3.

For balsam poplar, Pfaff (1988) and others have reported that the basic wood density is generally about 0.02 g/cm^3 less than in aspen wood. The overall average of three recorded mean values in Table 47 indicates a basic density of 0.358 g/cm^3, ovendry weight/green

Table 46. Some aspen strength properties with varying degrees of stem decay. Values are means with standard deviation in brackets (Bach et al. 1983; Wang and Micko 1985).

Property	Clear wood	Discolored wood	Wood with intermediate decay	Wood with advanced decay
Modulus of rupture, green wood (N/mm^2[a])	44.0 (4.0)	38.2 (5.7)	28.3 (6.4)	7.9 (4.5)
Modulus of elasticity, green wood (1000 N/mm^2)	8.408 (1.523)	7.090 (1.585)	4.816 (1.508)	1.802 (0.995)
Compression parallel to grain, green wood (N/mm^2)	17.9 (1.4)	14.8 (2.6)	12.3 (2.1)	3.8 (2.5)
Compression parallel to grain, ovendry wood (N/mm^2)	62.7 (8.0)	54.1 (6.8)	40.8 (12.9)	16.0 (12.5)
Hardness, green wood (N[b])	1752 (297)	1239 (255)	983 (265)	290 (277)
Hardness, ovendry wood (N)	2290 (304)	1925 (203)	1817 (464)	495 (201)
Basic density, ovendry weight/green volume (g/cm^3)	0.37 (0.017)	0.34 (0.017)	0.34 (0.021)	0.19 (0.046)

[a] 1 N/mm^2 = 1 megapascal = 145.038 lbs/in.^{2}.

[b] 1 N = 0.2248 lb.

volume, for balsam poplar in the prairie provinces. Wood density for balsam poplar on the basis of ovendry weight/ovendry volume was not provided in the latest edition of *Canadian Woods*, but the 1951 edition listed it at 0.42 g/cm^3. Prairie provinces data summarized by Singh (1984) recorded it as 0.409.

The average wood density for aspen and balsam poplar for the main forested area of the prairie provinces is presented in the following table.

Species	Wood density (g/cm^3) Ovendry wt/ green vol	Ovendry wt/ ovendry vol
Aspen	0.37	0.41
Balsam poplar	0.36	0.41

The differences listed above are probably not of practical significance. The degree to which wood densities vary from the typical values listed is described in several recent technical reports (Bach et al. 1983; Yanchuk et al. 1983; Singh 1984, 1987; Wang and Micko 1985; Singh and Kostecky 1986; Micko 1988). The literature contains little data on density of aspen and balsam poplar bark. In Minnesota, Lamb and Marden (1968) recorded a mean density of 0.452 g/cm^3 for aspen bark (ovendry weight/green volume) with a range from 0.37 to 0.52 g/cm^3. In Michigan, Erickson (1972) recorded even higher values for aspen bark (mean 0.505 g/cm^3; range 0.446–0.602 g/cm^3).

It is not clear whether there are significant regional differences in aspen's wood density within the prairie provinces. Basic wood density (ovendry weight/green volume) sampled in 10 aspen clones in the Edson area of Alberta averaged 377 kg/m^3 for breast-height samples (Micko 1988). Basic density of individual clones ranged from 329 to 411 kg/m^3. Eleven different clones sampled in the Slave Lake area have an average basic density of 349 kg/m^3, with a range from 304 to 395 kg/m^3. Singh (1984), using ovendry wood density instead of basic wood density, compared the 10 major tree species of the prairie provinces. Mean ovendry wood densities and related statistical characteristics are summarized in Table 48. There were only slight differences in mean wood densities from one province to another, when samples from various parts of the tree stem were pooled. Among the hardwoods, balsam poplar had the lowest mean ovendry wood density (0.409 g/cm^3, standard deviation

Table 47. Basic wood density of aspen and balsam poplar from the prairie provinces

Sample type and source	Basic wood density (ovendry wt/green vol, g/cm^3) Range	Mean	Standard deviation	Reference
Aspen wood—clear:				
Alberta	–[a]	0.363	±0.011	Micko 1998
Unspecified	–	0.374	±0.024	Kennedy 1974
Alberta	–	0.37	–	Bach et al. 1983
Manitoba/Saskatchewan	–	0.38	–	Irwin and Doyle 1961
Alberta	–	0.379	–	Mackay 1975
Alberta	0.32 to 0.40	–	–	Yanchuk et al. 1984
Alberta	–	0.368	±0.016	Wang and Micko 1985
Alberta	–	0.348	–	Thomas 1987
Average of above 7 means 0.369				
Defective aspen wood:[b]				
Stained	–	0.34	–	Bach et al. 1983
Intermediate decay	–	0.34	–	Bach et al. 1983
Advanced decay	–	0.19	–	Bach et al. 1983
Stained	–	0.335	–	Mackay 1975
Stained	–	0.342	±0.017	Wang and Micko 1985
Intermediate decay	–	0.339	±0.020	Wang and Micko 1985
Advanced decay	–	0.190	±0.047	Wang and Micko 1985
Balsam poplar wood—clear:				
Alberta	–	0.37	–	Cyr and Laidler 1987
Alberta	0.30 to 0.38	–	–	Pfaff 1988
Manitoba	–	0.37	–	Irwin and Doyle 1961
Alberta	–	0.334	–	Thomas 1987
Average of above 3 means 0.358				
Defective balsam poplar wood:				
Stained, Alberta	–	0.356	–	Mackay 1975

[a] Not applicable.

[b] All from Alberta.

[SD] 0.040), compared to 0.424 g/cm^3 (SD 0.033) for aspen, and 0.607 g/cm^3 (SD 0.045) for white birch. Wood density in aspen varies according to position in the tree. Aspen density tends to be high near the base of the tree, decreasing to a minimum at mid-height on the stem, and then increasing again near the top of the tree (Yanchuk et al. 1983, 1984, 1988). At all heights, wood density tends to be higher near the pith than it is farther out on the stem cross-section.

The relatively low density of aspen is an advantage in manufacture of particleboard because moderate pressure will bring the individual particles into close contact, ensuring a medium-density board with good strength. In general, nail-holding power varies with specific gravity, with the result that *Populus* species have about the same ability as white spruce to hold nails and other fastenings (Kennedy 1974).

Moisture content, tension wood, and wetwood are other important variables in aspen and balsam poplar wood. Standing poplar trees have a high moisture content, typically as high as 100% of oven-dry weight, with only minor differences between sapwood and heartwood. Variation also exists between species, with black cottonwood and balsam poplar generally having higher amounts of moisture than aspen. Seasonal and species variations have important implications for application of a consistent drying schedule (Kennedy 1974).

Tension wood is common in aspen and poplar (Wengert 1988). It is associated particularly with the

Table 48. Mean ovendry wood density (ovendry weight/ovendry volume, g/cm^3) and related statistical characteristics for the major tree species in the main forested area of the prairie provinces (Singh 1984)

Tree species	Mean	Minimum	Maximum	Standard error of mean	Standard deviation
Softwoods					
Jack pine	0.451	0.354	0.518	0.004	0.034
Lodgepole pine	0.444	0.376	0.539	0.005	0.036
Black spruce	0.457	0.387	0.584	0.0004	0.034
White spruce	0.404	0.313	0.527	0.005	0.037
Alpine fir	0.399	0.328	0.592	0.007	0.051
Balsam fir	0.372	0.307	0.522	0.005	0.037
Tamarack	0.530	0.455	0.635	0.005	0.041
Hardwoods					
Balsam poplar	0.409	0.234	0.516	0.005	0.040
Trembling aspen	0.424	0.360	0.497	0.004	0.033
White birch	0.607	0.512	0.693	0.006	0.045
All ten species	0.450	0.307	0.693	0.012	0.293

upper side of leaning stems and branches. Tension wood is characterized by masses of gelatinous fibers and a reduced vessel (pore) volume. The gelatinous layer is not lignified, but instead is almost entirely carbohydrate material. Alpha cellulose yields as high as 60% of the weight of the wood have been reported for poplar tension wood. This relatively high cellulose content is not always advantageous, however, since longer pulp beating times may be required. Tension wood in poplars has a significantly higher longitudinal shrinkage than normal wood (Kennedy 1974). This can lead to bowing and crooking in lumber, as well as buckling of veneer when it dries.

In aspen and balsam poplar, the distinction between heartwood and sapwood is less important than recognition of areas of wetwood. Two types of wetwood can occur: wetwood formed from the aging of normal sapwood nearest the heartwood or injured sapwood, and wetwood developed in previously formed heartwood. The two frequently occur together and are difficult to distinguish (Ward and Pong 1980). Wetwood can also occur in roots (Sachs et al. 1974). Wetwood is associated with mixed populations of anaerobic bacteria and is usually characterized by a darkened appearance and higher moisture content than the surrounding wood (Kennedy 1974). The greater capacity of wetwood to absorb moisture helps to maintain anaerobic conditions and these conditions, in turn, inhibit fungi that could cause decay (Ward and Zeikus 1980). Phycomycetes, yeasts, and several bacterial species have been isolated from wetwood (Hinds 1985), but bacteria have also been found in normal aspen wood. The role of bacteria in formation of wetwood has not been ascertained (Bacon and Mead 1971; Etheridge 1961; Knutson 1973). Although aspen wood is basic, its wetwood can be either acid or more alkaline than normal wood (Knutson 1973). In balsam poplar, wetwood is slightly basic, in comparison to slightly acidic sapwood and neutral heartwood (Wallin 1954).

Wetwood occurs in both conifers and hardwoods but frequency varies by species, age, and growing conditions. Ward and Pong (1980) indicated that wetwood is generally prevalent in balsam poplar and has scattered prevalence in aspen. Aspen is one of the species for which wetwood has been recorded in young trees (Hartley et al. 1961). Second-growth aspen in northern Minnesota contained more wetwood than the original aspen (Bacon and Mead 1971). Wallin (1954) found a relationship between wetwood formation in balsam poplar and soil type.

Compared to normal wood, wetwood in aspen is characterized by higher moisture content, lower wood density, reduced toughness, reduced compression strength, and lower imperviousness to passage of air and water. Weakness of the wetwood zone can result in collapse between heartwood and sapwood following kiln-drying, although collapse in air-dried lumber is not as serious (Hinds 1985). There is a need for more accurate and rapid methods of identifing wetwood in green lumber for segregation into different drying sorts; optimum processing methods are not yet worked out for mixtures of normal wood and wetwood (Ward and Pong 1980).

From various sources, Wengert (1988) summarized aspen's wood properties, along with its responses to various treatments. Those characteristics are summarized in Table 49. No directly comparable assessment has been compiled for balsam poplar. Where balsam poplar has been compared to aspen it has been in the context of specific anatomical and physical features of the wood (Micko 1987), chemical composition (Cyr and Laidler 1987), pulping characteristics (Thomas 1987) or use in waferboard/OSB production (Pfaff 1988). For those aspen wood characteristics and responses listed in Table 49, available information suggests that they are generally applicable to balsam poplar as well. The coarser texture of balsam poplar, compared to aspen, and its higher incidence of wet pockets in the wood (Samoil and Boughton 1987) could be the source of some response differences between the two species.

The most comprehensive data sources for physical and mechanical properties of aspen and balsam poplar are: Forestry Branch (1951); Irwin and Doyle (1961); Kennedy (1965); Kennedy (1974); Mullins and McKnight (1981); and Forest Products Laboratory (1987). Mullins and McKnight (1981) contains data for aspen but not balsam poplar. It was, therefore, necessary to revert to Forestry Branch (1951) for data on balsam poplar for this comparison (Table 50).

Primary Wood-using Industries Based on Aspen and Balsam Poplar

In the prairie provinces and northeastern British Columbia the current main uses of aspen are waferboard (Fig. 51), OSB (Fig. 52), bleached kraft pulp, CTM pulp, lumber, and pallets. Due to its general availability and increased customer acceptance, the use of aspen is steadily increasing. The abundance of aspen has detracted from increased use of balsam poplar, even though balsam poplar is a suitable raw material for some of the same products for which aspen is used (Samoil and Boughton 1987).

As recently as the mid 1980s, analysts were pessimistic about aspen's role in the pulp industry, mainly

Table 49. Characteristics of aspen wood and its response to various treatments (modified from Wengert 1988)

Wood characteristics	Wood responses
White color in normal wood, but discoloration frequent in mature trees	Machines easily; dulls knives slowly; low energy requirements
After drying, wood shrinks and swells very little with changes in relative humidity	Grain tears occasionally, especially end grain, when machining
Warps during drying because of tension wood and high tangential to radial shrinkage ratio	Surface fuzzes occasionally in sawing, sanding, and machining
Mature trees are typically quite defective—many knots but most of them remain tight	Sapwood and normal heartwood dry very easily
Splinterless	Wears smoothly
Odorless when dry	Paints very well
Decays easily	Wetwood, when present, is very difficult to dry
Relatively light weight	Weak in bending
Indistinct grain	High in toughness
	Glues, stains, and inks well
	Pulps well
	Both bark and wood are digestible by ruminants

Table 50. Average clear-wood strength values for aspen and balsam poplar in green and air-dry condition (Forestry Branch [1951] for balsam poplar values; Mullins and McKnight [1981] for aspen values.)

Value	Green condition		Air-dry condition	
	Aspen	Balsam poplar	Aspen	Balsam poplar
Basic density (g/cm^3)	0.37	0.37	0.41	0.42
Shrinkage, green to ovendry, based on dimensions when green (%)				
Radial	3.6	3.9	2.7	–[a]
Tangential	6.6	6.4	5.7	–
Volumetric	11.8	11.6	8.3	–
Modulus of rupture (MPa[b])	37.6	33.8	67.6	66.1
Modulus of elasticity (MPa)	9 030	7 998	11 200	11 169
Compression parallel to grain, crushing strength maximum (MPa)	16.2	14.3	36.3	34.9
Shear strength (MPa)	4.95	4.48	6.76	6.38
Compression perpendicular to grain, fiber stress at prop. limit (MPa)	1.37	1.17	3.52	3.03
Tension perpendicular to grain (MPa)	3.04	2.21	4.19	3.34

[a] Not applicable.

[b] 1 MPa = 1 megapascal = 145.038 lb/in.^{2}.

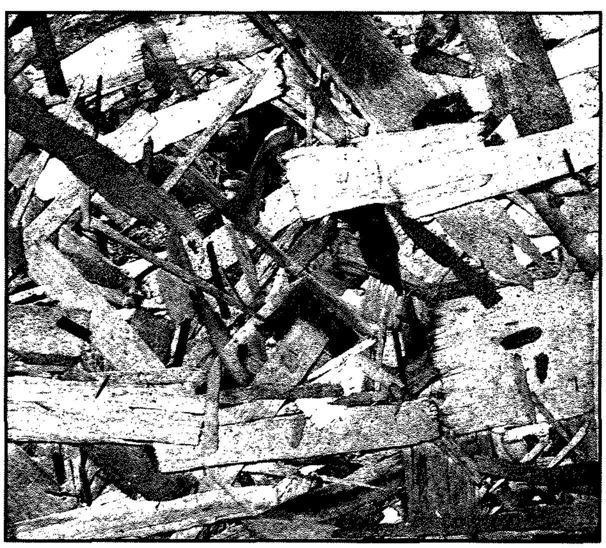

Figure 51. Reconstituted wood such as this waferboard is an ideal end product for aspen (photo courtesy of Alberta Research Council).

Figure 52. Oriented strandboard is another excellent end product for aspen (photo courtesy of Alberta Research Council).

because it has substantially shorter fibers than softwoods (Hipp Engineering Ltd. 1984). The requirement for chemical impregnation before pulping was considered to be a major disadvantage; without chemical pretreatment the resulting mechanical pulp would have poor bonding characteristics and low strength. The Hipp Engineering Ltd. study suggested that while mechanical or thermomechanical pulping of aspen may be possible in an integrated pulp and paper mill, it would not be practical for market pulp. This pessimism has rapidly disappeared as aspen, by the 1990s, has taken on a prominent role in the pulp industry of the western boreal region. Aspen is now recognized as an excellent raw material for pulp, paper, and particleboard products.

Aspen's importance in chemical pulping processes is continuing to increase and there is growing interest in the use of this fiber for printing grades of high-yield pulp (Breck 1987). Canada's tenth fine paper mill—the largest in western Canada and the first on the Canadian prairies—was completed in 1988 by Weyerhaeuser Canada Ltd. in Prince Albert, Saskatchewan. This mill, which is designed to annually produce 210 000 t of uncoated communication paper, mainly for bond, reprographic, and offset printing papers, and for forms and envelopes, is using 40% mixed spruce and jack pine and 60% aspen. The paper machine uses about 50% of the pulp mill's output at Prince Albert; plans call for annual pulp mill production to increase to 352 000 t/yr, with about 50% of that derived from aspen (K.E. Smith 1988).

Pulp

For chemical pulps, aspen fiber is ranked as the third highest quality among the world's hardwood species. According to Breck (1987), eucalyptus has the best fiber quality of any hardwood species, white birch is second, and aspen is third. Aspen is an excellent fiber for production of printing and writing paper. Decayed wood, incipient decay, and stain are viewed somewhat differently by the pulp and paper industry than is the case with solid wood products. For example, a patch of decayed aspen wood on a 2 × 4 stud will downgrade the entire stud, whereas the same amount of defect may be acceptable once it becomes blended into the homogenous mix that makes up pulp.

During incipient decay, fungal mycelia first attack the lignin in the fiber wall; this early decay symptom is unimportant in the resulting pulp product because lignin is not used in the chemical pulping process. When there is advanced rot, however, the cellulose structure is under attack and this has two effects on aspen utilization. The first is a reduction in yield of fiber and the second is a reduction in the intrinsic strength of the fiber (Breck 1987).

Although kraft pulping is the most forgiving of any of the pulping processes, even kraft mills cannot use raw materials in which advanced decay has progressed to total decay. If decayed aspen logs get into the kraft chipping process most of the decayed wood would be turned to powder by the force of chipping. This powder is removed by the screens and goes into a burner or waste disposal facility. The decayed raw material has no technical effect on the kraft pulping process, but it can increase the concentration of minerals significantly (Muhammad and Micko 1984). The main effect of decayed material is economic because the operator has been paid to bring wood to the mill, chip it, and then discard it (Breck 1987).

Wood quality is more important in the mechanical pulping process than it is in the kraft process. Aside from the loss of yield when decayed logs are used, stain and incipient decay require the use of more bleaching chemical, which is extremely expensive. Brightness level of mechanical pulp is critical if it is to break into the markets now held by kraft pulps (Breck 1987). In this context, aspen has an advantage over softwoods because it can be more easily bleached. This is a fortunate circumstance because stain is so prevalent in aspen; if it could not be readily bleached, the use of aspen for pulp would be far more limited.

The recent study by Econotech Services Ltd. (Thomas 1987) reported on results of tests to evaluate aspen and balsam poplar in comparison to eucalyptus for the following pulping processes: bleached kraft; bleached alkaline sulfite/anthraquinone (ASAQ); high yield sulfite; neutral sulfite semichemical (NSSC); bleached solvent (methanol); and chemithermomechanical (CTM). These tests revealed that chemical requirements for pulping of these hardwoods were lower than for softwoods. Compared to eucalyptus, aspen and balsam poplar produced kraft pulp of higher yield, but it was of somewhat lower strength. Balsam poplar kraft pulp was significantly higher in strength than that from aspen. One minor difference between the two species is that aspen yields slightly larger chips than balsam poplar. Both aspen and balsam poplar make satisfactory corrugating media using the NSSC process. Solvent pulping using methanol, as well as the ASAQ process, resulted in yields similar to kraft pulping. High yield sulfite pulping also produced pulps with good brightness. Thomas (1987), Cheyne (1990), and Karaim et al. (1990) have emphasized the suitability of aspen and balsam poplar for CTM pulp. For the forest manager wishing additional comparisons of aspen and balsam poplar in terms of pulping characteristics detailed information is available in recent reports by Cyr and Laidler (1987) and Thomas (1987).

Organosolv pulping processes may be well suited for use of all species in northern mixedwood stands, but some analysts have suggested that aspen may be the species best suited to organosolv pulping processes (Lora 1990). Although not yet developed beyond the pilot plant stage, the Paszner/Chang catalyzed organosolv process (Paszner 1986) is a representative example of this environmentally friendly alternative to kraft pulping. The Paszner/Chang process fulfills the desired conditions of short cooking time (30–40 minutes), high pulp yield with low lignin content and high pulp (cellulose) viscosity, and high pulp strength. Besides the high pulp yield, which provides 20–35% more pulp than the kraft process, this process results in valuable by-products. Other advantages of the organosolv pulping process include relatively low capital costs, very low process water requirements, low pulp manufacturing costs, and lack of environmental pollution. The latter feature is the main reason for lower capital costs than in sulfite and kraft pulp mills. Up to 50% of the capital cost for a kraft mill is for chemical recovery and pollution abatement. Since organosolv cooking liquors do not contain sulfur and the salts used as catalysts (calcium chloride, magnesium chloride, and magnesium sulfate) are environmentally harmless, effluents from the organosolv process do not require much treatment before discharge. Paszner suggested that integration of organosolv pulping with organosolv wood hydrolysis, would be more than double the output of Alberta's forests. In particular, the current high interest in the use of alcohol as an octane enhancer for gasoline in the United States could result in additional revenue that would have substantial effects on the profitability of using aspen for production of pulp and chemicals in western Canada.

A recent review by Dillén (1990) listed several advantages of the Alcell process, which is one of several different organosolv processes, and the Stake process, which is similar to CTMP (chemithermomechanical pulp) processes. The Alcell plant at Newcastle, New Brunswick, and the proposed Stake plant at Meadow Lake, Saskatchewan, which will accomplish defibration by steam explosion, will both use hardwoods exclusively. The relatively low lignin content of hardwoods, plus the fact that the lignin is concentrated in the middle lamella between the fibers makes hardwoods very well suited to these new pulping processes. Other advantages when compared with traditional pulping processes are: higher yield; lower capital costs; possibility of economically viable plants with low production capacity; an odorless process; and chlorine-free bleaching. Compared with CTMP, these new processes use less electricity and produce a pulp with greater strength (Dillén 1990).

Oriented Strandboard

Oriented strandboard production is now an important use for aspen, but less so for balsam poplar. This product is made of large, thin strands of aspen bonded together under intense heat and pressure. The ideal size of strands ranges from about 0.3 to 1.9 cm wide by about 7.5 cm long, by 0.06 cm thick (Russell Bohning, pers. com., November 1989). Waterproof phenolic resin makes OSB free of formaldehyde-related problems. Oriented strandboard is popular in the construction industry as a building material for paneling walls, and, roof and floor sheathing. Other uses include exterior cladding on farm structures, cottages, do-it-yourself projects, crating, shelving, and many other uses where toughness and sturdiness are necessary. Panels are easy to use with standard wood-working tools and fasten easily with conventional nailing or stapling techniques. Panels can be left unfinished or can be stained or painted. The standard 4 × 8 ft tongue-and-groove boards are available in 1/4-, 3/8-, 7/16-, and 5/8-in. thicknesses.

As of 1989, there were three OSB plants in operation in Alberta and two more were planned; in northeastern British Columbia, one OSB plant was in operation, and at least two more were planned. The main export markets are Texas, California, and Arizona, with new markets targeted for other southwestern states. Oriented strandboard is increasingly displacing plywood and other panelboards for wall, roof, and floor sheathing. Two of Alberta's existing OSB mills are experimenting with new products for home and office furnishings in which OSB is used either as the finishing surface or as core stock for veneer (Ondro and Bella 1987; Widman Management Ltd. 1987).

The OSB process tolerates more decay in aspen than is the case for lumber production (Denney 1987). For example, Pelican Spruce Mills Ltd. at Edson, Alberta, uses aspen logs that contain up to 50% incipient or advanced decay. Strongly decayed aspen, however, has no strength and is of no use in making wafers (Lars Bach, pers. com., November 1989). Where decayed wood does get into the OSB process it does not become part of the manufactured product. Instead it is added to the waste wood,which is used as fuel for drying strands. The harvest end of an OSB operation is where cull is important because logging and hauling are paid for on a firm-wood basis (Denney 1987).

For OSB production, balsam poplar is less desirable than aspen because it produces a fuzzier flake and is harder to dry. Balsam poplar also adds extra variability to board properties because there is greater variation in moisture content than in aspen. Pelican Spruce Mills Ltd. in Alberta has produced good OSB from pure balsam poplar but this requires a separate batch run and a different resin system than is used for aspen (Norman Denney, pers. com., October 1988). The Louisiana Pacific OSB mill in Dawson Creek, British Columbia, uses black cottonwood and balsam poplar in a separate production run and with a different drying schedule than aspen. The resulting cottonwood/poplar strands are used in the middle of the board because these species often have more darkly stained wood than aspen. By bonding aspen strands to the outer OSB surfaces, customer expectations of the clean, relatively white appearance that aspen gives to OSB is maintained even when cottonwood or balsam poplar are used in the core of the board.

Lumber and Plywood

Aspen lumber production continues to face special challenges because mostly clear decay-free aspen logs are essential for profitable lumber production. That is only one of the constraints to greater use of this species for lumber. Next to decay, poor dimensional stability during drying is the main problem limiting the use of aspen for lumber (Figs. 53 and 54). The presence of wetwood, uneven drying, and uneven machining are other problems in processing aspen for lumber (Wengert 1988). The frequency and severity of wetwood increases with age and log diameter. Specialized sawmills are needed to optimize production of random lengths and widths of sawn aspen lumber. Aspen requires from 2.5 to 4.0 times as long as softwood lumber to kiln dry (Rytz 1980; Ramananskis 1987).

Deterrents to aspen lumber manufacture are low yields because of small log sizes, expensive drying requirements, and the tendency of juvenile wood to warp (Bailey 1973). Aspen has not been favored for stud manufacture because of a high degree of warping and bowing due to the presence of tension wood (Mackay 1978), as well as checking and collapse due to uneven drying of wetwood areas (Brese 1977); however, a new sawing process called SDR (saw-dry-rip) substantially reduces warping and bowing when used with aspen and other hardwood species (Maeglin and Boone 1980, 1981, 1985; Judd 1982; Boone 1990; Maeglin 1990). Large-sized planks or flitches are sawn from a log and are dried at a high temperature. The flitches are then resawn, or ripped, parallel to the grain for lumber or studs. A modified SDR process has been used by small operators in the prairie provinces for several years (Russell Bohning, pers. com., November 1989).

Production of aspen and balsam poplar lumber or plywood results in enormous quantities of residue (Hiratsuka and Loman 1984). Lumber recovery from logs was estimated by Hiratsuka and Loman at only 15% of the total volume handled for one Alberta sawmill operation because of advanced and incipient decay. Even the kraft pulping process, although the most widely used of the pulping alternatives for use of decayed aspen, results in significant waste (Breck 1987). Both Neilson (1974) and Wengert (1988) considered it axiomatic that for an aspen lumber industry to be successful there must be more than one product involved, and a market for residues must be in place. Ideally, maximum use of harvested aspen would result from an integrated complex that included pulp, plywood, waferboard, lumber, and waste-using facilities (Hiratsuka and Loman 1984).

Uses of residue depend on whether one is dealing with fine residues and lumber residues (Nielson 1980). Potential uses of fine residues include animal bedding (particularly for feedlot cattle), poultry litter, fuel briquets, animal feed, soil amendment, potting medium, mulch, chemical spill absorbent, and wood flour. Lumber residue uses include toy blocks and toy parts, trellises, lathes, apiary parts, pallets, measuring sticks, stirrers, matches, shelving, and picture frames. Included with lumber residues are pulp chips, which are used in various pulp processes. Use of sawmill residues for production of medium density fiberboard (MDF) in Alberta was given a high rating in terms of technical feasibility by Woodbridge, Reed and Associates Ltd. (1985). Transportation costs are a problem, however, because the demand and market size for MDF in the prairie provinces is not big enough to absorb production. For this product, an economically viable mill must also be of relatively large size.

Fuel

Fuel values for aspen and balsam poplar are relatively low, but these species have other advantages as a fuel source. Aspen and balsam poplar were among the 10 tree species sampled in Manitoba for calorific values by Singh and Kostecky (1986). Calorific values for the stump, stem, treetop, bark, foliage, and branches are listed in Table 51 for six species of softwoods and four hardwood species. For all components combined, balsam poplar had the second lowest calorific value, 18.818 MJ/kg, just slightly higher than Manitoba maple; aspen had the third lowest calorific value (19.313 MJ/kg) of the 10 tree species. For the main biomass component, the stem, balsam poplar had the lowest value (17.709 MJ/kg) of the 10 species. In both aspen and balsam poplar the highest calorific content was in the treetop component (upper portion of stem). In aspen the lowest calorific content was in the stump (18.744 MJ/kg), and in balsam poplar it was in the foliage (17.660 MJ/kg).

Despite the relatively low calorific values shown for aspen and balsam poplar in Table 51 there are some compensating features of this abundant fuel source:

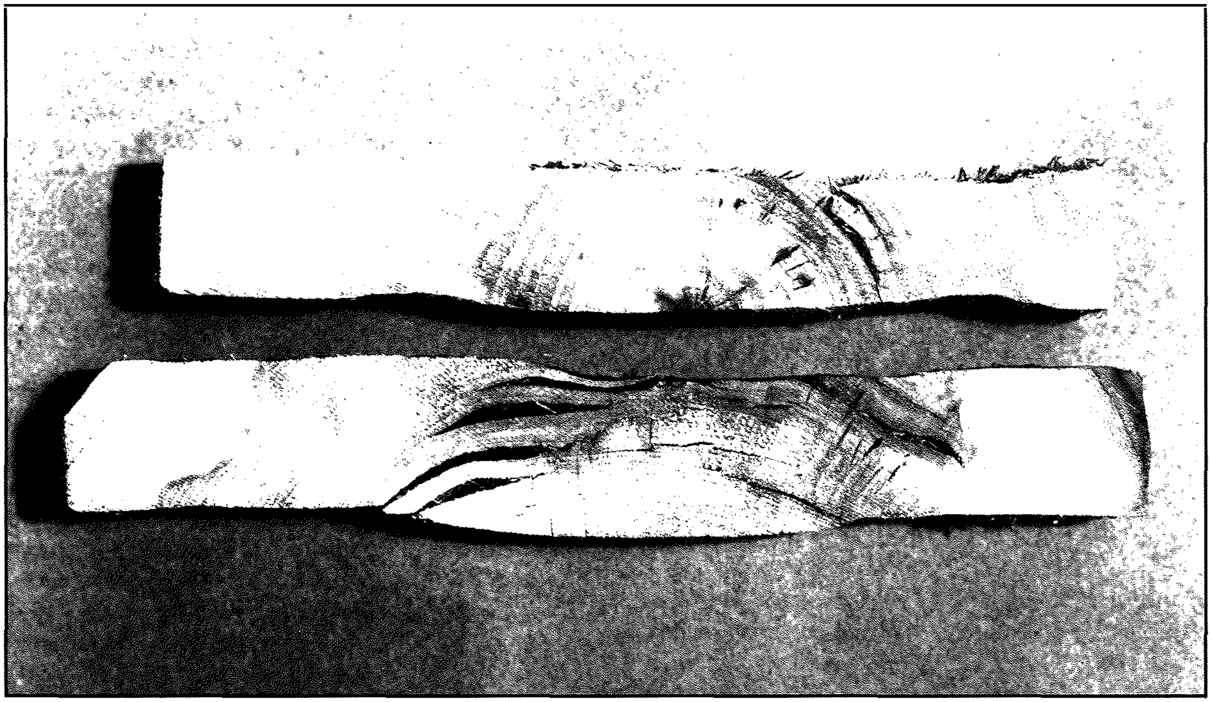

Figure 53. Major structural and dimensional problems exist for lumber production when unsound aspen wood is used (photo courtesy of A. Kabzems).

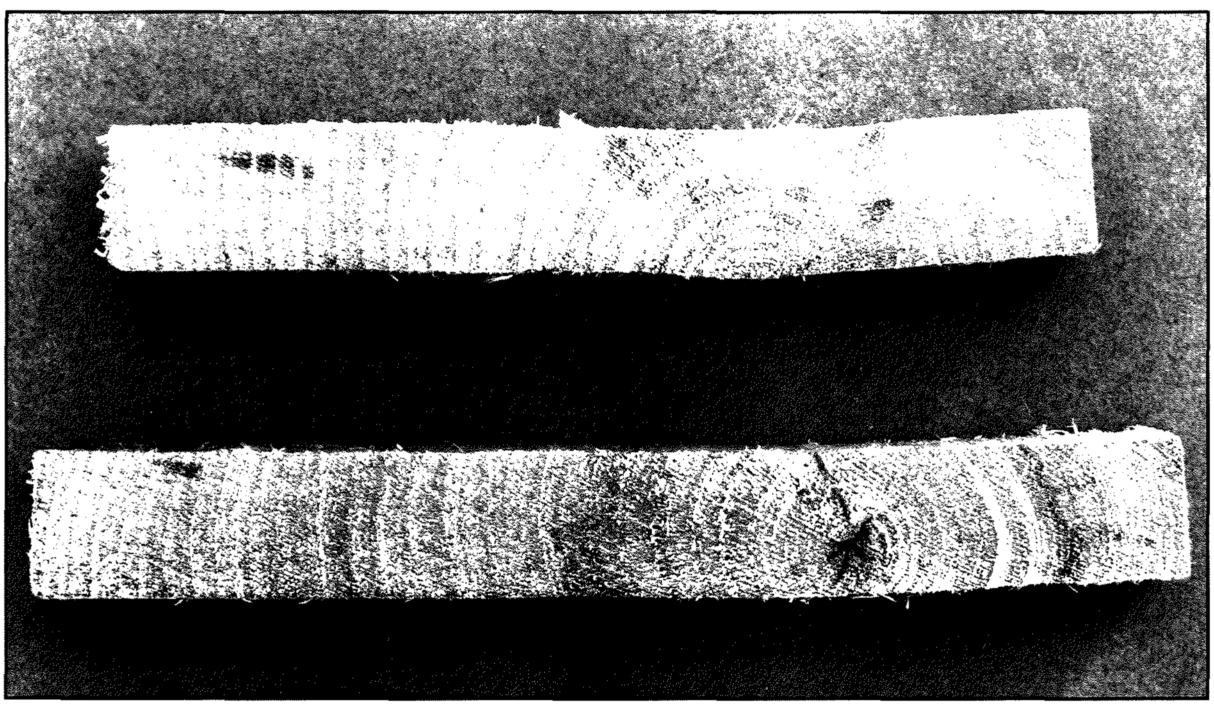

Figure 54. Even when stems appear to be decay-free, dimensional stability of sawn lumber is a problem in aspen (photo courtesy of A. Kabzems).

Table 51. Calorific values (MJ/kg) for aboveground components of aspen and balsam poplar in relation to other tree species in the prairie provinces (Singh and Kostecky 1986)

Species	Calorific values (MJ/kg[a])						
	Stump	Stem	Treetop	Bark	Foliage	Branches	Mean
Hardwoods							
Aspen	18.744	18.669	20.249	19.509	18.804	19.905	19.313
Balsam poplar	18.474	17.709	20.500	19.467	17.660	19.100	18.818
White birch	18.875	18.527	19.846	20.230	21.119	19.721	19.719
Manitoba maple	18.697	18.680	19.770	18.563	17.230	19.455	18.732
Mean hardwood	18.697	18.396	20.091	19.442	18.703	19.545	19.146
Standard error	0.193	0.201	0.193	0.386	0.467	0.179	
Softwoods							
White spruce	19.834	19.018	21.558	19.830	20.558	21.144	20.324
Black spruce	19.197	18.784	21.562	19.478	20.873	20.679	20.096
Jack pine	19.953	19.443	21.225	21.299	21.430	21.374	20.787
Eastern white cedar	19.370	19.960	19.542	18.737	21.446	18.668	19.620
Tamarack	19.889	18.783	21.283	19.490	20.089	21.463	20.166
Balsam fir	19.656	18.746	21.425	18.527	21.504	20.570	20.071
Mean softwood	19.650	19.122	21.099	19.560	20.983	20.649	20.178
Standard error	0.168	0.179	0.224	0.334	0.189	0.221	

[a] 1 MJ = 1 megajoule = 1×10^6 joules.

partly decayed wood and stems that are either very short or of poor form can be used as fuel; costs can be kept low because little processing is required; this fuel resource offers potential for small operators in remote locations; and fuel also serves as a good use for mill residues.

Singh and Micko (1984) estimated the gross potential of energy available in the volume of aspen and balsam poplar in the prairie provinces as 9665 petajoules (PJ) (1 petajoule = 10^{15} joules). If one assumes the recommended rotation age of 30 years for maximum biomass production from fully stocked dense aspen stands in the prairie provinces (Bella and De Franceschi 1980) then the 9665 PJ of gross potential energy could yield an annual energy production of about 322 PJ/year. Over 78% of this potential is represented by the merchantable stem, 13.9% by branches and foliage, and 7.5% by the nonmerchantable stem and stump. Singh and Micko (1984) estimated that if industrial use of hardwood merchantable stems is increased in the near future, the nonmerchantable portions could provide at least 72 PJ of equivalent energy on an annual basis.

Wengert (1988) provided the most detailed information on heat values for different moisture conditions of aspen biomass. Although Wengert's calorific values (MJ/ha) do not agree with aspen's oven-dry calorific value given by Singh and Kostecky (1986), they are presented in Table 52 to give fuel values to wood with different moisture conditions. Based on natural gas prices in 1987, aspen's fuel values per unit weight range from $17.90/t for green wetwood to $62.15/t for oven-dry bark (Table 52).

For economic reasons transportation distance from the source of supply should not be more than 100 km because of the relatively low heating value of aspen wood, compared to white birch (Wengert 1988). Despite this constraint, aspen has been used as fuel for industrial purposes for steam power, and as fuel for home heating and cooking. Capital costs involved with the necessary equipment for burning roundwood or mill residues to clean-air standards are additional constraints, especially if the wood has value for alternative uses. Wengert considered the present market for industrial fuel in existing mills to be small, especially if waste conifer wood is available as a source of fuel. Aspen's low weight per volume, rapid rate of burn when it is dry, as well as competitive prices from other fuels are deterrents to its industrial use as a fuel. This could change if petroleum fuels increase markedly in price.

The popularity of aspen and balsam poplar as firewood for home use in the prairie provinces is indicated

Table 52. Fuel value of aspen wood and bark under various moisture conditions (Wengert 1988)

Moisture content (%)	Condition	Heat available from wood of specified moisture content (MJ/kg)	Fuel value/t[a] (dollars)
Aspen wood			
0	Ovendry	16.51	60.42
10	Kiln dry	14.75	53.98
20	Air dry	13.28	48.60
40	Partially air dry	10.97	40.15
100	Green wood	6.82	24.96
150	Green wetwood	4.89	17.90
Aspen bark			
0	Ovendry	16.98	62.15
10	Kiln dry	15.21	55.67
20	Air dry	13.75	50.32
45	Green	10.93	40.00

[a] The fuel value of 1000 kg of ovendry wood was estimated as follows: 16.51 MJ/kg is equivalent to 16.51 GJ/t; in 1987 the average end-user cost of natural gas was \$3.66/GJ (Energy, Mines and Resources Canada 1988); therefore, the energy value of 1 t of ovendry aspen wood would be 16.51 × \$3.66 = \$60.42.

by the 30 000 m^3 cut for firewood by small private landowners in Alberta in 1987–88 (Ondro 1989). In the same year, cordwood cut from Alberta's commercial timberlands yielded another 11 500 m^3 of firewood, at a selling price of \$30–35/m^3 (\$80–90/cord). Most aspen and balsam poplar firewood is cut from two sources: as part of land clearing for agriculture on private lands; and from mixedwood spruce–aspen forest types on Crown lands. The high efficiency and low ash content of pelletized biomass fuel has the potential to greatly encourage use of aspen and biomass as an energy source (Russell Bohning, pers. com., November 1989).

Secondary Wood-using Industries Based on Aspen and Balsam Poplar

Secondary forest products comprise a varied group of remanufactured products derived from dimension lumber to make pallets, cartons, corrugated boxes, coffins, furniture, cabinets, trailer blocks, truck decking, and skids (Heit and Bohning 1988; Ondro 1989). Statistics Canada recognizes three major industry groups within the secondary forest products industry: wood industries; furniture industries; and paper and allied industries.

Very little secondary processing is currently carried out with aspen in the prairie provinces and northeastern British Columbia. Aspen lumber is typically used for low-grade applications such as pallets, rough boxes, or cable reels, all of which need little processing. Only a small quantity of aspen lumber is used for high value-added applications such as furniture, a situation not much different from the softwood industry in the prairie provinces (Karaim et al. 1990). Wengert et al. (1985), however, noted that there are special utilization opportunities because of aspen's odorless and splinterless wood and its good machining and gluing properties.

Specialty Products

The abundant supply of aspen and its low raw material cost in comparison to softwoods have not yet led to much of a change from the traditional pallet and box uses for aspen lumber (Rytz 1980; Wengert 1988). Specialty products such as furniture, however, have the potential to change this traditional picture (H.P.C. Construction Ltd. 1987; Reynolds and Donahue 1990). An example is Northland Children's Furniture of Spruce Grove, Alberta, which reportedly "can't turn out aspen furniture fast enough for eager customers throughout western Canada, Washington, Oregon, and California" (Forestry Canada and Alberta Forest Service 1989). This firm's best-selling items are baby cribs, which meet the standards set by Consumer and Corporate Affairs Canada. Other aspen products include change tables and commodes, high chairs, and toy boxes. For such products, the natural whiteness of aspen wood is a source of customer satisfaction.

From a variety of information sources, Karaim et al. (1990) summarized the requirements for manufacturing furniture from Alberta aspen:

Gluing: excellent gluing properties; Weldwood Prestoset or Lepage's Sure Grip gave equal performance; no staining problems.

Sanding: new belts required; must have sharp belt to prevent fuzzy finish; no major difficulties.

Finishing: both hot and cold spray lacquer tested and performed well; sealer coat (thinned) is required before application of two top coats.

Drying: six months to dry from a moisture content of 46% to 6%; some end checks; no serious problems.

Machining: very sharp knives are required for planing and cutting; dull knives result in fuzzy edges; when cross-cutting, ordinary steel saw blades are better than carbide tipped blades; no serious problems.

Fastening: very good for stapling; can staple right at ends of boards.

As the summary above indicates, there is evidence that as long as aspen lumber is graded and dried properly, there are no unusual problems in machining, fastening, gluing, sanding, and finishing. Consumer reaction to children's furniture manufactured from Alberta aspen has been encouraging. Both domestic and export opportunities appear to be abundant. Furthermore, children's furniture manufacture could serve as a spring-board into other lines of furniture manufacturing. Further expansion of this industry would benefit from steps such as: encouraging the selection of high quality clear wood from standard dimension mills; continuing to educate representatives of the primary and secondary forest industry on topics such as custom lumber drying and hardwood grading; and assisting the secondary industry in marketing and capital expansion (Karaim et al. 1990).

Shingles and Shakes

Production of aspen shingles or shakes does not look promising in the forseeable future. Prototype aspen shingles from the Lac La Biche area, Alberta, were evaluated by Silvacom Ltd. (1988), with the general conclusion that they were not suitable for roofing applications. The prototype required improvements to quality by elimination of knots, insect holes, and flat-sawn portions. The prototype revealed a need to increase the thickness and to produce taper-sawn shakes. The shakes show potential as a good roofing product. The Silvacom study recommended that jack pine shake production should be given a higher priority than aspen shake production in the prairie provinces.

Chopsticks

Estimates vary from 40 million to 130 million for the number of pairs of disposable chopsticks used and thrown away in Japan every day of the year (Tonan Commerce Ltd. 1987; Kirkwood 1989). Disposal of chopsticks after single use is not simply a result of affluent consumers; it is almost impossible to sanitize a wooden chopstick that has been used. Sterilization with concentrated dry heat would produce charcoal, wet heat would produce wood pulp, and irradiation is too costly. In both Japan and Korea, chopstick-making has remained a cottage industry, with no large plants for mass production. Furthermore, sources of suitable wood are scarce in those nations. It is uneconomical to attempt large-scale production where a suitable wood supply is scarce because only 40% of a log can be turned into chopsticks. For economic reasons, chopstick production must be located close to the source of the raw material (Kirkwood 1989).

Siting of plants for economical, large-scale production of chopsticks is challenging. Earlier site-selection surveys revealed that in northeastern British Columbia there was simply inadequate harvesting of aspen of appropriate size to justify a chopstick manufacturing mill (Kirkwood 1989). In Alberta, the aspen resource was scattered over too wide an area to be acceptable. The search criteria required stands of high grade, veneer-quality aspen that were already being harvested for other purposes. It was also necessary for such stands to be in an area of good accessibility.

Despite these rigid criteria, which resulted in slow development of chopstick manufacturing plants in Canada's boreal forest region, there were several new initiatives in 1989. Daesung Canada Inc. was building a plant in Prince George, British Columbia, to produce semifinished chopsticks that will be finished in Korea. Dawson Creek Chopsticks Inc. was also planning to use aspen to produce 144 000 cases of high-grade chopsticks each year. In Alberta, a joint venture between the Sturgeon Lake Indian Band, the Government of Alberta, and China's Harbin International Corporation for Technology and Economic Cooperation was planning a production facility near Valleyview, Alberta, to produce 15 million aspen chopsticks/day.

Aspen's light-weight, tough, colorless, tasteless, and odorless wood meets the current customer expectations for chopsticks. Furthermore, aspen is an abundant resource that is expected to be available after consumer preferences have become well entrenched. It has also been a relatively inexpensive raw material compared to other North American woods (Kirkwood 1989). Despite these potential advantages, aspen accounted for only 15% of the disposable chopsticks consumed in Japan in 1987; about 70% of them were made of cedar, spruce, or true firs (Tonan Commerce Ltd. 1987). The Tonan report suggested that the choice of species for this use was strictly a question of price, and that there was no firm evidence that aspen chopsticks are preferred by Japanese diners. There are, however, very strict quality requirements for clear, smooth, straight, and neatly separatable chopsticks. One difficulty in developing a market for disposable chopsticks is that distribution channels are complicated. Sale to an importer, or to a manufacturer if the chopsticks are semifinished, is the most common way to put aspen chopsticks into the Japanese marketplace (Tonan Commerce Ltd. 1987).

Chemical Feedstock

Use of aspen and poplars as a source of chemical feedstock is an active field of biotechnology research. The genus *Populus* is a preferred feedstock for alcohol production because this genus has a relatively low lignin content and its lignin is relatively easy to extract compared to that in softwoods. Present technology indicates that there are not likely to be any facilities built solely for ethanol production, but combined production of ethanol and lignin from *Populus* feedstock appears to be feasible. Bacterial enhancement of biochemical recovery of aspen raw material is an active field of research (Douglas 1988).

Production of liquid fuels from wood residues continues to attract interest. Direct liquefaction of wood residues from aspen has been developed at the laboratory scale by researchers at the University of Saskatchewan, University of Toronto, B.C. Research, and U.S. Bureau of Mines. The technology offers a sufficiently high conversion efficiency, but problems of scale of operation for commercial production versus the size of existing forest product operations require assessment (Ondro 1987).

Researchers at the University of Saskatchewan in the 1980s studied the conversion of poplar wood to an oil-like material that has a lower oxygen content and higher heat of combustion than the original wood (Eager et al. 1981, 1982; Eager, Pepper, and Mathews 1983; Eager, Pepper, Roy, and Mathews 1983; Mathews et al. 1985). These studies were in search of a substitute for Bunker-C fuel. Subsequent efforts have upgraded the oil, prepared by liquefaction of aspen wood, to yield a product rich in benzene, toluene, xylenes, and higher-molecular-weight aromatics that are valuable as components of gasoline.

Livestock Feed

Despite considerable research, aspen wood and bark are not yet widely used for livestock feed. Opinion is divided among animal nutrition specialists on the potential role of aspen for livestock feed. For example, Mellenberger et al. (1971) considered their results to be a successful demonstration of aspen bark as feed for goats. In contrast, when aspen wood and bark were chipped, Mathison et al. (1986) concluded that this material had limited potential as feed for cattle and sheep. Karaim et al. (1990) indicated there were still unanswered questions about this use of aspen, including the economic reality of an abundance of other low-cost livestock feed in Alberta.

Despite this degree of skepticism, there is a recurring interest in use of aspen for animal feed. Mathison et al. (1986) indicated that the main reasons are that aspen has the highest digestibility of native boreal tree species, and is more sensitive than most other trees to processing methods used to increase the nutritive value of feed derived from wood. The potential use of aspen as a livestock feed is of particular interest in Alberta where a relatively large area of land is covered by aspen.

In the case of aspen bark, much of the interest has come from forest products analysts anxious to do something with this commonly unused biomass. Among the benefits of using bark for animal feed are: elimination of pollution and costs associated with bark disposal procedures; availability of aspen bark rations at relatively low cost compared to conventional animal feed; and increase in return on capital investment for the aspen-using industry (Sourial 1981).

Measurements by Fritschel et al. (1976) indicated that aspen bark contains 53% carbohydrates but only 1.5% protein. The low protein content suggests that the best use is as feed for animals kept at maintenance levels. Alternatively, it is possible to mix and pelletize high protein material with aspen bark. Sheep fed on balanced nutritive rations consisting of 72.5% aspen bark gained more weight than those fed on 100% alfalfa and hay (Fritschel et al. 1976). Rations of steamed bark optionally treated with ammonia or alkali appear to provide a useful extension of forages such as alfalfa and hay.

When whole mature aspen were chipped and then ground through a hammer mill equipped with a 9.5-mm screen, Fritschel et al. (1976) reported on the resulting wood–bark mixture composition in comparison with alfalfa–grass hay harvested in September (Table 53).

In the trials by Mathison et al. (1986), digestibility of dry matter by cattle was 65% for hay, 53% for

Table 53. Analysis of wood–bark mixture composition in comparison to harvested alfalfa–grass hay mixture

Component	Alfalfa–grass hay	Ground aspen	Aspen–hay mixture[a]
Dry matter (%)	84.20	61.20	74.50
Organic matter (%)	90.20	93.30	91.50
Crude protein (%)	14.20	2.40	9.20
Hemicellulose (%)	13.90	15.20	14.40
Calcium (%)	1.29	0.49	0.95
Phosphorus (%)	0.25	0.06	0.17
Gross energy (Mcal/kg)	4.28	4.47	4.35

[a] Aspen–hay mixture comprises 58% hay and 42% aspen on a dry matter basis.

aspen–hay mixture, and 37% for ground aspen. Digestibility of aspen was even lower in sheep (31%), compared to their digestion of 63% of hay dry matter. It was on this basis that these researchers concluded that aspen had limited potential as livestock feed, especially for sheep. On the basis of the digestibility values, ground aspen would be worth only about 75% as much as barley straw for cattle, and only 50% as much as barley straw for sheep. These results confirmed the need to further upgrade ground aspen before it would be useful in cattle or sheep diets.

Mills devoted exclusively to production of aspen pellets for cattle do not yet exist in the prairie provinces; however, by 1988 an alfalfa pelleting mill in central Alberta was producing a small volume of fiber-rich aspen pellets for cattle feed. These pellets contain added protein, vitamins A, D, and E, and minerals. This product is considered to be an excellent feed supplement for cattle, but as of 1988 expanded aspen pellet production was being deferred, pending results of tests to evaluate the effects of this feed on cattle reproduction (Ondro 1989).

Some researchers suggest that fermentation of aspen wood shavings by isolates of wood-rotting fungi could form the basis of a practical system for converting poplar into feedstuff for ruminants (Reade and McQueen 1983). Feeds with digestibility comparable to conventional roughages can be produced in as little as 3 weeks by the appropriate selection of microorganisms, wood substrate, and fermentation conditions.

Economic Factors in the Utilization of Aspen and Balsam Poplar

The aspen and balsam poplar resource presents many of the same economic challenges that are familiar to softwood users. As with softwoods, an important objective is to identify the stand characteristics at harvest age that will offer the best return on investment. This requires decisions on what species mixes and what log sizes yield the best returns, and what ages are required to meet these optimum returns.

Beyond the economic factors that are common to softwood and hardwood management, aspen and balsam poplar have some additional features of economic importance. For example, historically aspen has been greatly underutilized (Maini and Cayford 1968; Wood 1967; DeByle and Winokur 1985). For many decades, aspen harvesting was characterized by removal of only the highest quality stems. Furthermore, harvesting costs that are high relative to product values have inhibited aspen use (Wengert et al. 1985). This is one of the reasons why there is a need for more developmental research into hardwood harvesting machines that would improve productivity, reduce the amount of wood handling, and reduce capital costs (Schneider 1988). Although felling and limbing costs are less for aspen than for conifers of the same size, this minor advantage is offset by the fact that aspen logs with decay can usually not be profitably sawn for lumber and they also reduce yields for pulp and OSB production. Experience to date suggests that profitable residue utilization is the key to successful processing of aspen wood products (Wengert 1988).

The traditional arguments against economical use of aspen centered on the presence of decay and poor market acceptance of aspen products (Thomas 1966; Wood 1967; Fregren 1980; Wengert et al. 1985). Attitudes have changed, however, partly because of the realization that the aspen–poplar resource in Canada is immense and, more importantly, much of it is very accessible. Other reasons for a change in attitude are technological advances, reduced availability of coniferous resources, new economic forces, changes in market opportunities, and better information on the volume and location of aspen resources (Beck 1988).

An obstacle to successful use of aspen is that its products have traditionally had to be priced low to compete with softwoods. In addition, Wood (1967) considered transportation costs to be particularly critical as a limiting factor for boreal hardwoods. Woodbridge, Reed and Associates Ltd. (1985) came to the same conclusion. Even more recently, Ramananskis (1987) estimated that aspen pallets could be economically hauled only 480 km. Another limiting factor is competition from increasingly available alternative products manufactured closer to market areas (Wood 1967; Wengert et al. 1985; Ekono Consultants Ltd. 1986; Breck 1987).

The evolution of hardwood use in Saskatchewan over the past 15 years exemplifies that major economic development of this resource depends on bulk users. In the 1970s, there were several attempts to manufacture aspen or poplar products in Saskatchewan, but none of these were economically successful. By 1973, however, the MacMillan Bloedel operation at Hudson Bay, Saskatchewan, was harvesting 330 000 m^3/yr of hardwood; this had increased to 407 000 m^3/yr by 1988. More important than this increase was the development of an integrated approach to hardwood harvesting, which has resulted in balsam poplar now making up about 15% of the harvested hardwood in the Hudson Bay area of Saskatchewan (Little 1988b). Another bulk user in Saskatchewan is Weyerhaeuser Canada Ltd., at Prince Albert, which in 1988 had a planned use of 433 000 m^3/yr of hardwood pulp (Smith 1989).

These examples of bulk users do not belittle the importance of searching for viable ways to use the hardwood resource for more demanding product standards, such as the current interest by FORINTEK in assessing the quality of hardwoods for lumber in the Carrot River area, Saskatchewan. It is unlikely, however, that specialized uses of aspen will ever replace bulk uses as the mainstay of the boreal hardwood industry.

What is aspen on a farm woodlot worth today if an industrial market exists? The most recent comparisons of economic returns from agricultural and aspen woodlot crops is the study prepared by Massie et al. (1990). An earlier source of information (Pearson 1988) is used here. In early 1988, aspen logs delivered to a mill in northeastern British Columbia had an average market price of \$21/m^3, and ranged from \$18/m^3 to \$25/m^3. At the same time, spruce and pine logs had an average delivered price of \$27/m^3, ranging from \$25/m^3 to \$30/m^3.

Pearson estimated the value of aspen on a farm woodlot as follows. If the farm aspen stand is 70 years old and merchantable, a volume of 230 m^3/ha at an average price of \$21/m^3 would provide a gross revenue of \$4830/ha. Net return after contract logging was estimated by Pearson to be about \$1020/ha (before tax and allowance for overhead). The current values of aspen on idle land, at ages of 10, 20, 30, 40, and 50 years were estimated as follows:

Age of aspen	Value/ha at age 50	Present value/ha
10	\$756.12	\$ 27.25
20	756.12	64.52
30	756.12	152.73
40	756.12	361.62
50	756.12	855.93

These estimates were based on the following assumptions: harvest at age 50 with a volume of 163 m^3/ha; purchase price at mill is \$21/m^3; logging cost delivered to mill is \$16.25/m^3; no overhead costs because they are already being paid; reforestation is by suckering, at no cost; and the interest rate is 9%. On the basis of these assumptions, the average gross return ha^{-1} yr^{-1} is \$78.11, and the average net return is \$17.12 ha^{-1} yr^{-1}. How does this estimated return from aspen compare with the return from cereal crops? Based on data from Saskatchewan, Fautley (1988) made the following estimates, ignoring years of crop failures:

Factors	Barley	Aspen
Expected annual yield/ha	2.31 t/ha	3.0 m^3/ha
Expected price/unit	\$46.00/t[a]	\$28.00/m^3
Gross annual return/ha	\$106.00/ha	\$84.00/ha

[a] Based on \$1.00/bu.

The estimated annual yield for aspen is based on an average stand of 112 m^3/ha. Assuming a 40-year rotation for aspen, the sustainable yield and allowable cut would be about 3.0 m^3 ha^{-1} yr^{-1}. When costs of production are considered for the Saskatchewan example, the estimated net return from barley is \$12.10 ha^{-1} yr^{-1} and for aspen is \$34.00 ha^{-1} yr^{-1}.

It is difficult to make direct comparisons of costs and returns for aspen and for cereals as crop alternatives. There are other economic considerations for cereal crops such as an estimated \$2.50/ha for Western Grain

Stabilization premiums, $7.40/ha for crop insurance premiums, and $12.50–25.00/ha under programs such as the Special Canadian Grains Program. These federal expenditures could be saved if marginal land were kept in aspen crops. Another factor not considered in the barley–aspen comparisons by Fautley is that there are sometimes crop failures and there is not necessarily a barley crop each year because of summer-fallowing. For example, if one year in three is summer fallow, the estimated annual return from barley should be reduced by one-third.

Policy, Management, and Regulatory Criteria for Use of Aspen and Balsam Poplar

Analysts in both northeastern British Columbia and Alberta have come to similar conclusions that the recently increased use of boreal hardwoods requires policy changes. For Alberta, Beck et al. (1989) noted that policy issues related to aspen use need to be examined in relation to harvest and use of existing forests, and establishment of future forests. Present policies in both of these broad subjects are still influenced by a conifer bias that evolved when aspen was commercially valueless. Now that it is no longer considered valueless, policies must be modified to recognize this ample resource.

In northeastern British Columbia, until recently the Ministry of Forests focused its attention on the coniferous resource. This traditional focus is now being altered at two levels. At the broadest level, forestry uses of land are being weighed against other uses such as agriculture, grazing, wildlife, recreation, and petroleum and hydroelectric developments. At the second level, within the forestry option, there are new land-use questions because existing or proposed commercial uses of the hardwood resource are rapidly changing the traditional concentration on conifers. Such changes require informed debate about the areas to be managed specifically for conifers, hardwoods, or mixedwood stands.

The land base that has the potential to produce hardwoods in northeastern British Columbia is facing pressure because of concurrent interests for several alternative land-use objectives. These objectives include conversion to conifer forests to meet commitments to existing conifer-based wood industries, conversion to agricultural land, although this has decreased recently, and conversion to wildlife habitat, involving controlled burns. The decreasing land base available for hardwood production is of major concern because it is the source of all raw material for the proposed hardwood industries in northeastern British Columbia (Peterson, Kabzems, and Peterson 1989).

Several prevalent circumstances have shaped present policies for management of boreal hardwoods. The first is that a relatively large proportion of aspen and balsam poplar in the prairie provinces is decayed to the point that utilization potential is limited. Furthermore, the lack of data to accurately quantify aspen and balsam poplar and plan for its use on a sustained yield basis has been a barrier to its use (Peterson, Kabzems, and Peterson 1989). As long as there was not intensive utilization of these hardwoods, there was little demand for more detailed inventory data on age-class structure and cull factors, and even less incentive to develop new policies for their management.

Most aspen harvesting is currently directed at pure stands (Henderson 1987). This is not surprising, because cutting hardwoods and softwoods from the same stands is easier said than done. Cutting rights for mixedwood stands are often held by two parties, one for the hardwoods, and one for the softwoods. This circumstance contributes to conflicts over the scheduling of road development, as well as different priorities for road maintenance, skid-trail development, and slash disposal (Harry J. Johnson, pers. com., July 1990). Rotation ages and harvesting times differ for hardwoods and softwoods. Unless carried out by the careful techniques recently developed for mixedwood harvesting (Sauder and Sinclair 1991), aspen extraction often damages the spruce that is not yet ready for harvest. Delaying the aspen harvest until the spruce is mature results in unusable, badly decayed aspen. Fortunately, these circumstances are changing on two fronts. New information is available on how to limit damage to understory spruce when older aspen are harvested, and attitudes are changing to allow both the hardwood and softwood components to be viewed as crops.

Similar circumstances exist where policy changes are required for the delineation and administration of forest land and agricultural land. For example, use of boreal hardwoods as a crop represents a major shift in thinking in northeastern British Columbia where aspen, until recently, was regarded as a weed. Integrating forestry and agriculture on the same land base requires attitude changes from individual farmers and ranchers whose lands support forests, as well as from administrators of Crown lands.

One idea that has evolved is to integrate agriculture and forestry by marketing a parcel of agricultural land and a woodlot as a package. The operator would then have the potential for improved viability through diversification. The commercial use of boreal hardwoods, however, is so recent that there is little experience and information to assist an operator in making sound economic decisions, such as whether it is economically better to wait 10 years to log an area and continue to operate a woodlot, or to clear the land for agriculture now (Max Nock, pers. com., January 1988).

The choice between forestry and nonforestry uses of hardwood-dominated land is not an easy decision. Phillips et al. (1988) described a method used in the Peace River region of Alberta for determining the opportunity cost of removing land from timber production. If forestry is the selected use in the first level of land-use choice, then the second level of choice is between achieving pure hardwood, pure coniferous, or mixedwood stands. Some of the approaches being applied in Alberta in the zone where agriculture and boreal forestry are in close contact, such as industrial procurement of wood from small private landowners, indicate that innovative steps are often possible even in the absence of clearly defined policy.

Where there is a choice between forestry or agriculture, flexibility is needed in land-use policies. Recent interviews in northeastern British Columbia revealed a consensus that investments in forest land, such as conifer planting and site preparation, should only be undertaken where there is a reasonable likelihood of harvesting the future forest crop (Peterson, Kabzems, and Peterson 1989). For example, after an area has been logged, the agricultural capability of the land should be reevaluated. If there is the possibility of future conversion to agricultural use, boreal hardwood species should be considered as acceptable regeneration because hardwoods can be marketable in a relatively short term, perhaps as little as 30 years. Investments into conifer establishment should only be made where there is little chance of agricultural demand for the land before the next rotation. Within existing agricultural lands, nonarable portions could be managed as woodlots for hardwoods. These suggestions point to the importance of flexibility in encouraging more rational management of the land base. One element of such land management is planning forestry roads to facilitate agricultural development. Range burning for forage management is also a common practice that would need to be curtailed if long-term hardwood management becomes the main land use in such areas.

Overlapping tenures, in which one tenure provides the softwood resource to the traditional softwood industry and the other provides a hardwood resource to a new industry raise many questions because policy is still being developed in this area. Clearly, new policies are needed for better administration of overlapping hardwood and softwood tenures. The Alberta experience illustrates that there are still more questions than answers. Policy questions recently summarized by C. Smith (1988) included the following:

- What tenure carries priority?
- Should any tenure carry priority?
- How much softwood must be present in a mixedwood stand for the softwood to carry priority or conversely how much hardwood must be present for it to have priority?
- How do administrators encourage logging operations to be integrated so that both resources are removed in one operation or, if that is not possible, how long a period can be tolerated between the two operations, particularly where the first operator is anxious to reforest?
- Where Crown land administrators are now allocating significant volumes of the hardwood resource, what should be done with softwoods in the understory? Should the softwoods be written off?
- At what stocking level for understory spruce should there be insistence on its protection?
- How can operations be scheduled in the same mixedwood stand when the hardwood resource matures up to 40 years earlier than the softwoods?

These important questions cannot be answered in this report; however, they do indicate that the establishment of a viable hardwood industry has introduced a new level of policy considerations that need to be addressed free of the conifer bias that has guided policy to date. Recent initiatives in Alberta include the development of harvesting policies that encourage companies to exchange wood of secondary interest to get access to species of primary interest, the bartering of different qualities of logs such as trading large aspen logs with center rot to an OSB plant in exchange for smaller sound aspen logs for pulping, as well as the use of overlapping coniferous and deciduous harvesting rights owned by one company as a way to optimize the integration of mixedwood harvesting (Henderson 1988a). In Alberta, Millar Western Industries Ltd. and Pelican Spruce Mills Ltd. have overlapping harvesting rights on several of their operating areas, and the recently announced Daishowa Canada Co. Ltd. and Alberta Newsprint Co. Ltd. projects will also utilize both coniferous and deciduous species. These overlapping harvesting rights and demand for both species will encourage one-phase logging.

Product Standards for Aspen and Balsam Poplar

A recent comprehensive review of forest management in relation to end-product quality stressed that forest managers should produce trees that are adaptable to many manufacturing processes instead of aiming for specific end uses that may no longer exist by the time the trees are harvestable (Barbour and Kellogg 1990). This advice applies to aspen and balsam poplar as much as it does to other species. In the case of these boreal hardwoods, one of the first steps to ensure adaptability to various manufacturing processes is to minimize incidence of decay in the harvested product. The defect level in aspen can directly affect whether the resource is economical to pulp (Breck 1987; MacLeod 1987).

Although the significance of decay to commercial use of aspen is well documented, one major problem is how to predict the extent of decay in existing or future hardwood stands. A further complication is that decay is unpredictably distributed throughout the tree. This means that if only 10–20% of the wood is decayed manufacturers still have difficulty recovering the sound wood economically. Timing is critical in the successful use of aspen because trees must be harvested after they are large enough for manufacture but before decay is well advanced (Woodbridge, Reed and Associates Ltd. 1985). The incidence of stem rot may decrease in the long term as aspen use expands and as increasingly younger stands are harvested. Some analysts have suggested that this could have the affect of increasing the relative importance of root rots and foliar diseases (Bryson 1989).

An earlier section indicated that there are severe constraints on aspen's use in lumber products because of the requirement for very high quality logs. Such logs are available on some sites, but their use is economical only if small operators can log them on a highly selective basis. This presents some problems because clear-cutting, rather than selective logging, is considered to be a prerequisite for good regeneration of aspen. Another difficulty with selective removal of high quality aspen logs is that they are often difficult to identify until the tree has been felled and bucked (Fig. 48).

As with most species, the most important aspen log is the butt log (Petro 1987). There is evidence that previous poor utilization and lack of clear-cutting has resulted in some second growth aspen stands of lower quality than original stands (Jarvis 1968). Several analysts have noted the need for further tests on scanning techniques, using portable field equipment, for detection of moisture and decay in standing trees (Swanson and Hailey 1987; Morley 1989).

These limitations will diminish as operators move away from the current practice of harvesting aspen mainly for a single use. If harvesting is followed by sorting of logs for integrated uses such as lumber, OSB, particleboard, or pulp then the forest manager can plan on area harvests with the assurance that raw material is directed to its best use. This type of sorting does add to operating costs.

Wetwood creates special problems for aspen product standards. Wetwood areas are hard to dry because they have such high moisture content (up to 160% of dry weight). Sawn aspen or balsam poplar wood that contains wetwood is more costly to dry (Ward and Pong 1980; Ward and Zeikus 1980; Ward 1986; Wengert 1988). Wetwood areas are relatively impermeable. Plugging of vessels with tyloses or with excessive amounts of extractives is the main cause of reduced permeability and increased drying time in aspen and balsam poplar wetwood (Kemp 1959; Petric 1972; Ward 1986).

The recent suggestion by Petro (1987) that improved marketability requires changes to present grading criteria for aspen lumber indicates that product standards for aspen are still evolving. There is an opportunity to focus on positive features in addition to the traditionally emphasized negative attributes because many product standards are not yet well established for boreal hardwoods.

The negative features that affect product standards include prevalence of decay and the variability and unpredictability of stain and decay within stems as well as a high incidence of crook in stems, and difficulties in debarking aspen stems. On the positive side, boreal hardwoods grow rapidly and have now been shown to be suitable for a wide variety of chipped, flaked, or pulped products. Other advantages include: good bleachability for paper-making; good absorption because of short, thin fibers; and good suitability for chemical pulping because of the high polysaccharide and low lignin content.

Marketing of Aspen and Balsam Poplar Products

Local policy guidelines and management practices are often mismatched with market realities. The demand for aspen products took a long time to develop, yet it caught local and regional forest managers unprepared (Denney 1988a). In northeastern British Columbia, forest managers were still viewing aspen as a species to eradicate or to classify as not sufficiently restocked lands at a time when there was already strong international interest in the boreal hardwood resource (Consulting

Foresters of British Columbia 1988). Fortunately, the Forest Resource Development Agreements of the late 1980s in the prairie provinces did have a strong focus on aspen and balsam poplar in terms of commercial development and market potential.

The marketing potential of Alberta boreal hardwoods is increasing across a broad front. Wengert (1988) and Karaim et al. (1990) summarized current market trends for various aspen and balsam poplar products as follows:

Pulp and paper: aspen has been used for the production of high quality chemimechanical and chemical pulps; the use of aspen pulp is increasing in the manufacture of fine papers and tissues.

Oriented strandboard (OSB)/maxi-chip: both aspen and balsam poplar are being used for the production of waferboard and OSB.

Veneer and plywood: although product value is high, manufacturing costs are also very high and market development would be necessary; the high quality hardwood resource required for these products is probably lacking in Alberta.

Construction lumber (8 × 4 dimension): very low product value; very low yields; many unsuccessful industrial trials.

Utility lumber (4 × 4 dimension): moderate-to-high potential for high quality logs over 24 cm in diameter; profitable residue uses are essential.

Furniture blanks or parts: high potential for medium and high quality logs; some market development needed; product value is high.

Children's furniture: the use of aspen for the production of children's furniture has been successfully demonstrated.

Shingles: the use of aspen for shingles was demonstrated in Alberta 70 years ago; interest in the production of aspen shingles is increasing.

Pallet stock: high potential, especially when there is profitable residue use; there are already active markets in Alberta.

Fuel: low potential for development of industrial markets; low weight to energy ratio is a problem, as well as competition from coal and natural gas, which are still very cheap in Alberta; briquet manufacturing is a possible future industry; aspen's potential for fuel could increase substantially through its use in production of pelletized biomass fuel, which produces less ash and has a higher energy content per unit weight than the wood from which it is processed.

Animal feed and roughage: interesting possibility, but still many unanswered questions, including safety of animals and humans; there is also an abundance of other low cost feed in Alberta.

Animal bedding: high potential as a use for all grades of logs; however, usually a by-product of sawmills; markets must be within 100 km of the source plant.

Other potential uses of aspen not in the list above include wood flour, excelsior, lathes for snow fences, building logs, and various veneer items such as tongue depressors. Marketing opportunities may exist for these and other small products (Karaim et al. 1990). Ironically, in 1988 Alberta was still a net importer of aspen for solid wood products, including aspen from Minnesota (Tom Grabowski, pers. com., October 1988).

Particleboard, taken here to include a range of products made primarily from wood residues from sawmills and plywood mills, differs from waferboard or OSB in that the wood particles do not have uniform length and thickness but are a random mixture of sizes. Medium density fiberboard (MDF) is a type of particleboard developed in the 1960s (Mullins and McKnight 1981). Conventional core particleboards tend to have high density surface layers over a low-density core layer, whereas MDF can be made nearly uniform in density throughout its thickness. By 1989 Alberta had only one MDF mill and it was using only softwood residues from several large sawmills in the Whitecourt area (Ondro 1989). The report by Woodbridge, Reed and Associates Ltd. (1985) stressed that the demand and market size for MDF in western Canada is very limited. Ondro (1989), however, predicted an increase in market potential in the near future as a result of the growth of secondary industries in Alberta and new uses for MDF.

Aspen management ultimately involves difficult decisions that are influenced by the marketplace. There are existing hardwood volumes that cannot be used with existing technology (Dempster 1987), often because of poor wood quality. Just as aspen managers cannot ignore the realities of aspen age class distributions, they must also recognize that wood quality criteria influence the marketability of many products. This point has been emphasized for a long time (Kennedy 1974; Wengert 1976). Some analysts have stressed that only a portion of the annual allowable cut is likely to be successfully used in a competitive market place. If that circumstance is accepted as a basic problem, then a key need is to define which aspen stands can be used with the least investment risk and the best chance of success (Barr 1987; Dempster 1987). Others have suggested that there should be an accelerated search for uses of the low-grade centers of otherwise good quality aspen logs and also for uses of the poorer quality logs in the upper parts of aspen stems (Petro 1987).

Risk can be reduced if there are effective ways to detect heart rot voids ahead of time. Recent research by Engineering Data Management, Inc. (1989) revealed that induced stress waves can provide a nondestructive method for analyses of heart rot voids in aspen stems. Stress wave analysis was able to detect not only the presence of heart rot voids but also the extent of voids within a log. This method provides an opportunity to monitor the progress of decay within aspen stands so that optimal times of harvest can be identified. Although these tests were performed on aspen log sections brought to a laboratory, developers of the test methods see no problem in construction of a simple, portable device for testing the extent of aspen heart rot in the field.

As with softwoods, the hardwood pulp and paper market is influenced by a broad range of factors. Market factors influencing the hardwood pulp and paper industry include: the emergence of a world market for most pulp and paper products, and with it world competition for price and effectiveness of such products; increasingly restrictive regulations on uses of raw materials; restrictions on the resulting effluents, the disposal of by-products, and encouragement of recycling; worldwide changes in the source and nature of raw materials from formerly naturally-regenerated forests to managed plantations; and the increasing importance of marginal farmland for forest production (Mullinder 1987). The current public interest in environmentally-friendly products such as bleach-free paper products and the interest in recycling of paper products are becoming important market forces. Environmental groups in both Canada and United States are strongly in support of recycled paper products and some states have passed laws that enforce recycling. In 1989, about 5% of pulp produced in Canada was from recycled paper, with a greater percentage in the United States (Russell Bohning, pers. com., November 1989). Markets for pulp and paper made from aspen or balsam poplar will not be immune to influences of heightened public concerns for the environment.

A former president of the Canadian Pulp and Paper Research Institute described changes in production processes that will enhance the marketability of paper through lower costs, improved performance to weight characteristics, and greater convenience of use (Mullinder 1987). Paper grades that can serve the communication needs of the computer industry are expected to show a continued rapid expansion. Some of the technological advances expected in the pulp and paper industry will involve the commercial application of scientific knowledge already available (MacLeod 1987). Increased pulp strength and the ability to stabilize highly bleached CTMP are two major challenges for both softwood and hardwood pulp. Use of one or more forms of oxygen for bleaching purposes can take the place of chlorine. Alberta's comparative advantage for CTMP production and marketing in the midwestern United States and the Pacific Rim countries is considered to be good (Ekono Consultants Ltd. 1986).

For paper making, the technical challenges will be the formation of a paper web at high speeds between twin forming wires, improvements in print quality, and reductions in the capital cost of paper machinery by improvements in the formed web. Competition from plastics, in particular, is a threat that may be softened by combining paper and plastics for optimum use and increased package design (Mullinder 1987).

Although there are indications that markets are ripe for new suppliers of pulp, Alberta aspen pulp does have competition, particularly from eucalyptus pulp produced in the southern hemisphere. Eucalyptus is well-suited to pulpwood plantations because rotations are short in tropical climates; however, the eucalyptus threat may be exaggerated because there was a time when some analysts expected that Brazil's production of eucalyptus pulp would satisfy the entire world demand. Had that been true, aspen pulp would not now be in production (Beck et al. 1989).

Aspen and Balsam Poplar for Rural and Urban Amenity Plantings

Although they lack the variety and brilliance of fall colors displayed by the hardwoods of eastern North America, aspen and balsam poplar stands provide the dominant autumn colors in the boreal region, as well as in the foothills, and mountains of western North America. These species tend to be taken for granted in the boreal region where they are so common. In the western United States, however, aspen is so highly prized for landscaping that aspen rustlers have been profiting from theft of young aspen. Buehrer (1987) estimated that in the early 1980s rustlers removed as many as 40 000 aspen/year in the South Park District of Pike National Forest, west of Denver, Colorado. Subsequent legislation has eased the situation by requiring any forest products cargo to be covered by permit. Ironically, the transplant success rate for young aspen of sucker origin is very poor because excavated suckers have been severed from the main roots sytem on which they are dependent. Consequently, many of the suckers removed from public lands were simply lost and made no contribution to the intended beneficiaries in urban areas.

Three factors—seasonal change, the typical fluttering motion of leaves, and the abundant penetration of light through the canopy—were identified by Johnson et al. (1985) as properties of aspen that give this species aesthetic appeal. Its fast growth, medium size, seasonal color variation, lacey form when silhouetted against a building or the sky, self-pruning habit, and relatively easy care are other desirable traits of aspen for urban use. Visual screening can be achieved with aspen only when there is sufficient space for clumps or massed plantings. The same applies to its use for noise abatement or windbreaks. Aspen's form is best suited for naturalistic plantings as opposed to formal garden plantings.

The absence of dense branching and its excellent self-pruning are the main deterrents to aspen's use as a windbreak. If used in conjunction with other species that do break the wind, however, aspen's characteristic suckering can add to the replenishment of windbreak plantings and suckers can provide some wind-filtering in the understory (Johnson et al. 1985).

Dawson and Read (1964) noted the great differences in growth, form, vigor, crown development, and resistance to disease, insects, drought, and winter injury in the genus *Populus* when they discussed superior trees for wind barrier plantings on the prairies. Recommended species for shelterbelts included cottonwood varieties only, however, with no mention of aspen. Aspen and balsam poplar were not mentioned in the study of southwest Saskatchewan shelterbelts by Waldron and Hildahl (1974), nor in the recommendations for amenity plantings by Johnson and Lesko (1977). These surveys revealed that hybrid poplars dominate amenity plantings in the portions of the prairie provinces south of the aspen parkland. Aspen and balsam poplar are, however, increasingly common in urban areas as one progresses northward into the aspen parkland and mixedwood section within the prairie provinces.

In a 1973 Alberta survey of 287 residential lots in Edmonton, St. Albert, and Sherwood Park, Waldron and Dyck (1975) noted that poplars (including northwest poplar, Griffin poplar, aspen, balsam poplar, and other unspecified *Populus* species) were the seventh most common genus of trees used for urban amenity planting. Only spruces, maples, birches, apples and crabapples, willows, and mountain ash were more common than poplars. Of the 72 200 poplars estimated to be present on residential lots in the greater Edmonton area during the survey, 28 100 were balsam poplar and 24 100 were aspen. At that time, the 72 200 poplars represented about 9.8% of the estimated 734 400 deciduous trees on residential lots in Edmonton, St. Albert, and Sherwood Park. The nursery replacement value of each aspen or balsam poplar was estimated to be $5 when evaluated in 1974 and would be substantially more now when adjusted for inflation. About 9% of the aspen present on residential lots in the greater Edmonton area were considered to be residual of former natural stands. Native and hybrid poplars on city properties in the prairie provinces are often singled out as a source of problems because they disrupt weeping tiles and their roots disrupt lawn surfaces (Harry J. Johnson, pers. com., July 1990). Aside from the direct use of aspen in urban plantings, aspen wood chips have been used as a mulch for ornamental gardens, as described by Holloway (1989) for plantings in Fairbanks, Alaska.

Except for balsam poplar's possible involvement as a genetic component of hybrid poplars, production of aspen and balsam poplar planting stock for amenity uses is not commercially significant. Where aspen and balsam poplar are prominent components of urban gardens and rural shelterbelts they are often there as residuals of a predisturbance forest. This is certainly the case for most cities, towns, and farms that lie within the aspen parkland and boreal regions, as well as the mountainous areas of Alberta and British Columbia. As far west as Victoria and the Saanich Peninsula on Vancouver Island, residual clones of aspen are present in some gardens and along road allowances.

If aspen were to be more widely propagated in nurseries for amenity plantings, some of the unusual characteristics that occur in certain natural clones may take on special value because of aesthetic appeal. An example of a trait that should be considered for incorporation into propagation stock is the red autumn leaves, instead of the familiar yellow, which occur in some clones, but very sporadically, throughout the boreal and foothills regions. Another potentially appealing trait is the vertically drooping branches of some aspen clones, which may provide the genetic basis of a "weeping aspen" for horticultural use.

Aboriginal and Bushcraft Uses of Aspen and Balsam Poplar

The preceding sections dealt with uses of aspen and balsam poplar from a technological and commercial point of view. There are also utilitarian qualities of these trees for those choosing to live off the land. Aboriginal uses of these species evolved over a long time, but only recently is there a published account of these uses (Kochanski 1988) to provide nonnative persons with a better appreciation of the great diversity of practical uses of these hardwoods. In agricultural areas that border on the aspen parkland or mixedwood forests, noncommercial uses of aspen and balsam poplar are well known. These uses include fuel, poles, corral rails, and home-made furniture. It is to the boreal forest-dweller that Kochanski looked for details of other uses of aspen and balsam poplar, as summarized below.

Aspen and Balsam Poplar Stemwood

In northern forests, aspen is second to willow as a favorite wood for open fires because of good blazing properties and pleasant smoke. Aspen is a favored matchwood with an ember that extinguishes quickly thereby reducing the chances of it blazing up after the flame is extinguished. When water is scarce for putting out a campfire, aspen is often the favored fuel to use. Its odorless and tasteless wood makes it a preferred species for carvings, furniture, ladles, cups, bowls, and as a pole around which to wrap bannock for cooking over a fire. Aspen is also used for the wooden components of horse-drawn equipment. Aspen doubletrees buried in sodden horse manure for a period of time are said to have improved strength and durability, comparable to that of eastern hardwoods. Frozen aspen stems split very easily, and stems split in half are used for teepees and lean-to construction. Decayed aspen heartwood, which is soft and punky, will glow slowly and can be used to carry fire. It can also be used as towelling for wet or greasy hands. Punky aspen wood and dry conks are used in the bow-drill method of fire-lighting. Balsam poplar stemwood is commonly used for rustic table-tops because trunk slices of this large-diameter tree will cure without cracking; dugout canoes were made from balsam poplar by native people who lived near large lakes. Green balsam poplar logs have a high fire resistance and are therefore well suited for building wall-backed fires.

Aspen and Balsam Poplar Bark

Horses can subsist on aspen bark if no other food is available. When aspen bark peels readily (May to mid-August) it can be used as first-aid splints or folded into temporary containers, berry baskets, and cooking vessels for use with hot rocks. Aspen bark has also been used as a flume for collecting water from hillside springs. Balsam poplar bark is excellent for floats for fish nets because of its bouyancy and resistance to waterlogging. In a prolonged rain when dry kindling is scarce, the dry interior of poplar bark can be shaved into kindling. Balsam poplar bark also makes a superior socket for the bow drill used for making a fire by friction and for bowls of smoking pipes. No other material in the boreal forest works as well as the inner bark of dead balsam poplar to enlarge the ember generated by the bow drill. Liquor from the live inner bark of balsam poplar can be used for making casts for broken limbs; the liquor resulting from inner bark that has been simmered for a day is evaporated to a hot syrup that is spread on a cloth and wrapped around the set broken bone. This type of cast will last up to 2 months.

Other Components of Aspen and Balsam Poplar

The smooth, fluffy ashes of aspen are sometimes used as a crude baking powder. The cambium layer of aspen is good-tasting and can be scraped off in late spring and dried for future use. The white powder on sun-exposed parts of aspen stems, if dusted on exposed skin, helps prevent sunburn. It is also a substitute for talcum, particularly inside of stockings to reduce chafing. Some native people mixed this powder with vitreous humor of the eye-balls of large animals to make body paint or to decorate artifacts. Fungi on boreal hardwoods also had important uses; for example, artist's conk (*G. applanatum*) on aspen or balsam poplar was used for drawings and writing; oyster mushroom (*Lyophyllum ulmarium* [Bull.:Fr.] Kuehn.) on aspen is a delectable food source; mycorrhiza (*Amanita muscaria*) on aspen, a poisonous and hallucinogenic fungus, is a potent fly-killer when made into a sweetened broth; and false tinder conk (*P. tremulae*) on aspen stem is favored for making durable bowls that resist checking or splitting. Cotton fluff attached to balsam poplar seeds, when mixed with liquid resin from blisters in bark of balsam fir, has been used as a dressing for burns and wounds. This fluff is also added to buffalo-berries and beaten to a froth to make "Indian ice cream". The sticky balm from balsam poplar buds in spring, if chewed, first produces a burning sensation and then numbs and soothes a sore throat or relieves a cough. Simmering the buds in fat produces a wound ointment for both humans and animals.

Aside from the aboriginal uses previously summarized, aspen and balsam poplar are indicators of other practical features of boreal mixedwood ecosystems. For example, green balsam poplar is higher in moisture content than any other northern wood. It is therefore a prime target for lightning strikes, and shelter should not be sought beneath balsam poplar during electrical storms. The punky, moist wood of rotten balsam poplar logs is very difficult to extinguish when it is burning. Aspen provides another use to the woods traveller whose north–south orientation can be guided by the hues of aspen stems. If one looks into an aspen stand from a distance, even on an overcast day, a whitish and bright hue indicates north. A greenish and darker hue, which tends to occur on the north sides of aspen stems, indicates that the viewer is looking south (Kochanski 1988).

Future Prospects

From a technological and economic point of view, the future is bright for use of aspen and balsam poplar in western Canada. Looking farther ahead, there are uncertainties about demand and trade patterns as well as domestic and trade policies (Beck et al. 1989). Technological and economic aspects of aspen's future are outlined in more detail in the following text. Howlett (1989) has described the present setting as the third cycle of expansion of the forest industry in the prairie provinces but predicted that the expansion will be limited in Manitoba and Saskatchewan in comparison to Alberta.

Most of the forecasts about the future of aspen and balsam poplar utilization are premised on the present age-class structure of this resource. It is a resource largely of fire origin and much of it is mature or overmature. Consequently, there is a relatively short period in which to commercially use much of today's inventory before it is lost to decay and natural stand breakup.

These circumstances—an inventory heavily weighted with mature to overmature age classes and younger age classes that, to date, are unmanaged—raise questions about the future of the resource. For example, aspen and balsam poplar are prominent components in the mix of deciduous woody species that naturally revegetate mixedwood ecosystems disturbed by harvesting or fire. This circumstance hastens the transformation of conifer-dominated stands to mixedwoods and of mixedwoods to hardwoods. There are ecological and economic circumstances, and maybe even policy and management strategies, that are pushing boreal and mixedwood forestry towards a heavier reliance on aspen.

It is not clear how soon plantation-produced *Populus* trees may begin to replace trees from natural stands as sources of pulp. Mullinder (1987) predicted that economics will favor a progressive switch to managed plantations because of their relatively high production rate, lower costs for road construction, silviculture and harvesting, compact supply areas often very close to processing plants, and potentially superior wood quality through genetic improvement programs. If a future trend towards plantation production of aspen and balsam poplar occurs, these species are exceptionally suitable candidates for use in short-rotation forestry; however, the degree and speed with which small-size woody material will be used for fiber production in the prairie provinces is not yet clear. To whatever extent this happens, aspen and balsam poplar will be the key species that short-rotation, fiber-production forestry will rely on in the boreal region of western Canada.

These points refer only to commercial use of aspen and balsam poplar. There are broader considerations that are just as important. It is more difficult to predict the future of these species in the broader context of forest land management. How the public and policy-makers will view northern hardwoods, within a sustainable development framework, in 5, 10, or more years is the greatest uncertainty of all. As previously suggested current public perceptions must be recognized and incorporated into hardwood management decisions.

Existing technology for manufacturing aspen products provides a bright future for the species. Furthermore, the aspen resource of the prairie provinces represents a substantial amount of the world's accessible forest biomass not yet committed for industrial processing. Therefore, it is not surprising that considerable technological research has focused on ways to use this resource. At the research level the Forest Products and Forest Industrial Development Research Program in Alberta has focused on aspen wood quality studies to enhance future uses of aspen (Côté 1985). These studies provide an optimistic view of what can be done to process the aspen resource. The technology is well established for the manufacture of composite wood, such as corrugated waferboard. New pulping techniques have demonstrated that paper making with this species is feasible. Blending of aspen pulp with softwood fiber offers the possibility of controlling paper properties (Brennan 1988).

Many products currently manufactured from solid aspen can be improved using techniques that are in various stages of development. For example, wood can be made more dense and can be dimensionally stabilized by treatments with penetrating resins that cure within the wood microstructure. Fire retardancy can be achieved by impregnation with appropriate chemicals (Winandy et al. 1988). Aspen can also be made more decay-resistant through processes that involve safe fungicides. All of these treatments are possible because of improved knowledge of the fine structure of aspen wood (Côté 1985).

Aspen wood that has been discolored and weakened by decay is potentially useful for conversion to products that are normally produced from petroleum. While the economics for production of chemical feedstocks from aspen may not yet be encouraging, the technology exists for this option. Once cellulose and hemicellulose from advanced decay can be converted to marketable products, aspen use could be improved by enzymatic treatment and hydrolysis of carbohydrate polymers that are broken down by decay to smaller units that are easily accessible (Cyr et al. 1983). These researchers found that decayed aspen wood contains similar quantities of cellulose and hemicellulose per unit weight as healthy wood and that the use of decayed wood as a source of sugars seems to have no drawback.

Hiratsuka and Loman (1984) pointed out that if research in cellulose and hemicellulose recovery from decayed aspen or balsam poplar can be synchronized with a demand for such products, the suggested pathological rotation age of 40–50 years for these species could become irrelevant. The value of the present large inventory of mature and overmature aspen would be increased if there were improved markets for cellulose and hemicellulose recovered from decayed wood. There are already promising results from current research at the Wood Quality Laboratory, University of Alberta, on modification of aspen hemicellulose and their derivatives (Michael Micko, pers. com., November 1989). Preparation and isolation of quaternary ammonium derivatives from aspen wood meal, especially hemicelluloses, has been described by Bains et al. (1984) and Antal et al. (1984). Such derivatives are used as additives for paper, ion exchangers, and flocculating agents. Bains and co-workers pointed out that the presence of modified hemicelluloses in pulp may be helpful in two ways: they can increase pulp hydration, which results in stronger paper, and they may improve the retention of fine materials and aid the draining rate. Additional potentially useful polymeric substances have been prepared from aspen wood meal (Antal et al. 1986), from steam-exploded aspen wood chips (Simkovic et al. 1987a), and from decayed aspen wood (Simkovic et al. 1987b).

There is a wide range of development options for aspen in western Canada. A study by Woodbridge, Reed and Associates Ltd. (1985) resulted in a ranking of aspen productoptions that appeared to have the greatest investment potential in northern Alberta. Markets and economic conditions can change such rankings abruptly, but it is illustrative to examine the Woodbridge rankings strictly on technical grounds. The pulp and paper development options for Alberta's hardwoods were ranked as follows:

Option	Development potential on technical grounds
Aspen bleached kraft pulp	High
Bleached CTMP	Medium--high
Uncoated wood-free papers	High
Uncoated ground-wood papers	Medium
Light weight coated paper	Medium
Tissues	Low
Newsprint	Low

The rankings for wood product development options were as follows:

Option	Development potential on technical grounds
Waferboard (oriented strandboard)	High
Construction plywood	Medium
Medium density fiberboard	High
Particleboard	High
Specialty plywood	Medium
Industrial handling lumber	High
Reconstituted lumber	High
Specialty lumber	High–medium
Moulded wood composites[a]	High[a]

[a] Added to Woodbridge, Reed listing by Lars Bach, pers. com., November 1989.

Excluding the possible development of specialty pulp and paper products, the overall Woodbridge, Reed assessment of potential for development of Alberta's hardwood resource was as follows:

Most Promising
Aspen/softwood CTMP
Lightweight coated paper
Bleached aspen kraft market pulp
Specialty lumber

Longer Term Potenial
Uncoated groundwood papers
Uncoated woodfree papers
Waferboard (Oriented strandboard)

Possible, But Not Given a High Ranking
Newsprint
Tissues

In the 5 years since the Woodbridge, Reed assessment the market potential for newsprint production from apsen raw material has changed. A substantial portion of aspen/softwood CTMP production is now destined for newsprint (Russell Bohning, pers. com., November 1989). Therefore, newsprint deserves a higher ranking than shown by the 1985 assessment. Furthermore, the Voith paper machine of Alberta Newsprint Co. Ltd. will annually use about 132 000 m^3 of aspen for newsprint production (Ondro 1989).

The substantial economic investment in pulp, paper, and OSB plants that rely on aspen and balsam poplar in the prairie provinces ensures that there will be a dramatic increase in use of these resources in the first half of the 1990s. The rate of increase is predicted to be slower in the late part of the 1990s as the readily accessible wood supply is diminished (Navratil, Bella, and Peterson 1990). In any case, it is unlikely that there would be market demand for a continuation of the exceptionally rapid rate of increase now being experienced in northern hardwood utilization. Other trends predicted by Navratil and co-workers include: a continued increase in the amount of aspen procured from private woodlots; changes in forest management strategies and policies as the shift from conifer to hardwood production intensifies; closer utilization and shorter rotations for the hardwood resource; increased use of on-site, small-scale chipping operations suitable for procurement of material from small woodlots; a gradual shift to use of smaller-sized aspen in pulping and chipping operations; use of younger age classes that will allow an increase in annual allowable cut because harvest will take place near the culmination of mean annual increment, around 30 years; and an increase in the value of the aspen resource, which will allow better management practices and higher investments in silviculture, depending upon returns from stumpage charges.

The immediate future for hardwood use in the prairie provinces and northeastern British Columbia is economically optimistic. In Alberta alone, the $1 billion value of sales of primary forest products in 1988 has been predicted to exceed $3 billion by the year 2000 (Brennan 1988). These estimates do not include the value of any secondary forest products. This projected increase is a result of eight new forestry development projects initiated in Alberta between 1987 and 1989. The amount of aspen proposed for use annually in new and proposed pulp and paper mills in Alberta is reported in Table 54.

In Meadow Lake, Saskatchewan, approval was granted in early 1990 for another CTMP mill to be built jointly by Millar Western Industries Ltd. and the Crown Management Board of Saskatchewan. This zero-effluent mill will use 100% aspen with all aspen chips being produced from whole logs on site, with harvesting taking place through a Forest Management Licence Agreement involving both Miller Western and Norsask Forest Products Ltd. (Stevenson 1990).

World demand for forest products is expected to continue to increase; the only uncertainty is the rate of increase. Increased demand can be met in four ways: increased harvest of existing inventories; increased land base used for production; increased utilization; and increased productivity through more intensive management. Beck et al. (1989) commented on the potential role of western Canada's aspen for each of these four options.

Table 54. Annual projected aspen use in new and proposed pulp and paper mills in Alberta (Ondro 1989; Navratil, Bella and Peterson 1990)

Mills	Start of operations	Raw material[a] Aspen (millions m^3)	Raw material[a] Softwood (millions m^3)
Millar Western[b]	1988	0.31	0.30
Daishowa Canada[c]	1990	1.19	0.63
Alberta Energy[b]	1991	0.26	0.05
Alberta-Pacific Forest Industries[c]	1991	1.80[d]	0.36
Procter & Gamble Cellulose[c]	1992	0.69	0.69
Alberta Newsprint	1990	0.13	0.50

[a] The relative amounts of aspen and softwood raw materials are approximate because the amounts actually used sometimes vary from amounts stated in agreements.

[b] Chemithermomechanical pulp.

[c] Bleached kraft pulp.

[d] Includes balsam poplar.

For the first option, aspen will play a prominent role since much of the existing inventory is aspen. For the second option, bringing new lands into production, aspen is already involved. Privately owned aspen on farmlands near processing centers in Prince Albert, Edson, Drayton Valley, and Dawson Creek have recently become a new source of wood supply, and there is reason to expect this source of raw material will continue to increase. For the third option, increased utilization, northern hardwoods are an obvious way to bring about such an increase because most of the harvest to date has been coniferous and it has limited potential for increased rates of harvest. For the fourth option, Beck and co-workers suggested that aspen may or may not play an important role in intensive management to increase supply.

There is economic uncertainty if the large areas of overmature aspen were forced to be harvested under a policy of "cut the oldest first", which is the present policy for softwood use. As Beck and co-workers pointed out, if a mill were forced to continuously use only "rotten apples from the barrel" the economic future of the operation could be threatened. It is now widely recognized that, ecologically and politically, the boreal mixedwood forests cannot be turned into pure boreal conifer or pure boreal hardwood forests (Samoil 1988). Much of it must remain as mixedwood and must be managed as such. The uncertainty, as Beck and co-workers stress, is how to do that without undue economic hardship.

How well do aspen and balsam poplar meet the criteria for growing stock of the future? Ideal growing stock should possess all of the following characteristics: a uniform product; a high amount of usable material in the tree at harvest time; easily regenerated crops; freedom from disease and defects; features that make the crop tree complementary to other land uses; and features that do not foreclose other options and land uses that may be more appropriate in the future (Sanders 1988). This is a tall order and it is important to consider how this expected demand is met by aspen and balsam poplar.

Uniformity of growing stock is desirable because stand tending and processing of forest products are more efficient if handling involves one particular size and species. Shade intolerant species such as aspen and balsam poplar, which typically occur in even-aged stands and which regenerate vegetatively after a disturbance, are well suited to a goal of uniformity. Such an approach, however, ignores the question of how to maintain diversity of habitats, which is so important for wildlife. One way to encourage diversity is to ensure that somewhere within a management unit there are areas of mixedwood and coniferous stands. This will require some effort on the part of boreal mixedwood forest managers because if hardwoods and softwoods are harvested together the hardwoods will predominate after a cutting cycle because they are the pioneer species.

Sanders (1988) used the term "harvest index" to describe the amount of usable material in a tree at harvest time. If the entire tree could be used for the primary product, the harvest index would be 100%. Aspen and balsam poplar are not ideally suited for achievement of a high harvest index because of their greater incidence of stem decay than in boreal coniferous species. This present handicap for aspen and balsam poplar would decrease if there were shorter rotations or if there were new ways to use decayed wood.

Aspen and balsam poplar easily meet the criterion set forth by Sanders, which stipulates that future forest crops must be easily regenerated. The requirements for sucker or stump sprout production are well understood. For aspen, there is also a good understanding of the number of stems required in the early phases of stand development to achieve a well-stocked stand of harvest age. This is not as well known for balsam poplar.

The desire for forest managers to produce future growing stock free of diseases and other defects is applicable to any crop species. The challenge to meet this objective may be greater for aspen and balsam poplar than it is for conifers because of the high incidence of decay in mature and overmature stands (Hiratsuka and Loman 1984), as well as the abundance of *Hypoxylon* in many younger stands.

Aspen has considerable potential as a crop tree that is complementary to other land uses. Aspen stands commonly have a herb–grass understory that provides more forage than under coniferous stands. Where commercial aspen stands occur near agricultural areas there are strong interests to make fiber production and cattle production complementary uses on the same land area. The key point made by Sanders (1988) is that sometimes complementary uses cannot be achieved unless the land area is dedicated to a single use for a certain period of time. For example, cattle need to be excluded from aspen stands until the new crop is well established. Cattle can damage aspen ecosystems not only by eating the tips of young suckers but by soil compaction and by physical injury to tree stems that create entry points for diseases.

Even if aspen is grown on rotations as short as 20 years, some intermediate treatments may be needed. Each treatment should be viewed as an opportunity to change direction with respect to the end product. A useful general rule is to keep slightly more trees in the stand than required for the desired end product. With shade intolerant species, such as aspen and balsam poplar, it is virtually impossible to increase stem numbers once a stand is established, but it is easy to remove trees if required for a better end product.

When boreal hardwoods are being managed, one way to increase the number of possible options for the future is to encourage spruce to develop in the understory. No one knows today what the relative values for softwoods and hardwoods will be at the next harvest cycle. Therefore, even if aspen is a manager's present focus, it may be unwise to close off the option for future harvestable conifers (Sanders 1988).

Young, productive ecosystems of deciduous woody species are predicted to feature prominently in future fiber production because total wood production can be extremely rapid in young boreal mixedwood stands of deciduous woody species. The following data provide some examples of apparent upper limits of aboveground standing crop of unmanaged aspen stands in the prairie provinces (Peterson et al. 1982) in comparison with regional averages compiled by Bella and De Franceschi (1980). In these examples, the sampled maxima were approximately double the regional averages for the same age. The maxima should not be extrapolated to large areas, but they can be used to set goals for potential yield in managed stands or to predict the naturally occurring standing crops that could be locally encountered by mechanized all-species biomass harvesters.

	Aspen standing crop, dry weight (t/ha)	
Age	Regional biomass yield (Bella and De Franceschi 1980)	Sampled maximum yield in same region (Peterson et al. 1982)
3	8.2	16.9
4	9.3	18.1
5	11.0	29.6

Standing crop values well above regional averages are not limited to only 3-, 4-, or 5-year-old stands or to aspen specifically. Other examples of relatively high standing crop are listed below, again in comparison with regional biomass yields compiled by Bella and De Franceschi (1980).

	Standing crop, dry weight (t/ha)		
		Maximum sampled by Peterson et al. (1982)	
Age	Aspen average on Alberta's best sites[a]	Species	Dry wt (t/ha)
8	14.3	Red-osier dogwood	23.0
9	19.1	Aspen–alder	32.6
		Willow	77.1
		Alder	68.7
12	35.6	Aspen–hazel	39.5
13	42.0	Balsam poplar	80.0
		Balsam poplar–willow	130.6
14	48.5	Aspen	73.3
16	62.0	Mountain maple	49.1
18	75.6	Hazel	28.2

[a] Site index 24 m at 50 yr (Bella and De Franceschi 1980).

These examples indicate that many young stands, of various deciduous woody species, achieve standing crops that greatly exceed regional averages for aspen standing crop of the same age on the best sites sampled in Alberta (aspen site index 24 m at age 50). The exceptions are 16-year-old mountain maple and 18-year-old hazel which, by that age have been markedly surpassed by the standing crop of aspen of the same age.

The relatively high standing crop values sampled in unmanaged stands in Alberta and Saskatchewan still fall short of the exceptionally high standing crop values recorded for young managed stands. For example, Nautiyal (1979) cited data from one hybrid poplar clone in Ontario that produced 28.7 t/ha of leafless biomass on a 2-year rotation. Siren (1979) indicated that natural willow stands in Sweden may produce up to 6 t/ha of dry standing crop/year. In experimental willow plantations in Ontario that have been harvested annually for 8 years, some willow clones have produced up to 22 t ha^{-1} yr^{-1}, based on dry weight of wood only, excluding foliage production (Louis Zsuffa, pers. com., May 1989); Swedish operations have achieved up to 40 t ha^{-1} yr^{-1} with the very best willow clones (Siren 1979).

These examples indicate the potential for very rapid production of fiber in young stands of deciduous woody species. To put this potential in perspective, Alberta's present mean annual increment in the mixedwood region is about 1.5 m^3 ha^{-1} yr^{-1}, which translates to about 1.1 $t^{-1}ha^{-1}yr$. A goal of 3–4 t ha^{-1} yr^{-1} has been suggested for intensively managed mixedwood stands in Alberta, although in similar boreal sites in Finland increments of up to 11 t ha^{-1} yr^{-1} have been achieved (Ken Higginbotham, pers. com., February 1988). In the prairie provinces, as mixedwood foresters move beyond their present preoccupation with how to handle the large amount of mature and overmature aspen, management of young, rapidly growing hardwood stands will be an attractive alternative for rapid fiber production.

There are indications that aspen use and management is already a public concern in western Canada. The 1989 National Survey of Canadian Public Opinion on Forestry Issues (Environics Research Group Limited 1989) confirmed that a substantial majority of 2500 Canadians polled are concerned about forest management in Canada today. In western Canada, that anxiety impinges directly on use and management of the aspen resource because the concerns most commonly voiced were: a dislike for large clear-cut areas; doubts that effective forest renewal programs are in place; and fears that future forests will resemble agricultural monocultures.

Since clear-cutting is the best way to ensure a new crop of suckers where aspen is harvested, it is relevant to note the public resistance that may exist for this form of harvesting. In the prairie provinces, 69% of respondents recorded disapproval of clear-cutting as a logging method. These concerns must be presumed to be based on public perceptions of coniferous harvesting because there is so little history of hardwood harvesting in western Canada. There is not a widespread public understanding that clear-cutting is the only effective way to achieve aspen regeneration. In cases where it is understood, the issue generally centers around the size of clear-cuts and disruption of wildlife habitat.

The Canadian public is familiar with nursery production of seedlings and with planting because this method of coniferous forest renewal has been well publicized in recent years. The effectiveness of naturally-occurring root sucker regeneration in aspen is not as well known to the public. Foresters are being asked why nurseries are not now gearing up for production of deciduous planting stock, in view of the large amount of hardwood harvesting on the horizon. This question suggests that there is a need for public information programs and demonstration areas to publicize that, except on compacted areas such as roads and landings, natural aspen sucker regeneration can generally substitute for nursery production and subsequent planting of aspen seedlings. The highest priority areas for hardwood planting programs are compacted areas that do not regenerate naturally by suckers or seedlings.

There is also public concern that aspen growing on public land is being made available for pulp and panelboard production at exceptionally low stumpage rates compared to conifers. The fact that aspen was until recently considered to be a weed may be a reason for anomalously low hardwood stumpage rates. Low cost of raw materials may also be deliberate to encourage industrial development of a formerly unused resource. The public concern over this circumstance seems justified. If stumpage rates are a reflection of the value that public land administrators place on the aspen resource and if silvicultural budgets are dependent on stumpage revenues, it is difficult to be optimistic about intensive management of the aspen and poplar resource in western Canada. This concern is based on the premise that care given to the management of a resource is in proportion to the value that administrators place upon that resource.

This review has confirmed that aspen and balsam poplar are resilient species in boreal mixedwood ecosystems, not only because they occupy a broad range of sites now (Corns 1989), but also because they have endured significant climatic shifts in the period since deglaciation (Larsen 1980). This resiliency bodes well for the future of aspen and balsam poplar. There is no evidence that aspen or balsam poplar are approaching any thresholds in relation to assumed temperature or precipitation changes. The question remains, however, do resilient species need resilient management?

Commercial interests in aspen and balsam poplar are expected to be as enduring as these species themselves. Canada has had its share of once-important forestry species that are now uncommon or of little commercial interest—eastern white pine and yellow birch are examples. Aspen and balsam poplar will likely be spared this fate, not only because of their very wide distribution, their effective natural regeneration, and their rapid growth in early stages of stand development, but also because their prime uses—particleboard, pulp and paper products—are themselves going to be of enduring interest in world markets. If aspen or balsam poplar was used primarily for lumber or specialty products instead of fiber and panel products, their market demand would have a less certain future.

Forest managers face special challenges if aspen is to maintain its reputation as the champion of multiple use (Thorp 1988). For the prairie provinces, Steneker (1976b) proposed guidelines to ensure that most other land uses are compatible with management for aspen fiber production. In terms of aesthetics and public perceptions, perhaps aspen's prime advantage over other forest tree species is its ability to quickly reestablish a green cover in clear-cut areas that are increasingly under public scrutiny.

If there is a concern about aspen's future, it is the uncertainty of how this resource will be managed when the gap is closed between annual allowable cut and actual harvest, a circumstance that could prevail before the end of this century. Of course, the closing of this gap will vary by jurisdiction. In Alberta's case, as of 1988, the deciduous annual allowable cut was 23.4% committed, 48.5% designated for future development, with 28.1% classified as unallocated accessible (Beck et al. 1989).

The steadily increasing harvest demand for aspen and balsam poplar will be matched to some extent by increases to the annual allowable cut. The latter will be feasible because the hardwood growing stock is increasing as these species are established on areas formerly occupied by conifers. In west-central Alberta, aspen regeneration is abundant on many cut-over areas of former lodgepole pine forest. The long term trend is a shift of the prairie provinces forest land base from coniferous types to mixedwoods and from mixedwoods to hardwoods (Navratil, Bella, and Peterson 1990). Appropriate management policies are not yet in place to handle this shift towards hardwood use (Beck et al. 1989). It is up to policy makers, foresters, researchers, and the public to work together to develop forest management and renewal strategies to sustain the northern hardwood resource in the prairie provinces. For this to occur it is necessary for the public to be well informed about management policies proposed for boreal hardwood and mixedwood forest types.

KNOWLEDGE GAPS AND RESEARCH NEEDS

The first aspen-related research in the prairie provinces was started by the predecessor of Forestry Canada in 1925 at Big River, Saskatchewan, followed in 1926 by the first experimental aspen thinnings in the Duck Mountain Forest Reserve and Riding Mountain National Park in Manitoba. Since that time much has been learned about aspen in this region, although balsam poplar has been studied in less detail. This long research record does not mean that there is no need for additional information. Good information on how site, stand characteristics, and harvesting methods influence aspen regeneration is available to forest managers. Many ecological, genetic, and physiological features of these species are also well known. Unfortunately, this ecological knowledge base does not extend to management of these boreal hardwoods because commercial use and management of hardwoods in the prairie provinces and northeastern British Columbia followed long after ecological and silvicultural research was started. It is, therefore, not surprising that attitudes, management strategies, and utilization options for this resource are undergoing rapid change.

This section discusses knowledge gaps and research needs in three ways. It begins by listing 16 high priority research needs. These opinions are just one component of priority setting because the research needs should be based on consensus among users, managers, researchers, and research planners who are involved with aspen and balsam poplar.

The second part of this section provides a list of 45 additional knowledge gaps that have been recently mentioned by specialists familiar with aspen and balsam poplar in the boreal part of their geographic range. This comprehensive list is not presented in any intended order of priority.

The third part of this section is a general review of other recent literature that summarizes the views of a variety of researchers and analysts who have offered opinions on research needs pertaining to boreal hardwoods.

High Priority Research Needs for Boreal Aspen and Balsam Poplar

High priority tasks are grouped under the following eight stages from stand establishment to marketing of the product: 1) ecology; 2) stand renewal; 3) stand management; 4) protection; 5) alternative uses; 6) harvesting; 7) processing; and 8) marketing. The resulting list of 16 research topics is limited to the two knowledge gaps considered to be the most important under each of these eight categories.

1. Ecology
   - Humus layer research in ecosystems that contain boreal hardwoods. The humus layer contains most of the roots, which is where root sucker formation and seedling establishment occur. It is also a crucial component of nutrient and carbon cycling.
   - Root research in aspen and balsam poplar stands of various ages because long-term management of these species must be centered around the care and manipulation of clonal root systems.
2. Stand renewal
   - Belowground and aboveground development of seedling-origin and sucker-origin stands of aspen and balsam poplar.
   - Reproductive capacity of root systems of various ages and in stands where aspen or balsam poplar make up varying proportions of the mixedwood species composition.
3. Stand management
   - Interspecific relationships between aspen, balsam poplar, and conifers where they occur together to clarify concepts such as "nurse crop", "competition", and "cooperation".
   - Advanced inventory data and growth and yield data for the hardwood component of boreal mixedwood stands.
4. Protection
   - Pathology and epidemiology of *Armillaria* root rot and other root-rot diseases in managed aspen forests.
   - Insects and diseases of young aspen stands, and particularly young stands that have originated from suckers after harvesting, rather than after fire.
5. Alternative uses
   - Techniques to incorporate wildlife management criteria into management of boreal hardwood and mixedwood stands.

- Optimum management of the forest land base with the most suitable species in the boreal mixedwood region. Policy discussion regarding encouragement of increased or decreased mixedwood stands.

6. Harvesting

- Hardwood harvesting machines and techniques to reduce ecosystem disturbance, improve productivity, reduce the amount of wood handling, and reduce capital costs.

- Scanning techniques for detection of moisture and decay in standing trees, and development of low-priced, portable scanning systems for use in the field.

7. Processing

- Aspen decay and stain effect on pulp quality and processing costs.

- Improved rapid and accurate methods to identify the presence, distribution, and amount of wetwood and the optimum processing methods for mixtures of normal wood and wetwood.

8. Marketing

- Market acceptability of aspen and balsam poplar products made from raw material that contains significant amounts of advanced decay, including the low grade centers of logs and the poorer quality logs from the upper parts of aspen stems.

- Improved marketability of boreal hardwood pulp made from organosolv or other processes that are environmentally more acceptable to the public than the traditional sulfite and kraft pulping processes.

Other Recent Research Suggestions from Aspen/Balsam Poplar Managers and Researchers

To complement the research topics presented in the preceding text, a more comprehensive list of other research suggestions made by specialists familiar with management and use of aspen and balsam poplar in the boreal part of their range follows. These research suggestions are grouped under three main headings that coincide with the main sections of this report—ecology, management, and use.

Keeping in mind that recent research and experience will have invalidated many of the research recommendations made 10 or more years ago, the following suggestions are drawn mainly from information gaps identified in the 1980s. Most suggested research topics are attributed to a forest researcher or manager currently involved with the aspen and balsam poplar resource.

Information Needs on the Ecology of Aspen and Balsam Poplar

The following list of suggested investigations is not intended to be an inventory of everything unknown about aspen and balsam poplar in a boreal setting. The list is selective and focuses on ecological subjects that have strong links with management or utilization questions. This deliberate selection does not imply that fundamental research on genetic, physiological, and other ecological topics should be suspended.

- Develop standards for selecting superior aspen and balsam poplar clones and expand breeding programs, which have traditionally focused on poplar hybrids, to include a greater variety of superior genotypes from natural stands of aspen or balsam poplar in the prairie provinces and northeastern British Columbia (Peterson, Kabzems, and Peterson 1989).

- Establish additional trials to determine if P content of soil is a limiting factor for productivity in upland hardwood and mixedwood sites in the prairie provinces (Strong and La Roi 1985), and to determine the amount of deep leaching that occurs in boreal mixedwood and hardwood ecosystems.

- Evaluate the formation of mycorrhizae on aspen as has been initiated by Laursen (1985) for Alaskan hardwoods.

- Describe changes in root biomass as aspen stands develop over time, and document the development of different types of belowground biomass (Peterson, Chan, Peterson, and Kabzems 1989). This research subject is consistent with the overwhelming emphasis on belowground studies in the "ecology" and "stand renewal" sections of the 16 priority research topics presented at the beginning of this chapter. It is also consistent with the trend for long-established research institutions, such as the Yale University School of Forestry and Environmental studies, to recently focus on new programs in belowground ecology of forest ecosystems.

- Determine how species such as aspen, with such a wide geographic range, adapt and survive under very different durations and intensities of evapotranspiration (Sucoff 1982).

- Examine the impact of the timing of water deficits on amount of growth and the induction of dormancy in aspen (Sucoff 1982).

- Broaden the information base on how temperature influences suckering under field conditions. The relationship of temperature with hormonal balance as it interacts with clonal variability and root depth is unclear; it is not known how much temperature thresholds may vary by clone (Hungerford 1988).

- Geographically expand present Alberta studies of ingress of aspen seedlings into areas previously containing softwood stands, and document the development, competition, and variability of such mixedwood stands that contain aspen of seedling origin.

- Determine whether female aspen clones exhibit greater growth than male clones in the prairie provinces and northeastem British Columbia, as has been suggested by research elsewhere (Sakai and Burris 1985).

- Obtain better information on aspen stand breakup, with clarification of site and other factors that influence this phenomenon. This research should include investigation of the timing and rates of stand deterioration and the successional pathways that follow various kinds of stand deterioration.

- Improve techniques to determine the quality of existing aspen stands and to assess whether existing stands will be available when required (Northern Alberta Development Council 1985; Smith 1987). This research is inseparable from the need for better age-class data (Dempster 1987), better methods to predict cull, and criteria to decide what to do with trees not usable in present processing plants.

- Identify and map decay-free clones in accessible aspen and balsam poplar stands (Hiratsuka and Loman 1984).

- Initiate research into microbial succession that leads to advanced decay, including the modes and sites of decay organism infection, and the nature and heritability of clonal decay resistance (Hiratsuka and Loman 1984).

- Address several questions posed by Manion and Griffin (1986) on *Hypoxylon* canker such as: What are the specific conditions associated with infection, and how do they relate to insect activity and other unknown factors? Do readily measurable natural defense mechanisms exist that could be used to breed for resistance to *Hypoxylon*? What are the chemical identities of the toxins associated with *Hypoxylon*, and what is their role in the disease process? What is the role of moisture stress in disease development, and can it be manipulated to minimize losses caused by *Hypoxylon* canker?

- Obtain better quantitative data on the effects of tent caterpillar outbreaks on aspen stemwood production (Bryson 1989).

Information Needed for Better Management of Aspen and Balsam Poplar

Recent research suggestions related to management of aspen and balsam poplar are listed below, in no intended order of priority.

- Increase research into economically feasible methods for maintaining the softwood component in mixedwood stands.

- Improve inventory methods to record the softwood understory beneath aspen. Long-term quantification of the relative amounts of hardwoods and softwoods in the prairie region; some foresters in the region have the impression, although it is not well quantified, that the amount of aspen relative to white spruce is steadily increasing. Inventory information needs to be complemented by methods that allow resource planners and managers to determine not just tree growth rates but timber value growth rates, as has been done in Maine for individual tree species, including aspen (Gansner et al. 1990).

- Obtain data to clarify the degree to which clonal variation influences the accuracy of inventory estimates for aspen and balsam poplar (Heidt 1983).

- Continue present efforts to improve aerial photographic differentiation of aspen, balsam poplar, and white birch to improve inventory and annual allowable cut calculations.

- Prepare computer models to evaluate the effects of various silvicultural treatments on future stand development, yield and financial value of managed stands of aspen and other boreal species on a variety of site types (Deschamps 1990). This research should build upon the substantial FORCYTE-related work already done (Peterson, Chan, Peterson, and Kabzems 1988; Peterson and Apps 1989; Peterson et al. 1989b; Kimmins et al. 1990; Grewal et al. 1990; Peterson 1989). In addition to the nutrient focus of FORCYTE there is a need for modeling that would address aspen management in mixedwood stands, both in terms of optimizing the combined resource and in terms of operability and harvest strategies (Michael J. Apps, pers. com., June 1990). The recent modeling by Gale and Grigal (1990), which focuses on soil and root aspects of productivity in aspen stands, should also be tested for boreal mixedwood stands. The alternative to clear-cutting aspen, proposed recently by Ruark (1990), and referred to as the reserve shelterwood system, is an untested suggestion needing further study.

- Initiate trials to clarify whether or not and under what circumstances disking could be a stimulus for sucker production and to determine if there are regional differences in aspen sucker development following summer versus winter logging.

- Obtain better information on stands that remain vigorous beyond age 60. Mature stands that maintain their integrity between ages 60 and 90 provide some of the most interesting management possibilties in northeastern British Columbia and the prairie provinces (Peterson, Kabzems, and Peterson 1989).

- Carry out additional evaluation of the economic importance of boreal hardwood regeneration that until now has been considered "free", including evaluation of costs involved in control techniques to achieve the desired, marketable deciduous–hardwood species (Weingartner 1981; Smith 1989).

- Obtain more information on optimum stocking levels for aspen or balsam poplar. From northeastern British Columbia to Manitoba, forest administrators are developing or reevaluating stocking standards for hardwoods; one of the poorly researched aspects of this subject is the optimum stocking levels for hardwoods and softwoods in mixed stands (Revel 1983). Regeneration of balsam poplar following harvest also requires more documentation.

- Obtain the quantitative data needed to understand the effects of residual overstories on sucker production and ultimate yields, including effects of particular species within the residual overstory. Information is also needed on the degree to which persistent aspen root systems in stands that have little or no conspicuous aspen in the canopy would respond to various silvicultural treatments.

- Clarify whether different regeneration approaches are needed for stands that contain clones with high incidence of decay (Little 1988a).

- Obtain more information on how to manage decayed stands to bring these areas into production (Little 1988a).

- Determine whether any pathogens such as *Armillaria* (Stanosz and Patton 1987a, b) or viruses (Berbee et al. 1976) will become more serious in clones regenerated on short rotations.

- Refine herbicide techniques to control aspen and balsam poplar in circumstances where these species are unwanted. Where the forest manager wants to reduce or eliminate aspen, long-term studies are needed using permanent plots to assess sucker response to preharvest control (Bancroft 1989).

- Determine how best to incorporate aspen clonal variation into silvicultural operations and how to vary treatments to match clonal distribution in a stand.

- Assess the economic impact of forest fires in aspen-dominated forests; it is in the economic context that Van Wagner (1990) suggested research to provide information that will permit prescribed fire to find its optimum role in Canadian forest management.

- Verify or amend present information on preferred sizes and orientations of clear-cuts for optimum wildlife habitat, specification of wildlife requirements for residual coniferous stands that provide cover, and assessment of the wildlife role of balsam poplar, which is often left unharvested when aspen is removed.

- In relation to predicted climatic warming, focus research on potential increases in fire intensity and frequency; in this context, insect and disease research may also need to be broadened to examine host responses if there is climatic warming and lengthening of growing seasons (Wheaton et al. 1987).

- Intensify research on how to rehabilitate mixedwood ecosystems that now have a sparse cover of decadent aspen as a result of previous selective removal of only the best stems; many of these high-graded ecosystems are very productive but are now covered by brush.

Although data from Manitoba and Saskatchewan indicate that a broad range of initial sucker densities will result in adequate stocking, studies in the Lake States (Lundgren and Hahn 1978) indicate that more information is needed on the range of site conditions in which full stocking is achievable, together with the economic and ecological feasibility of achieving full stocking. Work in Ontario (Basham 1981, 1988; Weingartner 1981) has revealed a need for further evaluation of site preparation techniques that have an influence on growth, stocking, and pathological quality of aspen regeneration. In the southern Rocky Mountains region there is a recognized need for research into economic methods for slash treatment where there are concurrent uses such as cattle grazing (Beeson 1987). Knowledge gaps similar to those cited above for Ontario, the Lake States, and the southern Rocky Mountains are considered to apply also to aspen ecosystems in the prairie provinces and northeastern British Columbia.

Information Needed to Enhance Uses of Aspen and Balsam Poplar

Recently identified information needs in relation to aspen and balsam poplar utilization are listed below.

- Gather data to define economic losses when harvesting does not also use the balsam poplar or birch that are often intermingled with aspen (Weingartner 1981).

- Carry out additional studies to isolate the factors that contribute to slow drying of wetwood, especially absorption--desorption properties of wetwood and the influence of soluble extractives on board moisture gradients during drying (Ward 1986).

- Obtain more detailed information on comparative strengths of normal aspen lumber and that containing wetwood (Ward and Pong 1980).

- Develop methods for closer liaison between manufacturers of hardwood harvesting equipment, silviculturists, and machine operators (Russell 1988; Schneider 1988).

- Develop improved methods for segregating aspen logs by quality classes and for grading aspen logs for lumber production (Petro 1987). Optimum use of the aspen resource for pulp also needs refinement in methods of grading the raw material (Thom 1988); a related need is to find better ways to define resource inventory data requirements in relation to each specific aspen manufacturing processes (Morgan 1987).

- Assemble more data on the rheology of aspen and balsam poplar wood, involving documentation of deformation under various thermomechanical and moisture conditions. This information is a prerequisite for improving the use of these woods for pulp, medium density fiberboard, OSB, Waveboard, Parallam, and other possible new wood composites (Russell Bohning and Michael M. Micko, pers. com., November 1989).

- Gather more data to assess the need for preservatives for taper-sawn aspen shakes (Silvacom Ltd. 1988).

- Develop new methods for pitch control during pulping operations (Allen 1987) and for control of mycotoxins in pulp chips (Hiratsuka and Loman 1984).

- Investigate, under controlled laboratory conditions, whether or not surfactants are cost effective for pitch control when added in a kraft digester during aspen pulping (Allen 1987).

- Determine whether resin added in pulp digesters is an effective way to control aspen pitch problems, and develop better ways to remove the resin in the kraft digester (Allen 1987).

- Assess the economics, food value, and health aspects of using aspen (whole trees, tops and leaves, and residues) as replacement for hay for cattle, sheep, and other livestock.

Other Recent Reviews of Aspen and Balsam Poplar Research Needs

The reader interested in other recent reviews of aspen or balsam poplar research priorities should consult the reports by Peterson, Kabzems, and Peterson (1989), Adams (1990), Navratil, Bella, and Peterson (1990), Expert Panel on Forest Management in Alberta (1990), and the proceedings of the Aspen management for the twenty-first century sponsored by the Poplar Council of Canada, Forestry Canada, and Alberta Forestry, Lands and Wildlife (Navratil and Chapman 1991).

The report by Peterson, Kabzems, and Peterson (1989) was based on research priorities identified in 1987 by a boreal hardwood working group in northeastern British Columbia. That working group identified 12 research problems and rated them as follows:

High priority problems
Outdated inventory
Land use conflict

Medium priority problems

Lack of awareness of hardwood use and management opportunities
Hardwood stocking standards
Stand tending requirements
Growth projections

Medium-to-low priority problems

Reforestation requirements for pure aspen and mixedwood types

Low priority problems

Slash disposal
Regeneration response
Compaction of soils
Erosion
Gene conservation

The Expert Panel on Forest Management in Alberta (1990) made several recommendations pertaining to the role of boreal hardwoods in reforestation systems. The panel's suggestions are summarized below, not only because they are recent but also because they are the result of a consensus-building process.

- Research should be conducted into effective ways to rehabilitate and reforest previously degraded mixedwood stands.

- During current and future hardwood/mixedwood harvesting, the utilization of balsam poplar and white birch should be improved to reduce waste and increase the stocking and vigor of the new hardwood crop.

- New techniques and standards should be developed for reforestation and growth of mixedwood stands.

- Research and development is needed to provide information on the regeneration and growth characteristics of balsam poplar and white birch relative to aspen on hardwood and mixedwood sites. This information should be incorporated into new hardwood reforestation standards, addressing both stocking and growth.

- Nursery programs in Alberta should include plans for hardwood production of both pure native species and hybrids for use in reforestation, as does the Weyerhaeuser program at Prince Albert, Saskatchewan. Aspen clones and hybrids should be given major emphasis.

- A survey of recent hardwood cutovers in Alberta should be conducted to determine the impact of current logging technology on stocking and growth of the new hardwood forest and to consider alternative logging technology to reduce negative impacts.

- A strategy should be developed for rehabilitating and reforesting previously degraded hardwood and mixedwood stands in Alberta.

This panel also pointed out that there are substantial areas of overmature hardwood stands on accessible, productive sites that require renewal, and they urged the development of effective means to achieve this.

The Canadian Institute of Forestry (CIF/IFC) policy statement on sustainable development (Canadian Institute of Forestry 1990) included research recommendations that apply as much to managed aspen and balsam poplar forests as they do to other forest types in Canada. In the view of the CIF, to translate the concept of sustainable forest land management from words to action requires improvements in: i) existing knowledge of forest ecosystems and the impacts/interactions of a wide range of natural and human activities; ii) the capability to predict the effects of forest harvesting, processing, management practices, and nonforestry stresses on forest ecosystems; and iii) the capability to predict the responses of forest ecosystems to these stresses.

There has recently been a concerted effort by the Forestry Research Advisory Council of Canada (1989) to prepare an annual cross-Canada survey of forest research priorities for use by the Canadian Council of Forest Ministers. Eighteen research priorities were listed under four general areas: managing the forest as an integrated ecosystem; renewing the forest; protecting the forest; and producing improved products from the "new forest". The listed research priorities were not specific to any particular tree species, but they are considered to be applicable to aspen and balsam poplar. For aspen and balsam poplar, one relevant issue that the Forestry Research Advisory Council of Canada did identify was "the opportunity presented by underutilized hardwood species". It was suggested that priority be given to research that would assist the development of new value-added uses of the significant volumes of underused hardwoods.

The kinds of ecological information needed to encourage more productive uses of boreal hardwood and mixedwood ecosystems will change as uses of the resource change and develop. The traditional response is for the forest manager to say, "Here are the ecological realities of northern hardwood and mixedwood stands, now what can we do with these resources, within the limits of those realities, using today's utilization and manufacturing technologies?" An alternative approach is for the forest manager to begin with the question "Here are today's technological and utilization realities, now what ecological information do we need to make the best use of those realities in northern hardwood and mixedwood management?" Some examples below suggest why this latter approach may now be the most appropriate of the two alternatives.

At the Northern Mixedwood Symposium, Russell (1988) predicted the use of small stems for OSB as pressure increases to ensure that value is not being left behind during harvesting. "Mini-mills" are now commercially viable. Reconstituted panels and certain types of pulp can also be processed using small raw materials in small plants. Other recent technological advances include: a variety of whole-tree harvesting and handling procedures described by Corcoran and Gill (1984); use of the chunk wood system for production of aspen flakeboard, using forest residue and material from the entire tree which, combined, will recover up to twice as much wood per unit area as conventional logging (Haataja et al. 1984); increased use of central conversion sites at which raw material from various harvest sites is accumulated at one place, converted at this central place, and then distributed to linked processing plants (Wippermann 1984); increased use of chippers at the harvest site (Wippermann 1984); field drying of harvested material, with foliage intact during the drying process to hasten moisture loss and therefore to increase the efficiency of field chipping and transport of chips (Wippermann 1984); and development of small portable machines that can debark 10–15 stems at a time, using material as small as 10 cm in diameter.

The examples above suggest that new utilization standards, using smaller biomass pieces and an increasing range of acceptable woody species, together with increased conversion directly at the harvest site, will create new kinds of postharvest ecological conditions that will require new lines of research. Changing utilization standards and changing harvest methods will raise new questions, not only in stands managed for maximum biomass production but also for those stands where management for wildlife, water, or recreational values are paramount.

Where the goal is maximum biomass production, using the highest level of utilization technologically possible, there will be a need for better information on the dimensions and structure of forest stands. This requires additional data on structural features such as crown dimensions, relative proportions of various biomass components, branch sizes, as well as data on branch integrity during transport. If there is a trend towards more drying and processing of raw materials in the field, there will be increased interest in physiological processes associated with water content and rates of weight loss upon drying for various tree components. Decisions on which components are to be removed from a harvest site and which are to be left will require better information than is currently available for management of slash, the forest floor, and nutrients.

These predicted research trends are not expected to replace the need for traditional autecological studies that define growth patterns within individual species, nor the need for synecological studies dealing with interspecific relations within northern hardwood or mixedwood ecosystems. The policy and utilization changes now taking place with respect to the aspen and balsam poplar resource in the prairie provinces and northeastern British Columbia, however, will undoubtedly help to identify a new set of ecological research needs.

Many of the research suggestions recently made by aspen specialists in areas south of the Canadian boreal distribution of this species are probably also applicable to the prairie provinces. For example, for aspen in the mountains of western United States there is still poor information on the condition, density, and development of lateral root systems. It is not yet known how lateral root systems change as new aspen or balsam poplar stands develop after harvest, nor how harvesting influences the lateral root system. Studies from elsewhere have provided estimates of nutrients removed from a site by whole-tree harvesting (Hornbeck and Kropelin 1982), but for aspen sites in the prairie provinces there is only limited information on the processes and rates of nutrient replenishment after their removal by harvest (Peterson, Chan, Peterson, and Kabzems 1989). For the Lake States, Perala (1984) emphasized that there are only limited data on the role of insects and diseases as potentially beneficial agents in development of aspen stands, especially in relation to self-thinning and expression of dominance; the same information gap exists for aspen and balsam poplar in the prairie provinces and northeastern British Columbia. In relation to growth prediction, some of the latest modeling of soil- and root-based productivity indexes for aspen have confirmed that productivity can be predicted with more certainty where fires have not occurred (Gale and Grigal 1990). Where fires have occurred there is a greater need to include other soil characteristics, such as nitrogen or organic matter content, to explain differences in site index values. Further research is needed to determine the validity of the assumptions used in Gale and Grigal's model of productivity index. The assumptions needing testing are: i) root responses to soil/site conditions are genetically controlled; ii) under optimum soil and site conditions a species will consistently produce a specific vertical root pattern, and iii) aboveground production is related to the response of a tree's vertical root pattern to soil/site characteristics. Additional work is needed to determine the optimum vertical root distribution for aspen and whether there are significant clonal differences in optimum vertical rooting patterns for this species.

The term "sustainable development" has recently captured public attention in Canada, as in other nations. The initial reaction of foresters is to equate sustainable development with their traditional concept of sustained yield; however, as Maini (1989) pointed out, these two concepts are not necessarily synonymous. Sustained yield in forestry is mainly concerned with a perpetual even annual flow of timber for commercial use. Sustainable forest development is a broader concept concerned with integrated forest management, maintaining the ecological integrity of the forest environment, and keeping future options open. Implementation of sustainable forest development has obvious implications for research because it requires: i) an understanding of the capacity of the forest environment to sustain a range of human use as well as diverse species and ecological processes; ii) managing current and future human activities within the environmental limits of the forest environment; and iii) using the forest environment without prejudicing its ecological integrity and use by future generations.

Forests dominated by aspen or balsam poplar will not be exempt from the challenges outlined above. These boreal hardwood species will also be influenced by the increasing demand for setting aside representative and unique forest types. This step involves additional withdrawal of forest land from industrial use. To offset the potential biomass production loss of these withdrawals there is no choice but to make better use of the forest land that has been designated for commercial harvests. To accomplish this, several steps are required: reductions in logging waste; more effective wood utilization; more intense silviculture, using genetically superior trees on selected sites; and recycling of certain forest products (Maini 1989). As the amount of land available for fiber production diminishes and hauling costs dictate that the products be procured within certain distances from the processing plants, then forestry will shift from a process based on gathering to one based on producing and managing resources (Manion and Griffin 1986).

Identification of information needed for better management of boreal hardwoods raises the question of what the forest manager should do in the meantime. A practical answer is to assume that aspen and balsam poplar can and must be managed before all the research results are in. Sanders (1988) suggested several guidelines for forest managers who must make decisions before research results are known. With a culinary theme, he suggested: do not put all the eggs in one basket; beware of the "new wine"; and take predictions with a pinch of salt. Examples of the first rule, whether dealing with hardwoods or softwoods, would be to not grow all new crops for pulpwood nor to space the stands at an early age for sawlog production. The advice about "new wine" is exemplified by a policy of not getting locked into a low-return fiber crop nor committing an entire forest management area to new genetic material.

The advice by Sanders (1988) to take predictions with a pinch of salt is based on the experience that it is often difficult to duplicate research findings on a large scale, particularly if the research is based on few trials. Research is generally carried out on sites selected for their uniformity, so that treatment differences are the only accountable variables. This means that sites different from the study sites, for example areas with variable water table depths, may have different silvicultural results or different yields than predicted by the research results from the carefully selected study site. This suggests that research should be followed by large-scale operational trials, a suggestion that is as important for management of aspen and balsam poplar as it is for conifers. For this guideline, Sanders (1988) suggested that a reasonable scale for an operational trial would be several hundred hectares under one management regime.

Aspen and balsam poplar will be involved in the predicted increase in production of composite board materials, use of small logs for manufacture of high-value composites, innovations in "added-value" solid wood, new product opportunities for wood residues, new kinds of panel products, and greater use of wood through new polymer microcrystals (Info-Tech 1989). This predicted increased use of aspen and balsam poplar will require additional data from several different sources. For some specialized products there is a need for more detailed information than is presently available on the quality of the wood raw material and ecological factors that influence the condition of the raw material. Procurement of high quality aspen wood for chopstick production is an example. In other cases, plans for improved utilization may call for new data on management practices that influence the growth rate, form, size, or condition of the desired raw material. This could involve, for example, questions about the optimal size for harvested material or optimal species mixes in the raw material used for processing.

Aside from its links with ecological and management variables, utilization research needs are defined by a variety of economic factors, including pricing of raw materials and finished products, market analyses, and customer expectations. Despite the complex links that utilization has with the inherent properties of the resource, its management and its marketing, research in this field has not lagged. Denney (1988a) noted that foresters have been wishing for utilization of boreal hardwoods for a long time but, during that wait, entrepreneurs, engineers, and sales people have revolutionized utilization opportunities, with forest managers being "left in the dust". This circumstance emphasizes why there are close links between research needs in ecology, management, and utilization.

Adams, R.D., ed. 1990. Aspen symposium '89. Proceedings of Symposium, July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Adams, R.D.; Gephart, J.S. 1990. Introduction to symposium and the aspen resource study. Pages 1–9 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Addison, P; Jensen, K. 1987. Long-range air pollution effects on the forest ecosystem. Pages 665–676 *in* Trans. 52nd North Am. Wildl. Nat. Resour. Conf., March 20–25, 1987, Quebec City, Quebec. Wildl. Manage. Inst., Washington, D.C.

Ahuja, M.R. 1984a. Protoplast research in woody plants. Silvae Genet. 33:32–37.

Ahuja, M.R. 1984b. Short note: a commercially feasible micropropagation method for aspen. Silvae Genet. 33:174–176.

Alban, D.H. 1982. Effects of nutrient accumulation by aspen, spruce, and pine on soil properties. Soil Sci. Soc. Am. J. 46:853–861.

Alban, D.H. 1985. Seasonal changes in nutrient concentration and content of aspen suckers in Minnesota. For. Sci. 31:785–794.

Alban, D.H.; Perala, D.A. 1990a. Ecosystem carbon following aspen harvesting in the upper Great Lakes. Pages 123–131 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Alban, D.H.; Perala, D.A. 1990b. Impact of aspen timber harvesting on soils. Pages 377–391 *in* S.P. Gessel, D.S. Lacate, G.F. Weetman, and R.F. Powers, eds. Sustained productivity of forest soils. Proc. Seventh North Am. For. Soils Conf., July 1988, Vancouver, British Columbia. Univ. British Columbia, Fac. For., Vancouver, British Columbia.

Alberta Fish and Wildlife Division. 1984. Status of the fish and wildlife resource in Alberta. Alberta Energy Nat. Resour., Fish. Wildl. Div., Edmonton, Alberta. ENR Rep. 1/87.

Alberta Forest Service. 1986. Slave Lake/Athabasca/Lac La Biche timber development area. Alberta For. Lands Wildl., For. Ind. Dev., Edmonton, Alberta. Alberta For. Dev. Opportunities. Vol. 7.

Allen, L.H. 1987. Pitch control during the production of aspen kraft pulp. Pages 79–91 *in* A. Wong and T. Szabo, eds. Proc. Workshop on Aspen Pulp, Paper and Chemicals. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Anderson, G.W. 1972. Diseases. Pages 74–82 *in* U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Lake States Aspen Rep. 21.

Anderson, G.W.; Anderson, R.L. 1968. Relationship between density of quaking aspen and incidence of hypoxylon canker. For. Sci. 15:107–112.

Anderson, G.W.; Martin, M.P. 1981. Factors related to incidence of hypoxylon cankers in aspen and survival of cankered trees. For. Sci. 27:461–476.

Anderson, N.A. 1987. Aspen utilization concerns associated with oriented strand board plants. Pages 59–66 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Anderson, N.A.; French, D.W.; Furnier, G.R.; Hackett, W.P.; Mohn, C.A. 1990. A summary of aspen genetic improvement research at the University of Minnesota. Pages 231–235 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Anderson, N.A.; Ostry, M.E.; Anderson, G.W. 1979. Insect wounds as infection sites for *Hypoxylon mammatum* on trembling aspen. Phytopathology 69:476–479.

Anderson, R.L. 1964. Hypoxylon canker impact on aspen. Phytopathology 54:253–257.

Andrejak, G.E.; Barnes, B.V. 1969. A seedling population of aspens in southeastern Michigan. Mich. Bot. 8:189–202.

Annas, R.M. 1977. Boreal ecosystems of the Fort Nelson area of northeastern British Columbia. Ph.D. thesis, Univ. British Columbia, Vancouver, British Columbia.

Antal, L.; Paszner, L.; Behera, N.; Micko, M.M. 1984. Influence of quaternary ammonium groups on mechanical properties of softwood organosolv pulps. Pages 223–227 *in* 1984 Research and development conference. Proc. Tech. Assoc. Pulp Pap. Ind., September 30 – October 3, 1984, Appleton, Wisconsin. TAPPI Press, Atlanta, Georgia.

Antal, M.; Simkovic, I.; Ebringerova, A.; Micko, M.M. 1986. New aspects in the cationization of lignocellulose materials. IV. Modification of aspen wood meal with quaternary ammonium groups. J. Appl. Polym. Sci. 31:621-625.

Arbokem Inc. 1986. Review of the chemical products produced from the Tigney exploded aspenwood process. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Arbokem Inc. 1987. Review of pulping and papermaking properties of aspen. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Ascher, A. 1990. Ground-breaking project gets results. For. Can., North. For. Cent., Edmonton, Alberta. Timberlines 13:1–3.

Bach, L.; Wang, E.I.C.; Micko, M.M. 1983. Wood quality of Alberta aspen: mechanical strengths of clear, stained, and decayed wood. Univ. Alberta Agric. For. Bull. 6(3):7–9.

Bacon, M.; Mead, C.E. 1971. Bacteria in the wood of living aspen, pine and alder. Northwest Sci. 45:270–275.

Bailey, A.W. 1972. Forage and woody sprout establishment on cleared, unbroken land in central Alberta. J. Range Manage. 25:119–122.

Bailey, A.W. 1981. Forages in northern agriculture: past, present, future. Univ. Alberta Agric. For. Bull. 4(1):27–34.

Bailey, A.W. 1986a. Prescribed burning for range and wildlife management. Univ. Alberta Agric. For. Bull. 9(3): 10–14.

Bailey, A.W. 1986b. Woodland to grassland: fire and grazing versus mechanical clearing in the Canadian aspen parkland. Pages 592–593 *in* P.J. Joss, P.W. Lynch, and O.B. Williams, eds. Rangelands: a resource under seige. Proc. Second Int. Rangeland Congr. Aust. Acad. Sci., May 13–18, 1984, Adelaide, Australia. Cambridge Univ. Press, N.Y.

Bailey, A.W.; Anderson, H.G. 1979. Brush control on sandy rangelands in central Alberta. J. Range Manage. 32:29–32.

Bailey, A.W.; Anderson, M.L. 1980. Fire temperatures in grass, shrub and aspen forest communities of central Alberta. J. Range Manage. 33:37–40.

Bailey, A.W.; Arthur, R.L. 1985. Cattle use of aspen suckers encroaching into native fescue rangeland. Univ. Alberta Agric. For. Bull. Suppl. 8:83–84.

Bailey, A.W.; Gupta, R.K. 1973. Grass–woody plant relationships. Can. J. Plant Sci. 53:671–676.

Bailey, A.W.; Irving, B.D.; FitzGerald, R.D. 1990. Regeneration of woody species following burning and grazing in aspen parkland. J. Range Manage. 43:212–215.

Bailey, A.W.; Wroe, A.L. 1974. Aspen invasion in a portion of the Alberta parklands. J. Range Manage. 27:263–266.

Bailey, G.R. 1973. Aspen: framing lumber yields high, but drying a problem. Can. For. Ind. 93(12):43–49.

Bains, B.; Antal, M.; Cyr, N.; Wang, E.; Micko, M. 1984. Modification of aspen woodmeal with quaternary ammonium functional groups I. Isolation of substituted hemicelluloses. J. Indian Acad. Wood Sci. 15(1):12–18.

Baker, R.W. 1989. Site preparation and aspen control in the SBS. Pages 99–103 *in* B.A. Scrivener and J.A. MacKinnon, eds. Learning from the past: looking to the future. Proc. North. Silvic. Comm. 1988 Winter Workshop, February 2–3, 1988, Prince George, British Columbia. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoira, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 30.

Bancroft, B. 1989. Response of aspen suckering to pre-harvest stem treatments: a literature review. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 87.

Banfield, A.W.F. 1974. The mammals of Canada. Univ. Toronto Press, Toronto, Ontario.

Barbour, R.J.; Kellogg, R.M. 1990. Forest management and end-product quality: a Canadian perspective. Can. J. For. Res. 20:405–414.

Barnes, B.V. 1959. Natural variation and clonal development of *Populus tremuloides* and *Populus grandidentata* in northern lower Michigan. Ph.D. thesis, Univ. Michigan, Ann Arbor, Michigan.

Barnes, B.V. 1961. Hybrid aspens in the lower peninsula of Michigan. Rhodora 63:311–324.

Barnes, B.V. 1966. The clonal growth habit of American aspen. Ecology 47:439–449.

Barnes, B.V. 1967. Indications of possible mid-Cenozoic hybridization in the aspens of the Columbia Plateau. Rhodora 69:70–81.

Barnes, B.V. 1969. Natural variation and delineation of clones of *Populus tremuloides* and *P. grandidentata* in northern lower Michigan. Silvae Genet. 18:130–142.

Barnes, B.V. 1975. Phenotypic variation of trembling aspen in western North America. For. Sci. 21:319–328.

Barr, B.M.; Braden, K.E. 1988. The disappearing Russian forest: a dilemma in Soviet resource management. Rowman and Littlefield, Hutchinson, London.

Barr, M.L.; Potter, L.D. 1974. Chlorophylls and carotenoids in aspen bark (*Populus tremuloides*). Southwest Nat. 19:147–154.

Barr, T. 1987. Aspen cull and its significance in bleached kraft production. Pages 55–58 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Barring, U. 1988. On the reproduction of aspen (*Populus tremula* L.) with emphasis on its suckering ability. Scand. J. For. Res. 3:229–240.

Barrows, J.S.; Sandberg, D.V.; Hart, J.D. 1976. Fire features of quaking aspen stands. Pages 14–21 *in* Aspen stands as wildfire fuel breaks. Eisenhower Consortium West. Environ. For. Res., Fort Collins, Colorado. Eisenhower Consortium Bull. 4.

Barter, G.W. 1965. Survival and development of the bronze poplar borer, *Agrilus liragus* Barter and Brown (Coleoptera: Buprestidae). Can. Entomol. 97:1063–1068.

Barth, A. 1942. Aspens, dens kultur og behandling for kvalitetsproduksjon. F.H. Frolichs Fond for Aspeskogbrukets Fremme, Oslo, Norway. Publ. 1.

Bartos, D.L.; DeByle, N.V. 1981. Quantity, decomposition, and nutrient dynamics of aspen litterfall in Utah. For. Sci. 27:381–390.

Bartos, D.L.; Lester, J.E. 1984. Effects of 2,4-D on a *Populus tremuloides* community in the western United States 22 years after treatment. Great Basin Nat. 44:459–467.

Bartos, D.L.; Mueggler, W.F. 1980. Influence of fire on vegetation production in the aspen ecosystem in western Wyoming. Pages 75–78 *in* M.S. Boyce and L.D. Hayden-Wing, eds. North America elk: ecology, behaviour and management. Univ. Wyoming, Laramie, Wyoming.

Basham, J.T. 1958. Decay of trembling aspen. Can. J. Bot. 36:491–505.

Basham, J.T. 1960. The effects of decay on the production of trembling aspen pulpwood in the Upper Pic region of Ontario. Can. Dep. Agric., For. Biol. Div., Ottawa, Ontario. Publ. 1060.

Basham, J.T. 1979. Trembling aspen decay research in Ontario. Pages 20/1–20/7 *in* D.C.F. Fayle, L. Zsuffa, and H.W. Anderson, eds. Poplar research, management and utilization in Canada. Proc. North Am. Poplar Counc. Annu. Meet., September 6–9, 1977, Brockville, Ontario. Ont. Minist. Nat. Resour., Ottawa, Ontario. For. Res. Inf. Pap. 102.

Basham, J.T. 1981. Stem decay and its implications for management in the boreal mixedwood forest of Ontario. Pages 252–258 *in* R.D. Whitney and K.M. McClain, eds. Boreal mixedwood symposium. Proc., September 16–18, 1980, Thunder Bay, Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. COJFRC Symp. Proc. O-P-9.

Basham, J.T. 1982a. Effects of herbicide treatment on the internal pathological quality of surviving aspen suckers. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-334.

Basham, J.T. 1982b. Scarification of 3-year old aspen suckers: 4- and 6-year effects on, and preliminary forecast of, the internal pathological quality of the survivors. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-341.

Basham, J.T. 1987. Assessment and prediction of stem decay in aspen stands. Pages 110–117 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Basham, J.T. 1988. Decay and stain 10 years later in aspen suckers subjected to scarification at age 3. Can. J. For. Res. 18:1507–1521.

Basham, J.T.; Navratil, S. 1975. An assessment of the pathological quality of aspen suckers established on cutovers in Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-236.

Basile, J.V. 1979. Elk–aspen relationships on a prescribed burn. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Note INT-271.

B.C. Ministry of Forests. 1988. Forestry fact sheet. B.C. Minist. For., Victoria, British Columbia.

Beck, J.A. 1988. Symposium summary. Pages 145–146 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Beck, J.A.; Constantino, L.; Phillips, W.; Messmer, M. 1989. Supply, demand and policy issues for use of aspen. For. Chron. 65:31–35.

Beeson, R.T. 1987. Case studies in the application of aspen research. Pages 30–32 *in* C.A. Troendle, M.R. Kaufmann, R.H. Hamre, and R.P. Winokur, eds. Management of subalpine forests: building on 50 years of research. Proc. Tech. Conf., July 6–9, 1987, Silver Creek, Colorado. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-149.

Belanger, R.R.; Manion, P.D.; Griffin, D.H. 1990. Amino acid content of water-stressed plantlets of *Populus tremuloides* clones in relation to clonal susceptibilty to *Hypoxylon mammatum* in vitro. Can. J. Bot. 68:26–29.

Bella, I.E. 1970. Simulation of growth, yield and management of aspen. Ph.D. thesis, Univ. British Columbia, Vancouver, British Columbia.

Bella, I.E. 1972. Simulation of growth: a new approach to yield forecasting. Pages 103–108 *in* Aspen Symp. Proc. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-1.

Bella, I.E. 1975. Growth–density relations in young aspen sucker stands. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-124.

Bella, I.E. 1986. Logging practices and subsequent development of aspen stands in east-central Saskatchewan. For. Chron. 62:81–83.

Bella, I.E.; De Franceschi, J.P. 1980. Biomass productivity of young aspen stands in western Canada. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-219.

Bella, I.E.; Jarvis, J.M. 1967. High total productivity of a young aspen stand in Manitoba. Woodlands Rev. 68:432–437.

Bendtsen, B.A.; Rees, L.W. 1962. Water-content variation in the standing aspen tree. For. Prod. J. 12:426–428.

Benson, M.K. 1972. Breeding and establishment—and promising hybrids. Pages 88–96 in Aspen Symp. Proc. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-1.

Benson, M.K.; Dubey, D. 1972. Aspen seedling production in a commercial nursery. Genet. Physiol. Notes 12.

Benson, M.K.; Einspahr, D.W. 1962. Improved method for nursery production of quaking aspen seedlings. Tree Plant. Notes 53:11–13.

Berbee, J.G.; Omuemu, J.O.; Martin, R.R.; Castello, J.D. 1976. Detection and elimination of viruses in poplars. Pages 85–91 *in* Intensive plantation culture: five years research. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-21.

Berguson, W.E.; Perala, D.A. 1988. Aspen fertilization and thinning: research results and future potential. Pages 176–183 *in* A.R. Ek and H.M. Hogan, eds. Proc. Minnesota timber supply: perspectives and analysis. Minn. Agric. Exp. Stn., Grand Rapids, Minnesota. Sci. J. Ser. 16.

Berlyn, R.W. 1965. The effect of some variables on the performance of a drum barker. Pulp Pap. Res. Inst. Can., Vancouver, British Columbia.

Bernath, S.C.; Verry, E.S.; Brooks, K.N.; Ffolliott, P.F. 1982. Modeling water yield response to forest cover changes in northern Minnesota. Pages 385–399 *in* Hydrological processes of forested areas. Proc. Can. Hydrol. Symp. '82, June 14–15, 1982, Fredericton, New Brunswick. Natl. Res. Counc. Can., Ottawa, Ontario.

Bernier, B. 1984. Nutrient cycling in *Populus*: a literature review with implications in intensively-managed plantations. For. Energy Agreement, Int. Energy Agency, Stockholm, Sweden and Environ. Can., Can. For. Serv. Ottawa, Ont. IEA/ENFOR Joint Rep.

Berry, A.B. 1973. Production of dry matter from aspen stands harvested on short rotations. Pages 207–218 *in* IUFRO Biomass Studies, Working Party on the Mensuration of the Forest Biomass, S4.01 Mensuration, Growth and Yield, August 19–25, 1973, Nancy, France and Vancouver, British Columbia. College of Life Sciences and Agriculture, Univ. Maine, Orono, Maine.

Berry, A.B.; Stiell, W.M. 1978. Effect of rotation length on productivity of aspen sucker stands. For. Chron. 54:265–267.

Berry, F.H. 1982. Reducing decay losses in high-value hardwoods: a guide for woodland owners and managers. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 595.

Bertenshaw, J.L. 1965. The clonal structure of selected aspen stands in northern lower Michigan. Ms. thesis, Univ. Michigan, Ann Arbor, Michigan.

Bickerstaff, A. 1946. The effect of thinning upon the growth and yield of aspen stands (for ten-year period after treatment). Can. Dep. Mines Resour., Lands Parks For. Branch, Dom. For. Serv., Ottawa, Ontario. Silvic. Res. Note 80.

Bickerstaff, A.; Wallace, W.L.; Evert, F. 1981. Growth of forests in Canada. Part 2. A quantitative description of the land base and the mean annual increment. Environ. Can., Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario. Inf. Rep. PI-X-1.

Biggs, W.G.; Walmsley, M.E. 1988. Research requirements to determine the effects of silvicultural herbicides on wildlife habitat: a problem analysis. Can. For. Serv., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Publ. 40.

Bird, C.D. 1969. Bryophytes of the aspen parkland of west-central Canada. Can. J. Bot. 47:187–212.

Bird, C.D.; Hong, W.S. 1975. The hepatic flora of Alberta: a phytogeographical analysis. Can. J. Bot. 53:1745–1768.

Bird, G.A.; Chatarpaul, L. 1986. Effect of whole-tree and conventional forest harvest on soil microarthropods. Can. J. Zool. 64:1986–1993.

Bird, G.A.; Rachar, D.B.; Chatarpaul, L. 1987. Increased skeletonization of leaf litter under snow following timber harvest. Ecology 68:221–223.

Bird, R.D. 1961. Ecology of the aspen parkland of western Canada, in relation to land use. Can. Dep. Agric., Res. Branch, Ottawa, Ontario. Publ. 1066.

Boekhoven, L.W.D. 1964. Relative suckering capacity of male and female aspen. Can. Dep. For., For. Res. Branch, Ottawa, Ontario.

Boivin, B. 1967. Flora of the prairie provinces. Sask. Nat. Hist. Soc., Saskatoon, Saskatchewan.

Bonnor, G.M. 1985. Inventory of forest biomass in Canada. Environ. Can., Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario.

Bonnor, G.M.; Boudewyn, P. 1990. Taper–volume equations for major tree species of the Yukon Territory. For. Can., Pac. Yukon Reg., Pac. For. Cent., Victoria, British Columbia. Inf. Rep. BC-X-323.

Bonnor, G.M.; Nietmann, K. 1987. Metric units in forestry: what do they mean? Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario.

Boone, R.S. 1990. Sorting aspen bolts and drying aspen flitches for SDR. Pages 295–299 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Borset, O. 1960. Silviculture of aspen. Scott. For. 14:68–80.

Bowes, G.G. 1975. Control of aspen and prickly rose in recently developed pastures in Saskatchewan. J. Range Manage. 28:227–229.

Bowes, G.G. 1976. Control of aspen poplar, balsam poplar, and prickly rose by picloram alone and in mixtures with 2,4-D. J. Range Manage. 29:148–150.

Bowes, G.G. 1982. Changes in the yield of forage following the use of herbicides to control aspen poplar. J. Range Manage. 35:246–248.

Bowes, G.G. 1983. Aspen poplar control with 2,4-D formulations. Can. J. Plant Sci. 63:323–325.

Brace, L.G.; Bella, I.E. 1988. Understanding the understory: dilemma and opportunity. Pages 69–86 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Bray, J.R.; Dudkiewicz, L.A. 1963. The composition, biomass and productivuty of two *Populus* forests. Bull. Torrey Bot. Club 90:298–308.

Brayshaw, T.C. 1965. Native poplars of southern Alberta and their hybrids. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Dep. For. Publ. 1109.

Brennan, J.A. 1988. The changing profile of the Alberta forest industry. Pages 32–34 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Breck, D. 1987. Aspen defects: their importance to pulp and paper. Pages 6–23 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Brese, W.G. 1977. Aspen utilization study. Alberta Bus. Dev. Tourism, Edmonton, Alberta.

Brinkman, K.A.; Roe, E.I. 1975. Quaking aspen: silvics and management in the Lake States. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 486.

Brissette, J.C.; Barnes, B.V. 1984. Juvenile height growth of aspen species and hybrids in southeastern Michigan. Can. J. For. Res. 14:959–961.

Brown, A.A.; Davis, K.P. 1973. Forest fire control and use. 2nd ed. McGraw-Hill, N.Y.

Brown, J.K. 1985. Role and use of fire in aspen. Pages 101–105 *in* Foresters' future: leaders or followers? Proc. Soc. Am. For. Natl. Conv., July 28–31, 1985, Fort Collins, Colorado. Soc. Am. For., Bethesda, Maryland.

Brown, J.K.; DeByle, N.V. 1987. Fire damage, mortality, and suckering in aspen. Can. J. For. Res. 17:1100–1109.

Brown, J.K.; DeByle, N.V. 1989. Effects of prescribed fire on biomass and plant succession in western aspen. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, Utah. Res. Pap. INT-412.

Brown, J.K.; Simmerman, D.G. 1986. Appraising fuels and flammability in western aspen: a prescribed fire guide. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, Utah. Gen. Tech. Rep. INT-205.

Bryant, J.P. 1981. Phytochemical deterrence of snowshoe hare browsing by adventitious shoots of four Alaskan trees. Science 213:889–890.

Bryant, J.P.; Kuropat, P.J. 1980. Selection of winter forage by subarctic browsing vertebrates: the role of plant chemistry. Annu. Rev. Ecol. Syst. 11:261–285.

Bryson, C. 1989. Aspen: Alberta's newest Cinderella crop. Univ. Alberta Agric. For. Bull. 12(3):11–15.

Bryson, C. 1990. Aspen. Univ. Alberta Agric. For. Bull. 13(2):5.

Buech, R.R.; Martin, C.J.; Rauscher, H.M. 1990. An application of expert systems for wildlife: identifying forest stand prescriptions for deer. AI Appl. Nat. Resour. Manage. 4(1):3–9.

Buehrer, J. 1987. The aspen rustlers. Am. For. 93(3/4):43–44.

Bunnell, F.L.; Armleder, H.M. 1989. Wildlife interactions with silvicultural treatments. Pages 131–133 *in* B.A. Scrivener and J.A. MacKinnon, eds. Learning from the past: looking to the future. Proc. North. Silvic. Comm. 1988 Winter Workshop, February 2–3, 1988, Prince George, British Columbia. For. Can., Pac.For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 30

Burger, D.; Pierpoint, G. 1990. Trends in forest site and land classification in Canada. For. Chron. 66:91–96.

Burk, T.E.; Sievanen, R.; Ek, A.R. 1990. Construction of forest growth models based on physiological principles. Pages 103–111 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Burke, M.J.; Gusta, L.V.; Quamme, H.A.; Weiser, C.J.; Li, P.H. 1976. Freezing and injury in plants. Annu. Rev. Plant Physiol. 27:507–528.

Burns, R.M., comp. 1983. Silvicultural systems for the major forest types of the United States. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 445.

Burns, R.M.; Honkala, B.H. 1990. Silvics of North America. Vol. 2, Hardwoods. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 654.

Cairns, A.L.; Telfer, E.S. 1980. Habitat use by 4 sympatric ungulates in boreal mixedwood forest. J. Wildl. Manage. 44:849–857.

Canada Department of Forestry and Rural Development. 1967. Trembling aspen in Manitoba. Papers presented at the 1965 Annual Meeting, Manit. Sect., Can. Inst. For. Can. Dep. For. Rural Dev., Inf. Tech. Serv. Div. Unpubl. Rep.

Canadian Forestry Service and Alberta Forest Service. 1987. Proceedings of the Aspen Quality Workshop held February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Canadian Institute of Forestry. 1990. Forests and global warming. Information for parliamentarians #29, April 1990. For. Chron. 66:83.

Canadian Nature Federation. 1990. Canadian Nature Federation releases its forest management policy. For. Chron. 66:78–81.

Cantin, M. 1965. The machining properties of 16 eastern Canadian woods. Can. Dep. For., Ottawa, Ontario. Dep. For. Publ. 1111.

Cantor, L.F.; Whitham, T.G. 1989. Importance of belowground herbivory: pocket gophers may limit aspen to rock outcrop refugia. Ecology 70:962–970.

Carroll-Hatch (International) Ltd. 1983. Market assessment for poplar products. Volume I. B.C. Minist. Ind. Small Bus. Dev., Victoria, British Columbia.

Case, J.W. 1977. Lichens on *Populus tremuloides* in western central Alberta, Canada. Bryologist 80:48–70.

Casteel, J. 1989. Foliar herbicide treatments for aspen: an operational viewpoint from John Casteel, Lakeland Mills Ltd., Prince George, B.C. Pages 7–8 *in* S. Watts, ed. UBC INFORMS Newsletter 3(1). For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 88.

Cayford, J.H.; Haig, R.A. 1961. Glaze damage in forest stands in southeastern Manitoba. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Tech. Note 102.

Cayford, J.H.; Hildahl, V.; Nairn, L.D.; Wheaton, M.P.H. 1959. Injury to trees from winter drying and frost in Manitoba and Saskatchewan in 1958. For. Chron. 35:282–290.

Cerezke, H.F.; Emond, F.J. 1989. Forest insect and disease conditions in Alberta, Saskatchewan, Manitoba, and the Northwest Territories in 1987. For. Can., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-300.

Cessna, A.J.; Waddington, J.; Bittman, S. 1989. Residues of 2,4-D and picloram in aspen poplar and soil after application with a roller. Can. J. Plant Sci. 69:205–212.

Chapin, F.S., III. 1980. The mineral nutrition of wild plants. Annu. Rev. Ecol. Syst. 11:233–260.

Chapin, F.S., III; Van Cleve, K. 1981. Plant nutrient absorption and retention under differing fire regimes. Pages 301–321 *in* H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners, tech. coords. Fire regimes and ecosystem properties. U.S. Dep. Agric., For. Serv., Washington, D.C. Gen. Tech. Rep. WO-26.

Chapin, F.S., III; Van Cleve, K.; Tryon, P.R. 1986. Relationship of ion absorption to growth rate in taiga trees. Oecologia 69:238–242.

Cheliak, W.H. 1980. Genetic variation in natural populations of *Populus tremuloides*. Pages 117–118 *in* B.P. Dancik and K.O. Higginbotham, eds. Proc. Sixth North Am. For. Biol. Workshop, August 11–13, 1980, Edmonton, Alberta. Univ. Alberta, Edmonton, Alberta.

Cheliak, W.M.; Dancik, B.P. 1982. Genic diversity of natural populations of a clone-forming tree *Populus tremuloides*. Can. J. Genet. Cytol. 24:611–616.

Cheliak, W.M.; Pitel, J.A. 1983. Electrophoretic identification of clones of *Populus tremuloides*. Can. J. For. Res. 14:740–743.

Cheyne, D.A. 1990. An introduction to market aspen bleached chemithermomechanical pulp. Pages 275–281 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Clark, J.D. 1988. The past in perspective: the northern mixedwood forest in Alberta. Pages 23–27 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Clark, J.S. 1990. Twentieth-century climate change, fire suppression, and forest production and decomposition in northwestern Minnesota. Can. J. For. Res. 20:219–232.

Clement, A.; Janin, G. 1976. Etude comparée de la répartition des principaux cations et du phosphore dans une tige de peuplier 'Fritzi-Pauley'. Plant Soil 45:543–554.

Clute, W.N. 1943. Meaning of plant names. XCII. Willows and poplars. Am. Bot. 49(3):78–84.

Coates, D.; Haeussler, S. 1986. A preliminary guide to the response of major species of competing vegetation to silvicultural treatments. B.C. Minist. For., Victoria, British Columbia. Land Manage. Handb. 9.

Collingwood, G.H.; Brush, W.D. 1964. Knowing your trees. Am. For. Assoc., Washington, D.C.

Commonwealth Bureau of Soils. 1971. Bibliography of soil relationships, nutrition and fertilizing of poplar (*Populus* spp), 1970–1956. Commonw. Bur. Soils, Harpenden, England. Serial 1454.

Consulting Foresters of British Columbia. 1988. Recommendations for F.R.D.A. 2 derived from forum conducted by Consulting Foresters of British Columbia. Consult. For. B.C., Vancouver, British Columbia.

Copony, J.A.; Barnes, B.V. 1974. Clonal variation in the incidence of hypoxylon canker on trembling aspen. Can. J. Bot. 52:1475–1481.

Corcoran, T.J.; Gill, D.R., eds. 1984. Proc. Symp. Counc. For. Eng./Int. Union For. Res. Organ., August 11–18, 1984. Univ. Maine, Orono, Maine and Univ. New Brunswick, Fredericton, New Brunswick.

Corns, I.G.W. 1983. Forest community types of west-central Alberta in relation to selected environmental factors. Can. J. For. Res. 13:995–1010.

Corns, I.G.W. 1989. Ecosystems with potential for aspen management. For. Chron. 65:16–22.

Corns, I.G.W.; Annas, R.M. 1986. Field guide to forest ecosystems of west-central Alberta. Environ. Can., Can. For. Serv., North. For. Cent., Edmonton, Alberta.

Cote, W.A. 1985. Alberta aspen: tomorrow's resource today. Alberta Res. Counc., Edmonton, Alberta.

Cottam, W.P. 1954. Prevernal leafing of aspen in Utah mountains. J. Arnold Arbor. Harv. Univ. 35:239–250.

Covington, W.W. 1975. Altitudinal variation of chlorophyll concentration and reflectance of the bark of *Populus tremuloides*. Ecology 56:715–720.

Coxson, D.S.; Parkinson, D. 1987. Winter respiratory activity in aspen woodland forest floor litter and soils. Soil Biol. Biochem. 19(1):49–59.

Coyne, P.I.; Van Cleve, K. 1977. Fertilizer induced morphological and chemical responses of a quaking aspen stand in interior Alaska. For. Sci. 23:92–102.

Cragg, J.B.; Carter, A.; Leischner, C.; Peterson, E.B. 1977. Litter fall and chemical cycling in an aspen (*Populus tremuloides*) woodland ecosystem in the Canadian Rockies. Pedobiologia 17:428–443.

Critchfield, W.B. 1960. Leaf dimorphism in *Populus trichocarpa*. Am. J. Bot. 47:699–711.

Crouch, G.L. 1981. Regeneration on aspen clearcuts in northwestern Colorado. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Note RM-407.

Crouch, G.L. 1983. Aspen regeneration after commercial clearcutting in southwestern Colorado. J. For. 81:316–319.

Crow, T.R. 1978. Biomass and production in three contiguous forests in northern Wisconsin. Ecology 59:265–273.

Cumming, H.G. 1987. Sixteen years of moose browse surveys in Ontario. Proc. North Am. Moose Conf. Workshop 22:125–156.

Cushwa, C.T.; Coady, J. 1976. Food habits of moose, *Alces alces*, in Alaska: a preliminary study using rumen contents analysis. Can. Field Nat. 90:11–16.

Cyr, N.; Laidler, J.K. 1987. Comparison of balsam and aspen poplar trees in Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Cyr, N.; Schulz, K.F.; Micko, M.M. 1983. Degradation and the relative accessibility of carbohydrates in decayed aspen wood. Cellul. Chem. Technol. 17:495–505.

Czapowskyj, M.M.; Safford, L.O. 1979. Growth response to fertilizer in a young aspen–birch stand. U.S. Dep. Agric., For. Serv., Northeast. For. Exp. Stn., Broomall, Pennsylvania. Res. Note NE-274.

D.A. Westworth and Associates Ltd. 1984. Impact on wildlife of short-rotation management of boreal aspen stands. Environ. Can., Can. Wildl. Serv., Edmonton, Alberta. ENFOR Proj. P-203.

Daly, E.G. 1950. Improvement cutting in a mixedwood stand. Project P-24. Can. Resour. Dev., Dep. For. Branch, Ottawa, Ontario. Silvic. Leafl. 46.

Dancik, B.P. 1990. Lost opportunities and the future of forestry: will we respond to the challenges? For. Chron. 66:454–456.

Danfield, W.; Martishus, J.; Hansen, E. 1983. Application date affects herbicide tolerance of hybrid poplars. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-301.

Dash, M.C. 1970. Ecology of Enchytraeidae (Oligochaeta) in Rocky Mountain forest soils (Kananaskis Region, Alberta, Canada). Ph.D. thesis, Univ. Calgary, Calgary, Alberta.

Daubenmire, R. 1953. Nutrient content of leaf litter of trees in the northern Rocky Mountains. Ecology 34:786–793.

Daubenmire, R.; Prusso, D.C. 1963. Studies of the decomposition rates of tree litter. Ecology 44:589–592.

Davidson, A.G.; Prentice, R.M. 1968. Insects and diseases. Pages 116-144 *in* J.S. Maini and J.H. Cayford, eds. Growth and utilization of poplar in Canada. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ontario. Dep. Publ. 1205.

Davis, R.B.; Jacobson, G.L., Jr. 1985. Late glacial and early Holocene landscapes in northern New England and adjacent areas of Canada. Quat. Res. 23:341–368.

Davison, R.W.; Atkins, R.C.; Fry, R.D.; Racey, G.D.; Weingartner, D.H. 1988. A silvicultural guide for the poplar working group in Ontario. Ont. Minist. Nat. Resour., Toronto, Ontario. Sci. Tech. Ser. Vol. 5.

Dawson, D.H.; Read, R.A. 1964. Guide for selecting superior trees for shelterbelts in the prairie plains. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Res. Pap. LS-13.

Day, M.W. 1944. The root system of aspen. Am. Midl. Nat. 32:502–509.

Day, M.W. 1958. Thinning aspen in upper Michigan. Mich. Agric. Exp. Stn. Q. Bull. 41:311–320.

Day, M.W.; Hammer, C.L.; Panshin, A.J. 1952. Preliminary observations on the effect of 2,4-D and 2,4,5-T on aspen. Mich. Agric. Exp. Stn., Q. Bull. 34:266–274.

Day, R.J.; Bell, F.W. 1988. Development of crop plans for hardwood and conifer stands on boreal mixedwood sites. Pages 87–88 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

DeByle, N.V. 1961. Tracing and evaluating functional root connections among stems within aspen clones. Ph.D. thesis, Univ. Michigan, Ann Arbor, Michigan.

DeByle, N.V. 1964. Detection of functional intraclonal aspen root connections by tracers and excavation. For. Sci. 10:386–396.

DeByle, N.V. 1976. The aspen forest after harvest. Pages 35–40 *in* Utilizing and marketing as tools for aspen management in the Rocky Mountains. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-29.

DeByle, N.V. 1981. Songbird populations and clearcut harvesting of aspen in northern Utah. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Note INT-302.

DeByle, N.V. 1985a. Animal impacts. Page 115–123 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

DeByle, N.V. 1985b. Management for esthetics and recreation, forage, water and wildlife. Pages 223–232 *in* N.V. DeByle and R.P. Winokur, eds. Aspen ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

DeByle, N.V. 1985c. Water and watershed. Pages 153–160 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

DeByle, N.V. 1985d. Wildlife. Pages 135–152 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

DeByle, N.V.; Bevins, C.D.; Fischer, W.C. 1987. Wildfire occurrence in aspen in the interior western United States. West. J. Appl. For. 2:73–76.

DeByle, N.V.; Winokur, R.P., eds. 1985. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Delcourt, P.A.; Delcourt, H.R. 1987. Long-term forest dynamics of the temperate zone: a case study of late-quaternary forests in eastern North America. Springer-Verlag, N.Y. Ecol. Stud. 63.

Delisle, G.P.; Hall, R.J. 1987. Forest fire history maps of Alberta, 1931 to 1983. Can. For. Serv., North. For. Cent., Edmonton, Alberta.

DeLong, C. 1988. A field guide for identification and interpretation of seral aspen ecosystems of the BWBSc1, Prince George Forest Region. B.C. Minist. For., Res. Branch, Victoria, British Columbia. Land Manage. Handb. 16.

Dempster, W.R. 1987. Proceedings summary. Pages 163–168 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Denney, N. 1987. Significance of aspen cull in oriented strand board plants. Pages 77–81 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Denney, N. 1988a. Problems of mixedwood management. Pages 48–49 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Denney, N. 1988b. The use of aspen in the production of oriented strand board. Pages 51–58 *in* R.L. Gambles, comp. Management and utilization of Alberta's poplars. Proc. Poplar Counc. Can. Tenth Annu. Meet., October 26–28, 1988, Edmonton, Alberta. Poplar Counc. Can., Fac. For., Univ. Toronto, Toronto, Ontario.

Deschamps, K.C. 1990. What I want in a computer model. Pages 33–37 *in* B.J. Boughton and J.K. Samoil, eds. Forest modeling symposium. Proc. Symp., March 13–15, 1989, Saskatoon, Saskatchewan. For. Can., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-308.

Dickmann, D.I.; Baer, J.; Bowersox, T.; Drew, A.; Monroe, M.; Ostry, M.; Rousseau, R., Solomon, J.; Weber, P.; Wright, L. 1987. Super trees or prima donnas? The truth about poplars. Am. Nurseryman 165(3):109–112.

Dickmann, D.I.; Stuart, K.W. 1983. The culture of poplars in eastern North America. Michigan State Univ., Dep. For., East Lansing, Michigan.

Dillén, S. 1990. Canada invests in new pulp process. Scand. Pulp Pap. Mag. 3:44–46.

Doerr, P.D.; Keith, L.B.; Rusch, D.H.; Fischer, C.A. 1974. Characteristics of winter feeding aggregations of ruffed grouse in Alberta. J. Wildl. Manage. 38:601–615.

Dormaar, J.F.; Lutwick, L.E. 1966. A biosequence of soils of the rough fescue prairie–poplar transition in southwestern Alberta. Can. J. Earth Sci. 3:457–471.

Doucet, R. 1989. Regeneration silviculture of aspen. For. Chron. 65:23–27.

Doucet, R.; Weetman, G. 1990. Canadian silviculture research: accomplishments and challenges. For. Chron. 66:85–90.

Douglas, L.J. 1988. Bioconversion of poplar. Pages 59–69 *in* R.L. Gambles, comp. Management and utilization of Alberta's poplars. Proc. Poplar Counc. Can. Tenth Annu. Meet., October 26–28, 1988, Edmonton, Alberta. Poplar Counc. Can., Fac. For., Univ. Toronto, Toronto, Ontario.

Drew, T.J.; Flewelling, J.W. 1977. Some recent Japanese theories of yield-density relationships and their application to Monterey pine plantations. For. Sci. 23:517–534.

Drouin, J.A. 1989. Herbicide efficacy trials in Alberta and Manitoba, 1980–85. For. Can., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-306.

D.R. Systems Inc. 1988. Aspen availability: field data and consolidation analysis. B.C. Minist. For., Victoria, British Columbia. Unpubl. Rep.

Eager, R.L.; Mathews, J.F.; Pepper, J.M. 1982. Liquefaction of aspen poplar wood. Can. J. Chem. Eng. 60:289–294.

Eager, R.L.; Mathews, J.M.; Pepper, J.M.; Zohdi, H. 1981. Studies on the products resulting from the conversion of aspen poplar to an oil. Can. J. Chem. 59:2191–2198.

Eager, R.L.; Pepper, J.M.; Mathews, J.F. 1983. A small-scale semi-continuous reactor for the conversion of wood to fuel oil. Can. J. Chem. Eng. 61:189–193.

Eager, R.L.; Pepper, J.M.; Roy, J.C.; Mathews, J.F. 1983. Chemical studies on oils derived from aspen poplar wood, cellulose, and an isolated aspen poplar lignin. Can. J. Chem. 61:2010–2015.

Ebata, T. 1989. Pest concerns during backlog reforestation. Pages 134–135 *in* B.A. Scrivener and J.A. MacKinnon, eds. Learning from the past: looking to the future. Proc. North. Silvic. Comm. 1988 Winter Workshop, February 2–3, 1988, Prince George, B.C. For Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 30.

Eckenwalder, J.E. 1977. North American cottonwoods (*Populus:* Salicaceae) of sections Abaso and Aigeiros. J. Arnold Arbor. Harv. Univ. 58:193–208.

Edlin, H.L. 1963. A modern silva or a discourse of forest trees. 6. Poplars—*Populus* species. Q. J. For. 57:200–210.

Egeberg, R., Jr. 1963. Inherent variations in the response of aspen to frost damage. Ecology 44:153–156.

Eggler, W.A. 1941. Primary succession on volcanic deposits in southern Idaho. Ecol. Monogr. 11:277–298.

Ehrentraut, G.; Branter, K. 1990. Vegetation management by manual and mechanical means in Alberta boreal forests. For. Chron. 66:366–368.

Einspahr, D.W. 1959. Nursery production of aspen seedlings. Tree Plant. Notes 35:22–24.

Einspahr, D.W. 1984. Somatic embryogenesis in forest genetics research. Page 5 *in* 1984 Research and development conference. Proc. Tech. Assoc. Pulp Pap. Ind., September 30 – October 3, 1984, Appleton, Wisconsin. TAPPI Press, Atlanta, Georgia.

Einspahr, D.W.; Benson, M.K. 1964. Production and evaluation of aspen hybrids. J. For. 62:806–809.

Einspahr, D.W.; Benson, M.K. 1967. Geographic variation of quaking aspen in Wisconsin and Upper Michigan. Silvae Genet. 16:106–112.

Einspahr, D.W.; Benson, M.K. 1968. Management of aspen on 10- to 20-year rotations. J. For. 66:557–560.

Einspahr, D.W.; van Buijtenen, J.P.; Peckham, J.R. 1963. Natural variation and heritability in triploid aspen. Silvae Genet. 12:51–58.

Einspahr, D.W.; Winton, L.L. 1977. Genetics of quaking aspen. U.S. Dep. Agric., For. Serv., Washington, D.C. Res. Pap. WO-25.

Einspahr, D.W.; Wyckoff, G. 1978. Growth response of hybrid aspen to intensive forest management. TAPPI (Tech. Assoc. Pulp Pap. Ind.) 61(3):49–52.

Ek, A.R.; Brodie, J.D. 1975. A preliminary analysis of short-rotation aspen management. Can. J. For. Res. 5:245–258.

Ekono Consultants Ltd. 1986. Study of the chemithermomechanical pulp (CTMP) production potential for Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Ellison, L.; Houston, W.R. 1958. Production of herbaceous vegetation in openings and under canopies of western aspen. Ecology 39:337–345.

Emond, F.J.; Cerezke, H.F. 1990. Forest insect and disease conditions in Alberta, Saskatchewan, Manitoba, and the Northwest Territories in 1989 and predictions for 1990. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-313.

Energy, Mines and Resources Canada. 1988. Canadian energy statistics. Energy, Mines Resour. Can., Energy Stats. Div., Ottawa, Ontario.

Engineering Data Management, Inc. 1989. Detection of heart rot voids in trees using stress wave analysis. For. Can., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Environics Research Group Limited. 1989. National survey of Canadian public opinion on forestry issues. For. Can., Ottawa, Ontario.

Erickson, J.R. 1972. The moisture content and specific gravity of the bark and wood of northern pulpwood species. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-141.

Etheridge, D.E. 1961. Factors affecting branch infection in aspen. Can. J. Bot. 39:799–816.

Evert, F. 1983. A national system of equations for estimating ovendry mass of trembling aspen, *Populus tremuloides* Michx. Environ. Can., Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario. Inf. Rep. PI-X-24.

Every, A.D.; Wiens, D. 1971. Triploidy in Utah aspen. Madrono 21:138–147.

Expert Panel on Forest Management in Alberta. 1990. Forest management in Alberta: report of the expert review panel. Alberta Energy, For. Lands Wildl., Edmonton, Alberta.

Falk, S.P.; Griffin, D.F.; Manion, P.D. 1989. Spatial pattern analysis and sampling of Hypoxylon canker in naturally occurring clones of *Populus tremuloides.* Plant Dis. 73:31–33.

Farmer, R.E., Jr. 1962. Aspen root sucker formation and apical dominance. For. Sci. 8:403–410.

Farmer, R.E., Jr. 1963. Vegetative propagation of aspen by greenwood cuttings. J. For. 61:385–386.

Farmer, R.E., Jr.; Freitag, M.; Garlick, K. 1989. Genetic variance and "C" effects in balsam poplar rooting. Silvae Genet. 39:62–65.

Farmer, R.E., Jr.; McKnight, J.S. 1967. *Populus*: a bibliography of world literature, 1854–1963. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., New Orleans, Louisiana. Res. Pap. SO-27.

Farmer, R.E., Jr.; Morris, D.M.; Weaver, K.B.; Garlick, K. 1988. Competition effects in juvenile jack pine and aspen as influenced by density and species ratios. J. Appl. Ecol. 25:1023–1032.

Farmer, R.E., Jr.; Reinholt, R.W. 1986. Genetic variation in dormancy relations of balsam poplar along a latitudinal transect in northwestern Ontario. Silvae Genet. 35:38–42.

Fautley, R. 1988. Economic returns to private woodlots utilizing aspen for sale in pulping. Pages 46–49 *in* Forestry or agriculture: a case for diversification. Information Seminar, Sponsored by Canadian Forestry Service, Victoria, British Columbia. Presented by Northern Lights College, April 29, 1988 Dawson Creek, British Columbia. Can. For. Serv., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 42.

Fechner, G.H.; Barrows, J.S. 1976. Aspen stands as wildfire fuel breaks. Eisenhower Consortium West. Environ. For. Res., Fort Collins, Colorado. Eisenhower Consortium Bull. 4.

Fisher, J.T.; Fancher, G.A. 1984. Effects of soil amendments on aspen seedling production. Pages 66–68 *in* P.M. Murphy, comp. The challenge of producing native plants for the Intermountain area. Proc. Intermt. Nurserymen's Assoc. 1983 Conf., August 8–11, 1983, Las Vegas, Nevada. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Gen. Tech. Rep. INT-168.

Fisher, J.T.; Neumann, R.W. 1987. Cultivation and weed control for aspen seedling establishment in the southern Rocky Mountains. Can. J. For. Res. 17:47–50.

FitzGerald, R.D.; Bailey, A.W. 1984. Control of aspen regrowth by grazing with cattle. J. Range Manage. 37:156–158.

Fitzpatrick, J.M.; Stewart, J.V. 1968. The poplar resource and its challenge to Canadian forestry. Pages 214–239 *in* J.S. Maini and J.H. Cayford, eds. Growth and utilization of poplar in Canada. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ontario. Dep. Publ. 1205.

Flaccus, E. 1959. Revegetation of landslides in the White Mountains of New Hampshire. Ecology 40:692–703.

Flanagan, P.W.; Van Cleve, K. 1983. Nutrient cycling in relation to decomposition and organic-matter quality in taiga ecosystems. Can. J. For. Res. 13:795–817.

Fletcher, R. 1985. Regenerating aspen. For. Res. West (1985):16–19.

Food and Agriculture Organization of the United Nations. 1979. Poplars and willows in wood production and land use. FAO For. Ser. 10.

Foote, K.C.; Schaedle, M. 1976. Physiological characteristics of photosynthesis and respiration in stems of *Populus tremuloides* Michx. Plant Physiol. 58:91–94.

Foote, K.C.; Schaedle, M. 1978. The contribution of aspen bark photosynthesis to the energy balance of the stem. For. Sci. 24:569–573.

Forbes, R.S.; Davidson, A.G. 1962. Examinations of wind-thrown poplar trees in New Brunswick. Can. For. Serv., Bi-Mon. Prog. Rep. 18(6):2.

Forest Products Laboratory. 1987. Wood handbook: wood as an engineering material. Rev. ed. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 72.

Forestry Branch. 1951. Canadian woods, their properties and uses. 2nd ed. Can. Dep. Res. Dev., For. Prod. Lab. Div., Ottawa, Ontario.

Forestry Canada. 1988. Canada's forest inventory 1986. For. Can., Petawawa Natl. For. Inst., Chalk River, Ontario.

Forestry Canada. 1989. Sustainable development and the Canadian forestry sector. For. Can., Ottawa, Ontario.

Forestry Canada and Alberta Forest Service. 1989. Child's play really pays off. Page 1 *in* Growing Partnership. Canada–Alberta For. Resour. Dev. Agreement.

Forestry Research Advisory Council of Canada. 1989. Forest research priorities in Canada: an overview for the Canadian Council of Forest Ministers. For. Chron. 65:478–483.

Fortin, J.A.; Piche, Y.; Godbout, C. 1983. Methods for synthesizing ectomycorrhizas and their effect on mycorrhizal development. Plant Soil 71:275–284.

Fowler, D.P.; Morgenstern, E.K. 1990. Tree improvement research and development in Canada. For. Chron. 66:97–101.

Fralish, J.S. 1972. Youth, maturity, and old age. Pages 52–58 *in* Aspen Symp. Proc. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-1.

Fralish, J.S.; Loucks, O.L. 1967. Prediction of aspen site index from correlation with site factors in Wisconsin. Univ. Wisconsin, For. Res. Note 132.

Fralish, J.S.; Loucks, O.L. 1975. Site quality evaluation models for aspen (*Populus tremuloides* Michx.) in Wisconsin. Can. J. For. Res. 5:523–528.

Fraser, D.A. 1959. Tree growth in relation to soil moisture. Pages 183–204 *in* T.T. Kozlowski, ed. Tree growth. Ronald Press, N.Y.

Fraser, G.A.; Phillips, W.E.; Lamble, G.W.; Hogan, G.D.; Teskey, A.G. 1985. The potential impact of the long range transport of air pollutants on Canadian forests. Environ. Can., Can. For. Serv., Ottawa, Ontario. Inf. Rep. E-X-36.

Fregren, D.H. 1980. The hardwood future in Alberta. Pages 145–147 *in* J.A. McIntosh and M.N. Carroll, eds. Utilization of western Canadian hardwoods. Proc. Symp., November 21–22, 1979, Prince George, British Columbia, Forintek Can. Corp., Vancouver, British Columbia. Spec. Publ. SP-2.

Fritschel, P.R.; Satter, L.D.; Baker, A.J.; McGovern, J.N.; Vatthauer, R.J.; Millett, M.A. 1976. Aspen bark and pulp residue for ruminant feedstuffs. J. Anim. Sci. 42:1513–1521.

Froning, K. 1980. Logging hardwoods to reduce damage to white spruce understory. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-229.

Funk, A. 1989. Observations on an aspen leaf spot disease and associated fungus, *Pollaccia borealis*. Can. J. Plant Path. 11:353–356.

Gale, M.R.; Grigal, D.F. 1987. Vertical root distributions of northern tree species in relation to successional status. Can. J. For. Res. 17:829–834.

Gale, M.R.; Grigal, D.F. 1988. Performance of a soil productivity index model used to predict site quality and stand production. Pages

403–410 *in* A.R. Ek, S.R. Shifley, and T.E. Burk, eds. Forest growth modelling and prediction. Vol. 1. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-120.

Gale, M.R.; Grigal, D.F. 1990. Development of a soil- and root-based productivity index model for trembling aspen. Pages 303–309 *in* R.K. Dix, R.S. Meldahl, G.A. Ruark, and W.G. Warren, eds. Process modeling of forest growth responses to environmental stress. Timber Press, Portland, Oregon.

Gambles, R.L., comp. 1988. Management and utilization of Alberta's poplars. Proceedings Poplar Council of Canada Tenth Annual Meeting, October 26–28, 1988, Edmonton, Alberta. Poplar Counc. Can., Fac. For., Univ. Toronto, Toronto, Ontario.

Gansner, D.A.; Arner, S.L.; Zarnoch, S.J. 1990. Timber value growth rates in Maine. North. J. Appl. For. 7:62–64.

Garner, G.J. 1988. Creating a forest that's an asset: a harvesting perspective. Pages 9.1–9.3 *in* T. Rotherham, J.V. Hatton, and J. Roy, eds. Forest crop planning: a corporate approach to strategic planning of forest fibres, trees and stands to meet future market needs: twenty-two expert views. Pulp Pap. Res. Inst. Can., Vancouver, British Columbia.

Garrett, P.W.; Zahner, R. 1964. Clonal variation in suckering of aspen obscures effect of various clearcutting treatments. J. For. 62:749–750.

Gifford, G.F. 1966. Aspen root studies on three sites in northern Utah. Am. Midl. Nat. 75:132–141.

Gifford, G.F. 1967. The influence of growth media, temperatures, and light intensities on aspen root and top growth. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Note INT-67.

Gifford, G.F.; Humphries, W.; Jaynes, R.A. 1983. A preliminary quantification of the impact of aspen to conifer succession on water yield within the Colorado River Basin. Utah State Univ., Water Res. Lab., Logan, Utah.

Gifford, G.F.; Humphries, W.; Jaynes, R.A. 1984. A preliminary quantification of the impacts of aspen to conifer succession on water yield. II. Modelling results. Water Resour. Bull. 20:181–186.

Gill, D. 1974. Snow damage to boreal mixedwood stands in Alberta. For. Chron. 50:70–73.

Godbout, C.; Fortin, J.A. 1985. Synthesized ectomycorrhizae of aspen: fungal genus level of structural characterization. Can. J. Bot. 63:252–262.

Gordon, A.G. 1981. Impacts of harvesting on nutrient cycling in the boreal mixedwood forest. Pages 121–140 *in* R.D. Whitney and K.M. McClain, eds. Boreal mixedwood symposium. Proc., September 16–18, 1980, Thunder Bay, Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont. COJFRC Symp. Proc. O-P-9.

Gordon, A.G. 1983. Nutrient cycling dynamics in differing spruce and mixedwood ecosystems in Ontario and the effects of nutrient removals through harvesting. Pages 97–118 *in* R.W. Wein, R.R. Riewe, and I.R. Methven, eds. Resources and dynamics of the boreal zone. Proc. Conf., August 1982, Thunder Bay, Ontario. Assoc. Can. Univ. North. Stud., Ottawa, Ontario.

Gordon, F.A. 1976. Spring burning in an aspen–conifer stand for maintenance of moose habitat, West Boulder River, Montana. Pages 501–538 *in* Proc. 14th Tall Timbers Fire Ecol. Conf., Fire Land Manage. Symp., October 8–10, 1974, Missoula, Montana. Tall Timbers Res. Stn., Tallahassee, Florida.

Gosz, J.R. 1980. Biomass distribution and production budget for a nonaggrading forest ecosystem. Ecology 61:507–514.

Gottfried, G.J.; Jones, J.R. 1975. Logging damage to advance regeneration on an Arizona mixed conifer watershed. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Pap. RM-147.

Gottschalk, K.W.; Gansner, D.A.; Herrick, O.W.; Mason, G.N. 1987. Coping with gypsy moth: guidelines for forest management. Pages 72–76 *in* Economic and social development: a role for forests and forestry professionals. Proc. Soc. Am. For. Natl. Conv., October 18–21, 1987, Minneapolis, Minnesota. Soc. Am. For., Bethesda, Maryland.

Grabowski, T.I.J. 1981. A stand growth model for trembling aspen in the prairie provinces of Canada. M.A. thesis, Univ. Alberta, Edmonton, Alberta.

Grabowski, T.I.J.; Heidt, J.; Titus, S.J. 1981. An improved stand growth model for trembling aspen in the prairie provinces of Canada. Pages 61–64 *in* Proc. Third Bioenergy R & D Semin., March 24–25, 1981, Ottawa, Ontario. Natl. Res. Counc. Can., Ottawa, Ontario.

Graham, S.A.; Harrison, R.P. 1954. Insect attacks and Hypoxylon infections in aspen. J. For. 52:741–743.

Graham, S.A.; Harrison, R.P., Jr.; Westell, C.E., Jr. 1963. Aspens: phoenix trees of the Great Lakes region. Univ. Michigan Press, Ann Arbor, Michigan.

Green, J.E.; Salter, R.E. (Delta Environmental Management Group Ltd.) 1987a. Methods for reclamation of wildlife habitat in the Canadian prairie provinces. Environ. Can., West. Reg., Edmonton, Alberta and Alberta Rec. Parks Wildl. Found., Edmonton, Alberta.

Green, J.E.; Salter, R.E. (Delta Environmental Management Group Ltd.) 1987b. Reclamation of wildlife habitat in the Canadian prairie provinces. Vol. II. Habitat requirements of key species. Environ. Can., West. Reg., Edmonton, Alberta and Alberta Rec. Parks Wildl. Found., Edmonton, Alberta.

Green, J.E.; Salter, R.E.; Fooks, C.E. (Delta Environmental Management Group Ltd.) 1987. Reclamation of wildlife habitat in the Canadian prairie provinces. Vol. I. Techniques for the creation and enhancement of wildlife habitat. Environ. Can., West. Reg., Edmonton, Alberta and Alberta Rec. Parks Wildl. Found., Edmonton, Alberta.

Green, R.N.; Courtin, P.J.; Klinka, K.; Slaco, R.J.; Ray, C.A. 1984. Site diagnosis, tree species selection, and slashburning guidelines for the Vancouver forest region. B.C. Minist. For., Vancouver, British Columbia. Land Manage. Handb. 8.

Greene, J.G. 1971. Clonal variation in *Populus tremuloides* Michx. on the east slope of the Front Range, Boulder County, Colorado. Ph.D. thesis, Univ. Colorado, Boulder, Colorado.

Greenprint for Canada Committee. 1989. Greenprint for Canada: a federal agenda for the environment. Greenprint Can. Comm., Ottawa, Ontario.

Greenway, S.H. 1990. Aspen regeneration: a range management problem. Rangelands 12(1):21–23.

Grewal, H.; Apps, M.J.; MacIsaac, D. 1990. Using a traditional growth and yield model (STEMS) to drive a management simulator (FORCYTE-11). Pages 225–232 *in* L.C. Wensel and G.S. Biging, eds. Forest simulation systems. Proc. Int. Union For. Res. Organ. Conf., November 2–5, 1988, Berkeley, California. Univ. California Press, Berkeley, California.

Grime, J.P. 1977. Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. Am. Nat. 111:1169–1194.

Gross, H.L.; Basham, J.T. 1981. Diseases of aspen suckers in northern Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-329.

Gruell, G.E. 1980. Fire's influence on wildlife habitat on the Bridger-Teton National Forest, Wyoming. Vol. II. Changes and causes, management implications. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Pap. INT-252.

Gullion, G.W. 1977. Maintenance of the aspen ecosystem as a primary wildlife habitat. Pages 256–265 *in* T.J. Peterle, ed. Proc. 13th Int. Cong. Game Biol., March 11–15, 1977, Atlanta, Georgia. Wildl. Soc., Washington, D.C.

Gullion, G.W. 1984. Managing northern forests for wildlife. Minn. Agric. Exp. Stn., St. Paul, Minnesota. Misc. J. Ser. Publ. 13.

Gullion, G.W. 1986. Northern forest management for wildlife. Univ. Alberta, Edmonton, Alberta. For. Ind. Lect. Ser. 17.

Gullion, G.W. 1987. Aspen management for ruffed grouse. Pages 137–139 *in* Economic and social development: a role for forests and forestry professionals. Proc. Soc. Am. For. Natl. Conv., October 18–21, 1987, Minneapolis, Minnesota. Soc. Am. For., Bethesda, Maryland.

Gullion, G.W. 1990. Management of aspen for ruffed grouse and other wildlife—an update. Pages 133–143 *in* R.D. Adams, ed. Aspen symposium '89, Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Haataja, B.A.; Adams, R.D.; Arola, R.A. 1984. Total tree chunkwood as raw material for flake products. Pages 157–163 *in* T.J. Corcoran and D.R. Gill, eds. Proc. Symp. Counc. For. Eng./Int. Union For. Res. Organ., August 11–18, 1984. Univ. Maine, Orono, Maine and Univ. New Brunswick, Fredericton, New Brunswick.

Haeussler, S.; Coates, D. 1986. Autecological characteristics of selected species that compete with conifers in British Columbia: a literature review. B.C. Minist. For., Victoria, British Columbia. Land Manage. Rep. 33.

Hagglund, B.; Peterson, G., eds. 1985. Broadleaves in boreal silviculture—an obstacle or an asset? Sver. Lantbruksuniv. Inst. Skogsskotsel Rapp. 14.

Hall, R.B.; Colletti, J.P.; Schultz, R.C.; Faltonson, R.R.; Kolison, S.H., Jr.; Hanna, R.D.; Hillson, T.D.; Morrison, J.D. 1990. Commercial-scale vegetative propagation of aspens. Pages 211–219 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Hambly, E.S.L. 1985. Aspen: silvics, management and utilization—a literature review with special reference to Ontario. Ont. Nat. Resour., Fast Growing Hardwoods Tech. Dev. Group, Brockville, Ontario.

Hamel, D.R. 1983. Forest management chemicals. A guide to use when considering pesticides for forest management. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 585.

Harmon, M.E.; Franklin, J.F.; Swanson, F.J.; Sollins, P.; Gregory, S.V.; Lattin, J.D.; Anderson, N.H.; Cline, S.P.; Aumen, N.G.; Sedell, J.R.; Lienkaemper, G.W.; Cromack, K., Jr.; Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15:133–301.

Harniss, R.O. 1981. Ecological succession in aspen and its consequences on multiple use values. Pages 31–39 *in* N.V. DeByle, ed. Proc. Symp. Situation Manage. Two Intermt. Species: Aspen and Coyotes. Vol. 1. Aspen. Utah State Univ., Logan, Utah.

Harniss, R.O.; Bartos, D.L. 1985. Survey of aspen stands treated with herbicides in the western United States. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, Utah. Res. Pap. INT-340.

Harper, K.T.; Shane, J.D.; Jones, J.R. 1985. Taxonomy. Pages 7–8 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Harrington, J.B. 1987. Climatic change: a review of causes. Can. J. For. Res. 17:1313–1339.

Hart, E.D., comp. 1976. *Populus*: a bibliography of world literature, 1964–1974. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., New Orleans, Mississippi. Res. Pap. SO-124.

Hart, J.H. 1990. Effect of gypsy moth on aspen in Michigan. Pages 173–176 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Hartig, G.L. 1851. Lehrbuch fur Forster. [Textbook for professional foresters.] Vol. 2. 9th ed. H. Hartig, Stuttgart.

Hartley, C.; Davidson, R.; Crandall, B.S. 1961. Wet wood, bacteria, and increased pH in trees. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wisconsin. Rep. 2215.

H.A. Simons (International) Ltd. 1986. Improving fibre utilization in the aspen structural panelboard industry. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Hassall, M.; Parkinson, D.; Visser, S. 1986. Effects of the collembolan *Onychiurus subtenuis* on decomposition of *Populus tremuloides* leaf litter. Pedobiologia 29:219–225.

Hawkes, B.C.; Feller, M.C.; Meehan, D. 1990. Site preparation: fire. Pages 131–139 *in* D.P. Lavender, R. Parish, C.M. Johnson, G. Montgomery, A. Vyse, R.A. Willis, and D. Winston, eds. Regenerating British Columbia's forests. Univ. British Columbia Press, Vancouver, British Columbia.

Heeney, C.J.; Kemperman, J.A.; Brown, G. 1980. A silvicultural guide to the aspen working group in Ontario. Ont. Minist. Nat. Resour., For. Res. Branch, Toronto, Ontario.

Heidt, J. 1983. Clonal variation in height growth of trembling aspen in central Alberta. Univ. Alberta Agric. For. Bull. 6(3):20–23.

Heikurinen, J.K.K. 1981. Current management practices in the boreal mixedwood forest: Northeastern Region. Pages 184–192 *in* R.D. Whitney and K.M. McLain, eds. Boreal mixedwood symposium. Proc., September 16–18, 1980, Thunder Bay, Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. COJFRC Symp. Proc. O-P-9.

Heilman, P.E.; Peabody, D.V., Jr.; DeBell, D.S.; Strand, R.F. 1972. A test of close-spaced, short-rotation culture of black cottonwood. Can. J. For. Res. 2:456–459.

Heinonen, T. 1983. Haavikon lannoituskoe. [Summary: a fertilization experiment in a *Populus tremula* stand]. Silva Fenn. 17(1):65–70.

Heinselman, M.L. 1954. The extent of natural conversion to other species in the Lake States aspen–birch type. J. For. 52:737–738.

Heinselman, M.L.; Zasada, Z.A. 1955. A review of literature relating to quaking aspen sites. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Stn. Pap. 32.

Heit, M.J.; Bohning, R.A. 1988. Secondary forest products industry in Alberta, 1986. For. Chron. 64: 461–463.

Henderson, C.J. 1987. Aspen management practices in Alberta. Pages 71–76 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv. North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Henderson, C.J. 1988a. Managing aspen in the mixedwood forest. Pages 50–52 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Henderson, C.J. 1988b. Alberta's experience in poplar management and harvesting. Pages 1–8 *in* R.L. Gambles, comp. Management and utilization of Alberta's poplars. Proc. Poplar Counc. Can. Tenth Annu. Meet., October 26–28, 1988, Edmonton, Alberta. Poplar Counc. Can., Fac. For., Univ. Toronto, Toronto, Ontario.

Hendrickson, O.Q. 1987. Winter branch nutrients in northern conifers and hardwoods. For. Sci. 33:1068–1074.

Hendrickson, O.Q.; Burgess, D.M.; Chatarpaul, L. 1987. Biomass and nutrients in Great Lakes–St. Lawrence forest species: implications for whole-tree and conventional harvest. Can. J. For. Res. 17:210–218.

Herring, L. 1989. Silvicultural responses in the boreal white and black spruce zone. Pages 42–45 *in* B.A. Scrivener and J.A. MacKinnon, eds. Learning from the past: looking to the future. Proc. North. Silvic. Comm. 1988 Winter Workshop, February 2–3, 1988, Prince George, British Columbia. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 30.

Hildahl, V.; Campbell, A.E. 1975. Forest tent caterpillar in the prairie provinces. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-135.

Hildahl, V.; Reeks, W.A. 1960. Outbreaks of the forest tent caterpillar, *Malacosoma disstria* Hbn., and their effects on stands of trembling aspen in Manitoba and Saskatchewan. Can. Entomol. 92:199–209.

Hilton, J.E. 1970. Forage production and utilization in the aspen parkland of Alberta following aerial application of 2,4-D and 2,4,5-T. M.Sc. thesis, Univ. Alberta, Edmonton, Alberta.

Hilton, J.E.; Bailey, A.W. 1972. Cattle use of a sprayed aspen parkland range. J. Range Manage. 25:257–260.

Hilton, J.E.; Bailey, A.W. 1974. Forage production and utilization in a sprayed aspen forest in Alberta. J. Range Manage. 27:375–380.

Hinds, T.E. 1976. Diseases of western aspen. Pages 24–29 *in* Utilization and marketing as tools for aspen management in the Rocky Mountains. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-29.

Hinds, T.E. 1985. Diseases. Pages 87–106 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Hinds, T.E.; Krebill, R.G. 1975. Wounds and canker diseases on western aspen. U.S. Dep. Agric., For. Serv. For. Pest Leafl. 152.

Hinds, T.E.; Shepperd, W.D. 1987. Aspen sucker damage and defect in Colorado clearcut areas. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Pap. RM-278.

Hipp Engineering Ltd. 1984. A pulpmill development opportunity in northeast British Columbia. B.C. Minist. Ind. Small Bus. Dev., Victoria, British Columbia.

Hiratsuka, Y. 1987. Forest tree diseases of the prairie provinces. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-286.

Hiratsuka, Y.; Gibbard, D.A.; Bakowsky, O.; Maier, G.B. 1990. Classification and measurement of aspen decay and stain in Alberta. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-314.

Hiratsuka, Y.; Loman, A.A. 1984. Decay of aspen and balsam poplar in Alberta. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-262.

Hocker, H.W., Jr. 1982. Effects of thinning on biomass growth in young *Populus tremuloides* plots. Can. J. For. Res. 12:731–737.

Hoff, C.C. 1957. A comparison of soil, climate, and biota of conifer and aspen communities in the central Rocky Mountains. Am. Midl. Nat. 58:115–140.

Holdaway, M.R. 1988. The effects of climate, acid deposition and their interaction on Lake States forests. Pages 67–71 *in* Healthy forests, healthy world. Proc. Soc. Am. For. Natl. Conv., October 16–19, 1988, Rochester, New York. Soc. Am. For., Bethesda, Maryland.

Holdaway, M.R.; Brand, G.J. 1983. An evaluation of the STEMS tree growth projection system. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Pap. NC-234.

Holloway, P. 1989. Utilization of aspen wood chip and stone mulches for ornamental plantings in Fairbanks, Alaska. Pages 58–70 *in* Proc. Eighth Annu. Alaska Greenhouse Nursery Conf., Fairbanks, Alaska.

Holmsen, S.D. 1989. Mowing to reduce aspen competition in young spruce plantations in northern Alberta. For. Eng. Res. Inst. Can. Pointe Claire, Quebec. Tech. Note TN-132.

Holsten, E.H.; Hard, J. 1985. Efficacy of *Bacillus thuringiensis* Berliner for suppressing populations of large aspen tortrix in Alaska. Can. Entomol. 117:587–591.

Hoover, R.L.; Wills, D.L., eds. 1987. Managing forested lands for wildlife. Colo. Div. Wildl. and U.S. Dep. Agric., For. Serv., Rocky Mt. Reg., Denver, Colorado.

Hornbeck, J.W.; Kropelin, W. 1982. Nutrient removal and leaching from a whole-tree harvest of northern hardwoods. J. Environ. Qual. 11:309–316.

Horton, K.W. 1956. The ecology of lodgepole pine in Alberta and its role in forest succession. Can. Dep. North. Aff. Natl. Resour., For. Branch, For. Res. Div. Tech. Note 45.

Horton, K.W. 1981. Biomass yield tables for aspen in Ontario. Environ. Can., Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario. ENFOR Proj. P-30(1).

Horton, K.W. 1984. Silvicultural treatments to maximize biomass production in aspen stands. Environ. Can., Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario. ENFOR Proj. P-257.

Horton, K.W.; Hopkins, E.J. 1965. Influence of fire on aspen suckering. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Dep. For. Publ. 1095.

Horton, K.W.; Maini, J.S. 1964. Aspen reproduction: its characteristics and control. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Monogr. 64-0-12.

Hosie, R.C. 1979. Native trees of Canada. 8th ed. Fitzhenry and Whiteside Ltd. Ottawa, Ontario.

Houston, W.R. 1954. A condition guide for aspen ranges of Utah, Nevada, southern Idaho and western Wyoming. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Pap. 32.

Howlett, M. 1989. The forest industry on the prairies: opportunities and constraints to future development. Prairie Forum 14(2):233–258.

H.P.C. Construction Ltd. 1987. Children's furniture manufacturing from Alberta aspen, pine and spruce. Can. For. Serv., North. For. Cent., Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Hubbard, J.W. 1972. Effects of thinning on growth and yield. Pages 126–130 *in* Aspen Symp. Proc. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-1.

Hubbes, M. 1962. Inhibition of *Hypoxylon pruinatum* by pyrocatechol isolated from bark of aspen. Science 136:156.

Hubbes, M. 1966. Inhibition of *Hypoxylon pruinatum* (Klotzsche) Cke. by aspen bark meal and the nature of active extractives. Can. J. Bot. 44:365–386.

Hudson, R.J.; Blyth, C. 1986. Mixed grazing systems of the aspen boreal forest. Pages 380–383 *in* P.J. Ross, P.W. Lynch, and O.B. Williams, eds. Rangelands: a resource under seige. Proc. Second Int. Rangeland Cong. Aust. Acad. Sci., May 13–18, 1984, Adelaide, Australia. Cambridge Univ. Press, N.Y.

Hulme, M.A. 1988. The recent Canadian record in applied biological control of forest insect pests. For. Chron. 64:27–31.

Hungerford, R.D. 1988. Soil temperatures and suckering in burned and unburned aspen in Idaho. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, Utah. Res. Note INT-378.

Hunt, H.M. 1976. Big game utilization of hardwood cuts in Saskatchewan. Pages 91–126 *in* J.A. Hancock and W.E. Mercer, eds. Proc. 12th North Am. Moose Conf. Workshop, March 23–26, 1976, St. John's, Newfoundland.

Hunt, K.; Keays, J.L. 1973. Short rotation trembling aspen trees (*Populus tremuloides* Michx.) for kraft pulp. Can. J. For. Res. 3:180–184.

Info-Tech. 1989. Maintaining an edge. Proceedings of a Conference on the Forest Industry Technology for the 1990s, October 25–26, 1989, Edmonton, Alberta. Info-Tech, Calgary, Alberta and Alberta For. Lands Wildl., For. Ind. Dev. Div., Edmonton, Alberta.

Irwin, J.D.; Doyle, J.A. 1961. Properties and utilization of Canadian poplars. Can. Dep. For., For. Prod. Res. Branch, Ottawa, Ontario. Tech. Note 24.

Irwin, L.L. 1975. Deer–moose relationships on a burn in northeastern Minnesota. J. Wildl. Manage. 39:653–662.

Irwin, L.L. 1985. Foods of moose (*Alces alces*) and white-tailed deer (*Odocoileus virginianus*) on a burn in boreal forest. Can. Field. Nat. 99:240–245.

Isebrands, J.G.; Ek, A.R.; Meldahl, R.S. 1982. Comparison of growth model and harvest yields of short rotation intensively cultured *Populus*: a case study. Can. J. For. Res. 12:58–63.

Ives, W.G.H. 1984. *Malacosoma disstria* Hübner, forest tent caterpillar (Lepidoptera: Lasiocampidae). Pages 311–319 *in* J.S. Kelleher and M.A. Hulme, eds. Biological control programmes against insects and weeds in Canada, 1969–1980. Commonw. Agric. Bur., Slough, England.

Ives, W.G.H.; Wong, H.R. 1988. Tree and shrub insects of the prairie provinces. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-292.

Jackson, M.; Akerlund, G.; Hoglun, H. 1983. CTMP and CMP from North American aspen (*Populus tremuloides*). Pages B158–B161 *in* Proc. 69th Can. Pulp Pap. Assoc. Annu. Meet., February 3–4, 1983, Montreal, Quebec. Can. Pulp Pap. Assoc., Montreal, Quebec.

James, T.D.W.; Smith, D.W. 1977. Short-term effects of surface fire on the biomass and nutrient standing crop of *Populus tremuloides* in southern Ontario. Can. J. For. Res. 7:666–679.

James, T.D.W.; Smith, D.W. 1978a. Seasonal changes in the caloric value of the leaves and twigs of *Populus tremuloides*. Can. J. Bot. 56:1804–1805.

James, T.D.W.; Smith, D.W. 1978b. Seasonal changes in the major ash constituents of leaves and some woody components of trembling aspen and red osier dogwood. Can. J. Bot. 56:1798–1803.

Jarvis, J.M. 1968. Silviculture and management of natural poplar stands. Pages 70–87 *in* J.S. Maini and J.H. Crayford, eds. Growth and utilization of poplar in Canada. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ontario. Dep. Publ. 1205.

Jarvis, J.M.; Steneker, G.A.; Waldron, R.M.; Lees, J.C. 1966. Review of silvicultural research: white spruce and trembling aspen cover types, mixedwood forest section, boreal forest region, Alberta, Saskatchewan, Manitoba. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ontario. Dep. Publ. 1156.

Jaynes, R.A. 1978. A hydrologic model of aspen–conifer succession in the western U.S. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Pap. INT-213.

Jobidon, R.; Thibault, J.R. 1981. Allelopathic effects of balsam poplar on green alder germination. Bull. Torrey Bot. Club 108:413–418.

Jobidon, R.; Thibault, J.R. 1982. Allelopathic growth inhibition of nodulated and unnodulated *Alnus crispa* seedlings by *Populus balsamifera*. Am. J. Bot. 69:1213–1223.

Johnson, C.W.; Brown, T.C.; Timmons, M.L. 1985. Esthetics and landscaping. Pages 185–188 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Johnson, H.J. 1986. The release of white spruce from trembling aspen overstoreys: a review of available information and silvicultural guidelines. Can. For. Serv., Manit. Dist. Off., Winnipeg, Manitoba and Manit. Dep. Nat. Resour., Winnipeg, Manitoba. Canada–Manitoba For. Renewal Agreement. Unpubl. Rep.

Johnson, J.D.; Lesko, G.L. 1977. Recommendations for species selection and management in the amenity plantations of southern Saskatchewan. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-181.

Johnston, R.S. 1969. Aspen sprout production and water use. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Note INT-89.

Johnston, R.S.; Tew, R.K.; Doty, R.D. 1969. Soil moisture depletion and estimated evapotranspiration on Utah mountain watersheds. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Pap. INT-67.

Johnstone, W.D. 1977. Interim equations and tables for the yield of fully stocked spruce–poplar stands in the mixedwood forest section of Alberta. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-175.

Johnstone, W.D.; Peterson, E.B. 1980. Above-ground component weights in Alberta *Populus* stands. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-226.

Jones, A.R.C.; Grant, J. 1983. Hybrid poplars or hardwood coppice? An agroforestry option to economically increasing wood production in eastern Canada. For. Chron. 59:143–145.

Jones, B.S.; Berguson, W.E.; Vogel, J.J. 1990. Aspen thinning as a viable cultural tool. Pages 205–210 *in* R.D. Adams, ed. Aspen symposim '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Jones, J.R. 1975. Regeneration on an aspen clearcut in Arizona. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Note RM-285.

Jones, J.R. 1976. Aspen harvesting and reproduction. Pages 30–34 *in* Utilization and marketing as tools for aspen management in the Rocky Mountains. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Note RM-282.

Jones, J.R.; DeByle, N.V. 1985a. Genetics and variation. Pages 35–39 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, J.R.; DeByle, N.V. 1985b. Morphology. Pages 11–18 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, J.R.; DeByle, N.V. 1985c. Other physical factors. Pages 83–86 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, J.R.; Schier, G.A. 1985. Growth. Pages 19–24 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, J.R.; Shepperd, W.D. 1985a. Harvesting. Pages 219–222 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, J.R.; Shepperd, W.D. 1985b. Intermediate treatments. Pages 209–216 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, J.R.; Shepperd, W.D. 1985c. Rotations. Pages 217–218 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, J.R.; Trujillo, D.P. 1975. Development of some young aspen stands in Arizona. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Pap. RM-151.

Jones, J.R.; Winokur, R.P.; Shepperd, W.D. 1985. Management overview. Pages 193–195 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Jones, K.L. 1983. Current knowledge of the effects of cattle grazing on aspen in the Alberta parkland. Rangelands 5:59–60.

Jozsa, L.A.; Parker, M.L.; Bramhall, P.A.; Johnson, S.G. 1984. How climate affects tree growth in the boreal forest. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-255.

Jozsa, L.A.; Powell, J.M. 1987. Some climatic aspects of biomass productivity of white spruce stem wood. Can. J. For. Res. 17:1075–1079.

Judd, J. 1982. New sawing process will have impact on nation's hardwoods and help extend softwood resource. For. Prod. J. 32(1):9–11.

Kabzems, A.; Kosowan, A.L.; Harris, W.C. 1986. Mixedwood section in an ecological perspective: Saskatchewan. 2nd. ed. Sask. Parks Renew. Resour., For. Div., Prince Albert, Saskatchewan and Can. For. Serv., Sask. Dist. Off., Prince Albert, Saskatchewan. Tech. Bull. 8.

Karaim, B.W.; Wengert, E.M.; Szabo, T. 1990. Opportunities for aspen and balsam poplar utilization in Alberta. Pages 253–274 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Kaufert, F.H. 1937. Factors influencing the formation of periderm in aspen. Am. J. Bot. 24:24–30.

Kauppi, P.; Posch, M. 1985. Sensitivity of boreal forests to possible climatic warming. Clim. Change 7:45–54.

Kayll, A.J. 1968. The role of fire in the boreal forest of Canada. Can. Dep. Rural Dev., For. Branch, Petawawa For. Exp. Stn., Chalk River, Ontario. Inf. Rep. PS-X-7.

Keays, J.L.; Hatton, J.V.; Bailey, G.R.; Neilson R.W. 1974. Present and future uses of Canadian poplars in fibre and wood products. Environ. Can., Can. For. Serv., West. For. Prod. Lab., Vancouver, British Columbia. Inf. Rep. VP-X-120.

Kemp, A.K. 1959. Factors associated with the development of collapse in aspen during kiln drying. For. Prod. J. 9(3):124–130.

Kemperman, J.A. 1977. Aspen clones: development, variability and identification. Ont. Minist. Nat. Resour., Div. For., For. Res. Branch, Thunder Bay, Ontario. For. Res. Inf. Pap. 101.

Kemperman, J.A. 1978. Sucker–root relationships in aspen. Ont. Minist. Nat. Resour., Div. For., For. Res. Branch, Maple, Ontario. For. Res. Note 12.

Kemperman, J.A.; Barnes, B.V. 1976. Clone size in American aspens. Can. J. Bot. 54:2603–2607.

Kemperman, J.A.; Basham, J.T.; Navratil, S. 1978. Preliminary assessment of defect variation among aspen clones in northern Ontario. Ont. Minist. Nat. Resour., Div. For., For. Res. Branch, Maple, Ontario. For. Rep. 104.

Kemperman, J.A.; Lyon, N.F.; Navratil, S. 1976. Incidence and volume of defect in second growth aspen stands in northern Ontario. Ont. Minist. Nat. Resour., Div. For., For. Res. Branch, Maple, Ontario. For. Res. Rep. 102.

Kennedy, E.I. 1965. Strength and related properties of woods grown in Canada. Can. Dep. For. Rural Dev., For. Prod. Res. Branch, Ottawa, Ontario. Dep. For. Publ. 1104.

Kennedy, R.W. 1968. Anatomy and fundamental wood properties of poplar. Pages 149–169 *in* J.S. Maini and J.H. Cayford, eds. Growth and utilization of poplars in Canada. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ontario. Dep. Publ. 1205.

Kennedy, R.W. 1974. Properties of poplar that affect utilization. Pages 54–65 *in* R.W. Neilson and C.F. McBride, eds. Poplar utilization symposium. Proc., May 23–24, 1974, Edmonton, Alberta. Environ. Can., Can. For. Serv., West. For. Prod. Lab., Vancouver, British Columbia. Inf. Rep. VP-X-127.

Kienzler, M.; Alban, D.H.; Perala, D.A. 1986. Soil invertebrate and microbial populations under three tree species on the same soil type. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-337.

Kiil, A.D. 1970. Effects of spring burning on vegetation in old partially cut spruce–aspen stands in east-central Alberta. Can. Dep. Fish. For., Can. For. Serv., For. Res. Lab., Edmonton, Alberta. Inf. Rep. A-X-33.

Killingbeck, K.T. 1986. The terminological jungle revisited: making a case for use of the term resorption. Oikos 46:263–264.

Killingbeck, K.T. 1988. Hurricane-induced modification of nitrogen and phosphorus resorption in an aspen clone: an example of diffuse disturbance. Oecologia 75:213–215.

Killingbeck, K.T.; May, J.D.; Nyman, S. 1990. Foliar senescence in an aspen (*Populus tremuloides*) clone: the response of element resorption to interramet variation and timing of abscission. Can. J. For. Res. 20:1156–1164.

Kimmins, J.P. 1987. Forest ecology. Macmillan Publ. Co., N.Y.

Kimmins, J.P.; Scoullar, K.A.; Apps, M.J.; Kurz, W.A.; Comeau, P.G. 1990. Predicting the yield and economic returns of forest management in a changing and uncertain future: the hybrid simulation approach and its representation in FORCYTE-11. Pages 247–256 *in* L.C. Wensel and G.S. Biging, tech. eds. Forest simulation systems. Proc. Int. Union For. Res. Organ., November 2–5, 1988, Berkeley, California. Univ. California, Div. Agric. Nat. Resour., Oakland, California. Bull. 1927.

Kirby, C.L.; Bailey, W.S.; Gilmour, J.G. 1957. The growth and yield of aspen in Saskatchewan. Sask. Dep. Nat. Resour., For. Branch, Prince Albert, Saskatchewan. Tech. Bull. 3.

Kirkwood, J. 1989. Billions of chopsticks for Asia's tables. B.C. Bus. 17:33.

Kittredge, J., Jr. 1938. The interrelations of habitat, growth rate, and associated vegetation in the aspen community of Minnesota and Wisconsin. Ecol. Monogr. 8:151–246.

Kittredge, J.R., Jr.; Gevorkiantz, S.R. 1929. Forest possibilities of aspen lands in the Lake States. Minn. Agric. Exp. Stn. Tech. Bull. 60.

Klinka, K.; Feller, M.C.; Green, R.N.; Meidinger, D.V.; Pojar, J.; Worrall, J. 1990. Ecological principles: applications. Pages 55–72 *in* D.P. Lavender, R. Parish, C.M. Johnson, G. Montgomery, A. Vyse, R.A. Willis, and D. Winston, eds. Regenerating British Columbia's forests. Univ. British Columbia Press, Vancouver, British Columbia.

Klinka, K.; Green, R.N.; Trowbridge, R.L.; Lowe, L.E. 1981. Taxonomic classification of humus forms in ecosystems of British Columbia. B.C. Minist. For., Victoria, British Columbia. Land Manage. Rep. 8.

Knapik, L.J.; Russell, W.B.; Riddell, K.M.; Stevens, N. 1988. Forest ecosystem classification and land system mapping pilot project, Duck Mountain, Manitoba. Can. For. Serv., Manit. Dist. Off., Winnipeg, Manitoba and Manit. Dep. Nat. Resour., Winnipeg, Manitoba. Canada–Manitoba For. Renewal Agreement. Unpubl. Rep.

Knutson, D.M. 1973. The bacteria in sapwood, wetwood, and heartwood of trembling aspen (*Populus tremuloides*). Can. J. Bot. 51:498–500.

Kochanski, M.L. 1988. Northern bushcraft. Lone Pine Publ., Edmonton, Alberta.

Kozlowski, T.T. 1971. Growth and development of trees. Academic Press, N.Y.

Kozlowski, T.T.; Clausen, J.J. 1966. Shoot growth characteristics of heterophyllous woody plants. Can. J. Bot. 44:827–843.

Krajina, V.J.; Klinka, K.; Worrall, J. 1982. Distribution and ecological characteristics of trees and shrubs of British Columbia. Univ. British Columbia, Fac. For., Vancouver, British Columbia.

Kramer, A. 1972. A review of the ecological relationships between mule and white-tailed deer. Alberta Fish Wildl. Div., Edmonton, Alberta.

Kramer, P.J.; Kozlowski, T.T. 1960. Physiology of trees. McGraw-Hill, N.Y.

Krauter, K.J. 1976. Decomposition of *Epilobium angustifolium* L. in a cool temperate deciduous woodland. M.Sc. thesis, Univ. Calgary, Calgary, Alberta.

Lamb, F.M. 1967. Aspen wood characteristics, properties, and uses: a review of recent literature. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Pap. NC-13.

Lamb, F.M.; Marden, R.M. 1968. Bark specific gravities of selected Minnesota trees species. For. Prod. J. 18(9):76–82.

La Roi, G.H. 1967. Ecological studies in the boreal spruce–fir forests of the North American taiga. Ecol. Monogr. 37:229–253.

Larsen, C.P.S. 1989. Fine resolution palaeoecology in the boreal forest of Alberta: a long term record of fire–vegetation dynamics. M.Sc. thesis, McMaster Univ., Hamilton, Ontario.

Larsen, J.A. 1980. The boreal ecosystem. Academic Press, N.Y.

Laursen, G.A. 1985. Mycorrhizae: a review of the importance of fungi from high-latitude forests in Alaska. Agroborealis 17(2):58–66.

Law, K.N.; Lapointe, M.; Lo, S.-N.; Valade, J. 1987. Overview of high-yield pulping of aspen. Pages 44–62 *in* A. Wong and T. Szabo, eds. Proc. Workshop on Aspen Pulp, Paper and Chemicals. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Leblanc, J.-D.; Sutherland, B.J. 1987. Comparative evaluation of seven site preparation tools in a residual poplar mixedwood stand in Saskatchewan. Can. For. Serv., Great Lakes For. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-381.

Lees, J.C. 1962. A discussion on white spruce natural regeneration in Alberta's spruce/aspen stands. Emp. For. Rev. 41(3):214–219.

Lees, J.C. 1963. Partial cutting with scarification in Alberta spruce–aspen stands. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Dep. For. Publ. 1001.

Lees, J.C. 1964. A test of harvest cutting methods in Alberta's spruce–aspen forest. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Dep. For. Publ. 1042.

Lees, J.C. 1966. Release of white spruce from aspen competition in Alberta's spruce–aspen forest. Can. Dep. For., Ottawa, Ontario. Dep. For. Publ. 1163.

Lehn, G.A. 1979. Natural variation in merchantable stem biomass among clones of trembling aspen. M.Sc. thesis, Univ. Alberta, Edmonton, Alberta.

Lehn, G.A.; Higginbotham, K.O. 1982. Natural variation in merchantable stem biomass and volume among clones of *Populus tremuloides* Michx. Can. J. For. Res. 12:83–89.

Lepper, M.M.; Keenan, F.J. 1986. Development of poplar glued–laminated timber. I: Tensile strength and stiffness of poplar laminating stock. Can. J. Civil Eng. 13:445–459.

LeResche, R.E.; Bishop, R.H.; Coady, J.W. 1974. Distribution and habitats of moose in Alaska. Nat. Can. 101:143–178.

LeResche, R.E.; Davis, J.L. 1973. Importance of nonbrowse foods to moose on the Kenai Peninsula, Alaska. J. Wildl. Manage. 37:279–287.

Libby, W.J. 1982. What is a safe number of clones per plantation? Pages 342–360 *in* H.M. Heybroek, B.R. Stephan, and K. von Weissenberg, eds. Resistance to diseases and pests in forest trees. Proc. Third Int. Workshop Genet. Host–Parasite Interactions For., September 14–21, 1980, Wageningen, The Netherlands. Cent. Agric. Pub. Doc., Wageningen, The Netherlands.

Lindsey, J.P.; Gilbertson, R.L. 1978. Basidiomycetes that decay aspen in North America. J. Cramer, Lehre, West Germany.

Little, E.L., Jr. 1971. Atlas of United States trees. Vol. 1. Conifers and important hardwoods. U.S. Dep. Agric., For. Serv., Washington, D.C. Misc. Publ. 1146.

Little, E.L., Jr. 1979. Checklist of United States trees. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 541.

Little, M.T. 1988a. Harvest of spruce and aspen in the Hudson Bay region: the Jack Spratt principle. Pages 56–60 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. NOR-X-296.

Little, M.T. 1988b. Saskatchewan's experience in poplar management and harvesting—a very fine swan indeed. Pages 9–17 *in* R.L. Gambles, comp. Management and utilization of Alberta's poplars. Proc. Poplars Counc. Can. Tenth Annu. Meet., October 26–28, 1988, Edmonton, Alberta. Poplar Counc. Can., Fac. For., Univ. Toronto, Toronto, Ontario.

Loman, A.A. 1987. Comments in discussion. Pages 119–120 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Looman, J. 1987. The vegetation of the Canadian prairie provinces. IV. The woody vegetation, Part 3: Deciduous woods and forests. Phytocoenologia 15:51–84.

Lora, J.H. 1990. Opportunities for organosolv pulping of aspen. Pages 305–309 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Lousier, J.D.; Parkinson, D. 1978. Chemical element dynamics in decomposing leaf litter. Can. J. Bot. 56:2795–2812.

Lundgren, A.L.; Hahn, J.T. 1978. The extent and characteristics of low productivity aspen areas in Wisconsin. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-45.

Lutz, H.J. 1956. Ecological effects of forest fires in the interior of Alaska. U.S. Dep. Agric., For. Serv., Washington, D.C. Tech. Bull. 1133.

MacCracken, J.G.; Viereck, L.A. 1990. Browse regrowth and use by moose after fire in interior Alaska. Northwest Sci. 64:11–18.

MacLeod, J.M. 1987. Chemical pulping of aspen: possibilities and realities. Pages 25–43 *in* A. Wong and T. Szabo, eds. Proc. Workshop on Aspen Pulp, Paper and Chemicals. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

MacLeod, W.K. 1952. Yield and volume tables for aspen in central and northern Alberta. M.F. thesis, Univ. British Columbia, Vancouver, British Columbia.

MacLeod, W.K.; Blyth, A.W. 1955. Yield of even-aged fully stocked spruce–poplar stands in northern Alberta. Can. Dep. North. Aff. Nat. Resour., For. Branch, For. Res. Div., Ottawa, Ontario. Tech. Note 18.

Mackay, J.F.G. 1975. Properties of northern aspen discolored wood related to drying problems. Wood Fiber 6(4):319–329.

Mackay, J.F.G. 1978. Drying trembling aspen lumber in direct fired kilns. For. Prod. J. 24(10):32–35.

Mackintosh, E.E. 1979. Impact of recreation on vegetation and soils in Rushing River Provincial Park, Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-290.

Maclean, D.A. 1990. Impact of forest pests and fire on stand growth and timber yield: implications for forest management planning. For. Chron. 66:167–168.

Maeglin, R.R. 1990. Structural lumber from aspen: using the saw–dry–rip (SDR) process. Pages 283–293 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Maeglin, R.R.; Boone, R.S. 1980. High quality studs from small hardwoods by the S-D-R process. Pages 36–51 *in* Proc. 23rd

Annu. Joint Meet. Midwest Wisconsin–Michigan Wood Seasoning Assoc., December 1980.

Maeglin, R.R.; Boone, R.S. 1981. Manufacturing quality structural lumber from hardwoods using the Saw-Dry-Rip process. Pages 29–45 *in* Proc. Ninth Annu. Hardwood Symp., May 25–28, 1981. Hardwood Res. Counc., Pipestem, West Virginia.

Maeglin, R.R.; Boone, R.S. 1985. Evaluation of mixed hardwood studs manufactured by the Saw-Dry-Rip (SDR) process. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wisconsin. Res. Note FPL-0249.

Mahendrappa, M.K.; Foster, N.W.; Weetman, G.F.; Krause, H.H. 1986. Nutrient cycling and availability in forest soils. Can. J. Soil Sci. 66:547–572.

Maier, G.B.; Darrah, D. 1989. Decay levels in mature aspen stands Whitecourt, Alberta. For. Can., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Maini, J.S. 1960. Invasion of grassland by *Populus tremuloides* in the northern Great Plains. Ph.D. thesis, Univ. Saskatchewan, Saskatoon, Saskatchewan.

Maini, J.S. 1965a. On the organization and growth of aspen roots. I. Unusual root growth following stem and root injury. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Project 0-24.

Maini, J.S. 1965b. On the organization and growth of aspen roots. II. Rapidly-tapering and cord-like roots. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Proj. 0-24.

Maini, J.S. 1965c. On the organization and growth of aspen roots. III. Relationship between length of root cutting and production of suckers. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Proj. 0-24.

Maini, J.S. 1966. Apical growth of *Populus* spp. II. Relative growth potential of apical and lateral buds. Can. J. Bot. 44:1581–1590.

Maini, J.S. 1967. Variation in the vegetative propagation of *Populus* in natural populations. Bull. Ecol. Soc. Am. 48(2):75–76.

Maini, J.S. 1968. Silvics and ecology of *Populus* in Canada. Pages 20–69 *in* J.S. Maini and J.H. Cayford, eds. Growth and utilization of poplar in Canada. Can. Dep. For. Rural Devel., For. Branch, Ottawa, Ontario. Dep. Publ. 1205.

Maini, J.S. 1989. Sustainable development and the Canadian forest sector. Can. Counc. For. Minist., Ottawa, Ontario.

Maini, J.S.; Cayford, J.H., eds. 1968. Growth and utilization of poplar in Canada. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ontario. Dep. Publ. 1205.

Maini, J.S.; Horton, K.W. 1964. Influence of temperature and moisture on initiation and initial development of *Populus tremuloides* suckers. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Rep. 64-0-11.

Maini, J.S.; Horton, K.W. 1966. Vegetative propagation of *Populus* spp. I. Influence of temperature on formation and initial growth of aspen suckers. Can. J. Bot. 44:1183–1189.

Malhotra, S.S.; Blauel, R.A. 1980. Diagnosis of air pollutant and natural stress symptoms of forest vegetation in western Canada. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-228.

Malik, N.; Vanden Born, W.H. 1986. Use of herbicides in forest management. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-282.

Mallett, K.I. 1990. Host range and geographic distribution of *Armillaria* root rot pathogens in the Canadian prairie provinces. Can. J. For. Res. 20:1859–1863.

Manion, P.D.; Griffin, D.H. 1986. Sixty-five years of research on hypoxylon canker of aspen. Plant Dis. 70:803–808.

Marr, J.W. 1947. Frost injury to aspen in Colorado (Abstract). Bull. Ecol. Soc. Am. 28:60.

Marr, J.W. 1961. Ecosystems of the east slope of the Front Range in Colorado. Univ. Colo. Stud. Ser. Biol. 8.

Martin, R.R.; Berbee, J.B.; Omuemu, J.O. 1982. Isolation of a potyvirus from declining clones of *Populus*. Phytopathology 72:1158–1162.

Massie, M.M.; Peterson, E.B.; Kabzems, R.D. 1990. An economic strategy for managing aspen on private lands in northeast British Columbia. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 124.

Mathews, J.F.; Tepylo, M.G.; Eager, R.L.; Pepper, J.M. 1985. Upgrading of aspen poplar wood oil over HZSM-5 zeolite catalyst. Can. J. Chem. Eng. 63:686–689.

Mathison, G.W.; Milligan, L.P.; Weisenburger, R.D. 1986. Ruminant feed evaluation unit: evaluation of aspen as a feedstuff for cattle. Univ. Alberta Agric. For. Bull. (Suppl. 9):53–55.

Mattson, W.J.; Addy, N.D. 1975. Phytophagous insects as regulators of forest primary production. Science 190:515–522.

McAninch, C.D.; Hoover, R.L.; Kufeld, R.C. 1987. Silvicultural treatments and their effects on wildlife. Pages 213–241 *in* R.L. Hoover and D.L. Wills, eds. Managing forested lands for wildlife. U.S. Dep. Agric., For. Serv., Rocky Mt. Reg., Denver, Colorado.

McCallum, B. (G.R.A. Abel Consultants) 1984. Ecological considerations for the wildlife of the Champion Forest Management Area, Alberta. Alberta For. Lands Wildl., Edmonton, Alberta.

McColl, J.G. 1980. Seasonal nutrient variation in trembling aspen. Plant Soil 54:323–328.

McDonough, W.T. 1979. Quaking aspen—seed germination and early seedling growth. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Pap. INT-234.

McDougall, F.W. 1988. Management of boreal mixedwood forests. Pages 3–4 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

McGowan, J.D. 1973. Fall and winter foods of ruffed grouse in interior Alaska. Auk 90:636–640.

McIntosh, J.A.; Carroll, M.N., eds. 1980. Utilization of western Canadian hardwoods. Proceedings of Symposium held November 21–22, 1979, at Prince George, British Columbia. Forintek Can. Corp., West. For. Prod. Lab., Vancouver, British Columbia. Spec. Publ. SP-2.

McNamara, K. 1980. Differences between quaking aspen genotypes in relation to browsing preference by elk. Pages 83–88 *in* M.S. Boyce and L.D. Hayden-Wing, eds. North American elk: ecology, behaviour and management. Univ. Wyoming, Laramie, Wyoming.

McNicol, J.G.; Timmerman, H.R.; Gollatt, R. 1980. The effects of heavy browsing pressure over eight years on a cutover in Quetico Park. Proc. North Am. Moose Conf. Workshop 16:360–373.

McRae, D.J. 1985. Prescribed burning of boreal mixedwood slash in the Ontario Clay Belt region. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. Inf. Rep.O-X-367.

McTaggart-Cowan, I.; Hoar, W.S.; Hatter, J. 1950. The effect of forest succession upon the quantity and upon the nutritive values of woody plants used as food by moose. Can. J. Res. Sect. D Zool. Sci. 28:249-271.

Mellenberger, R.W.; Satter, L.D.; Millett, M.A.; Baker, J. 1971. Digestion of aspen, alkali-treated aspen, and aspen bark by goats. J. Anim. Sci. 32:756–763.

Micko, M.M. 1987. Alberta aspen vs. black poplar wood quality differences. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Micko, M.M. 1988. Wood density of some of Alberta's commercial wood species. Alberta. For. Lands Wildl., For. Ind. Dev. Div. Edmonton, Alberta.

Miller, W.E. 1983. Decomposition rates of aspen bole and branch litter. For. Sci. 29:351–356.

Millers, I. 1972. Injury to young trembling aspen stems. U.S. Dep. Agric., For. Serv., Durham, New Hampshire. For. Pest Manage. Rep. S-72-4.

Monti, P.W.; Mackintosh, E.E. 1979. Effect of camping on surface soil properties in the boreal forest regions of northwestern Ontario, Canada. Soil Sci. Soc. Am. J. 43:1024–1029.

Moore, T.A. 1985. Seasonal fungal biomass dynamics in an interior Alaskan paper birch (*Betula papyrifera* Marsh) and quaking aspen (*Populus tremuloides* Michx.) stand and effects of long-term fertilization. Ph.D. thesis, Univ. Alaska, Fairbanks, Alaska.

Morgan, D. 1987. Alberta Forest Service inventory methods. Pages 67–70 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Morgan, M.D. 1969. Ecology of aspen in Gunnison County, Colorado. Am. Midl. Nat. 82:204–228.

Morley, P.M. 1989. That's A for aspen. Logging Sawmilling J. 20(1):18–20.

Morris, D.M.; Farmer, R.E., Jr. 1985. Species interactions in seedling populations of *Populus tremuloides* and *Populus balsamifera*: effects of density and species ratio. Can. J. For. Res. 14:593–595.

Moss, E.H. 1932. Vegetation of Alberta. IV. The poplar association and related vegetation of central Alberta. J. Ecol. 20:380–415.

Moss, E.H. 1938. Longevity of seed and establishment of seedlings in species of *Populus*. Bot. Gaz. 99:529–542.

Moss, E.H. 1953. Forest communities in northwestern Alberta. Can. J. Bot. 31:212–252.

Moss, E.H. 1955. The vegetation of Alberta. Bot. Rev. 21:493–567.

Mowrer, H.T. 1988. Is managing aspen density worthwhile? Pages 201–209 *in* Proc. Future Forests of the Mountain West: a Stand Culture Symp. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, Utah. Gen. Tech. Rep. INT-243.

Mueggler, W.F. 1988. Aspen community types of the Intermountain Region. U.S. Dep. Agric., For. Serv., Intermt. Res. Stn., Ogden, Utah. Gen. Tech. Rep. INT-250.

Mugasha, A.G. 1986. Within- and between-species competition and individual tree growth in a young jack pine–aspen stand. M.S. thesis, Lakehead Univ., Thunder Bay, Ontario.

Mugasha, A.G. 1989. Evaluation of simple competition indices for the prediction of volume increment of young jack pine and trembling aspen trees. For. Ecol. Manage. 26:227–235.

Muhammad, A.F.; Micko, M.M. 1984. Accumulation of calcium crystals in the decayed wood of aspen attacked by *Fomes igniarius*. IAWA (Int. Assoc. Wood Anal.) Bull. 5:237–241.

Mullinder, J. 1987. Technical challenges of the future. Pulp Pap. J. 40(7):41.

Mullins, E.J.; McKnight, T.S., eds. 1981. Canadian woods: their properties and uses. 3rd ed. Univ. Toronto Press, Toronto, Ontario.

Müntzing, A. 1936. The chromosomes of a giant *Populus tremula*. Hereditas 21:383–393.

Murphey, W.K.; Bowier, J.J. 1975. The response of aspen (*Populus tremuloides*) to irrigation by municipal waste water. Tappi (Tech. Assoc. Pulp Pap. Ind.) 58:128–129.

Murphy, P.J. 1988. Policy development needs for successful mixedwood management. Pages 138–144 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. NOR-X-296.

Mutch, R.W. 1970. Wildland fires and ecosystems—a hypothesis. Ecology 51:1046–1051.

Nautiyal, J.C. 1979. The place of forestry in the energy question. Can. J. For. Res. 9:68–75.

Navratil, S. 1979. Virus and virus-like diseases of poplar: are they threatening diseases? Pages 1–17 *in* D.C.F. Fayle, L. Zsuffa, and H.W. Anderson, eds. Poplar research, management and utilization in Canada. Proc. North Am. Poplar Counc. Annu. Meet. September 6-9, 1977, Brockville, Ontario. Ont. Minist. Nat. Resour., Ottawa, Ontario. For. Res. Inf. Pap. 102.

Navratil, S. 1987. Aspen management—improved knowledge from research. Pages 87–109 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Navratil, S.; Bella, I.E. 1988. Regeneration, development and density management in aspen stands. Pages 19–37 *in* R.L. Gambles, comp. Management and utilization of Alberta's poplars. Proc., Tenth Annu. Meet. Poplar Counc. Can., October 26–28, 1988, Edmonton, Alberta. Poplar Counc. Can., Fac. For., Univ. Toronto, Toronto, Ontario.

Navratil, S.; Bella, I.E.; Peterson, E.B. 1990. Silviculture and management of aspen in Canada: the western Canada scene. Pages 39–60 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Navratil, S.; Chapman, P.B., eds. 1991. Aspen management for the 21st century. Proceedings of a symposium held November 20–21, 1990, Edmonton, Alberta. For. Can., Northwest Reg., North. For. Cent. and Poplar Counc. Can., Edmonton, Alberta.

Navratil, S.; Phillips, P.; Morton, R. 1990. Aspen competition and lodgepole pine growth in mixed regeneration in western Alberta. Pages 43–44 *in* E. Hamilton, comp. Vegetation management: an integrated approach, Proc. Fourth Annu. Veg. Manage. Workshop, November 14–16, 1989, Vancouver, British Columbia. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 109.

Navratil, S.; Winship, R.J. 1978. Antagonism of *Peniophora polygonia* against *Fomes igniarius* (Abstract). Phytopathol. News 12:166–167.

Neilson, R.W. 1974. Considerations for an integrated poplar complex. Pages 233–239 *in* R.W. Neilson and C.F. McBride, eds. Poplar utilization symposium. Proc., May 23–24, 1974, Edmonton, Alberta. Environ. Can., Can. For. Serv., West. For. Prod. Lab., Vancouver, British Columbia. Inf. Rep. VP-X-127.

Neilson, R.W.; McBride, C.F., eds. 1974. Poplar utilization symposium Proc., May 23 and 24, 1974, Edmonton, Alberta. Environ. Can., Can. For. Serv., West. For. Prod. Lab., Vancouver, British Columbia. Inf. Rep. VP-X-127.

Nielsen, E.L.; Moyle, J.B. 1941. Forest invasion and succession on the basins of two catastrophically drained lakes in northern Minnesota. Am. Midl. Nat. 25:564–579.

Nielson, R.W. 1980. Secondary or minor products challenges. Pages 53–59 *in* J.A. McIntosh and M.N. Carroll, eds. Utilization of western Canadian hardwoods. Proc. Symp., November 21–22, 1979, Prince George, British Columbia. Forintek Can. Corp., West For. Prod. Lab., Vancouver, British Columbia. Spec. Publ. SP-2.

Nietfield, M.; Hudson, R.J. 1984. Foraging ecology of wapiti in the boreal mixed-wood forest, central Alberta. Pages 131–139 *in* R.W. Nelson, ed. Proc. 1984 West. States Prov. Elk Workshop, April 17–19, 1984, Edmonton, Alberta. Alberta Energy Nat. Resour., Fish Wildl. Div., Edmonton, Alberta.

Nietfield, M.; Wilk, J.; Woolnough, K.; Hoskin, B. 1984. Wildlife habitat requirement summaries for selected wildlife species in Alberta. Alberta Energy Nat. Resour., Fish Wildl. Div., Edmonton, Alberta. ENR Tech. Rep. T/73.

Novakowski, N.S. 1967. The winter bioenergetics of a beaver population in northern latitudes. Can. J. Zool. 45:1107–1118.

Ohmann, L.F.; Batzer, H.O.; Buech, R.R.; Lothner, D.C.; Perala, D.A.; Schipper, A.L., Jr. 1978. Some harvest options and their consequences for the aspen, birch and associated conifer forest types of the Lake States. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-48.

Oldemeyer, J.L.; Franzmann, A.W.; Brundage, A.L.; Arneson, P.D.; Flynn, A. 1977. Browse quality and the Kenai moose population. J. Wildl. Manage. 41:533–542.

Olmsted, C.E. 1980. The ecology of aspen with reference to utilization by large herbivores in Rocky Mountain National Park. Pages 89–97 *in* M.S. Boyce and L.D. Hayden-Wing, eds. North American elk: ecology, behaviour and management. Univ. Wyoming, Laramie, Wyoming.

Ondro, W.J. 1987. Economics of 15 options for industrial utilization of poplars. Prep. for Can. For. Serv., North. For. Cent., Edmonton, Alberta. Draft rep. Unpubl. Rep.

Ondro, W.J. 1989. Utilization and market potential of poplars in Alberta. For. Can., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-305.

Ondro, W.J.; Bella, I.E. 1987. Market potential for Alberta's poplar products. Pages 51–60 *in* B.A. Barkley and G. McVey, eds. Poplar culture to the year 2000. Proc. Poplar Counc. U.S. Can. Joint Meeting, June 22–24, 1987, Syracuse, New York and Cornwall, Ontario. Ont. Minist. Nat. Resour., Toronto, Ontario and SUNY Coll. Environ. Sci. For., Syracuse, New York.

Orians, G.H.; Solbrig, O.T., eds. 1977. Convergent evolution in warm deserts. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania.

Ostry, M.E.; Anderson, G.W. 1979. Hypoxylon canker incidence on pruned and unpruned aspen. Can. J. For. Res. 9:290–291.

Ostry, M.E.; Anderson, N.A. 1990. Disease resistance in a wild system: Hypoxylon canker of aspen. Pages 237–241 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Ostry, M.E.; Bucciarelli, B.; Sain, S.; Hackett, W.P.; Anderson, N.A. 1990. Developing tissue culture systems for increasing the disease resistance of aspen. Pages 315–318 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Ostry, M.E.; Henderson, F.L. 1990. Populus: a bibliography of world literature, 1975–1988. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep.

Ostry, M.E.; Wilson, L.F.; McNabb, H.S.; Moore, L.M. 1989. A guide to insect, disease and animal pests of poplars. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 677.

Oswald, E.T.; Brown, B.N. 1990. Vegetation establishment during 5 years following wildfire in northern British Columbia and southern Yukon Territory. For. Can., Pac. Yukon Reg., Pac. For. Cent., Victoria, British Columbia. Inf. Rep. BC-X-320.

Panning, D.J.; Gertjejansen, R.O. 1985. Balsam poplar as a raw material for waferboard. For. Prod. J. 35(5):48–54.

Panshin, A.J.; de Zeeuw, C. 1980. Textbook of wood technology. Structure, identification, properties, and uses of the commercial woods of the United States and Canada. 4th ed. McGraw-Hill, N.Y.

Parkerson, R.H. 1977. The effects of N, P and K fertilization on the lower stem xylem of quaking aspen in interior Alaska. Ph.D. thesis, Univ. Alaska, Fairbanks, Alaska.

Parkinson, D. 1971. Studies on fungi in Canadian aspen forest soil. Pages 425–430 *in* P. Duvigneaud, ed. Productivity of forest ecosystems. UNESCO, Paris, France.

Pastor, J. 1990. Nutrient cycling in aspen ecosystems. Pages 21–38 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Pastor, J.J.; Bockheim, J.G. 1984. Distribution and cycling of nutrients in an aspen–mixed-hardwood–spodosol ecosystem in northern Wisconsin. Ecology 65:339–353.

Paul, G.; Verry, E.S. 1980. Changes in water yield resulting from changes in land use. *In* North Country Futures: industrial impacts on forest resources, communities and you. Proc. Symp., March 27–29, 1980. Minn. Dep. Nat. Resour., St. Paul, Minnesota.

Pauley, S.S.; Mennel, G.F. 1957. Sex ratio and hermaphroditism in a natural population of quaking aspen. Minn. For. Notes 55.

Paszner, L. 1986. Innovations for hardwood utilization: catalysed organosolv pulping and saccharification. Pages 63–78 *in* A. Wong and T. Szabo, eds. Proc. Workshop on Aspen Pulp, Paper and Chemicals. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Pearson, A. 1988. Forestry in the Peace River. Pages 32–45 *in* Forestry or agriculture: a case for diversification. Information Seminars sponsored by Canadian Forestry Service, Victoria, British Columbia, Presented by Northern Lights College, April 29, 1988, Dawson Creek, British Columbia and April 30, 1988, Fort St. John, British Columbia. Can. For. Serv., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 42.

Peek, J.M. 1974. A review of moose food habits studies in North America. Naturaliste Can. 101:195–215.

Peek, J.M.; Urich, D.L.; Mackie, R.J. 1976. Moose habitat selection and relationships to forest management in northeastern Minnesota. Wildl. Monogr. 48.

Peet, R.K. 1981. Forest vegetation of the Colorado Front Range: composition and dynamics. Vegetatio 45:3–75.

Perala, D.A. 1971. Aspen successfully regenerated after killing residual vegetation with herbicides. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-106.

Perala, D.A. 1972. Regeneration: biotic and silvicultural factors. Pages 97–102 *in* Aspen Symp. Proc. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-1.

Perala, D.A. 1973. Stand equations for estimating aerial biomass, net productivity, and stem survival of young aspen suckers on good sites. Can. J. For. Res. 33:288–292.

Perala, D.A. 1974a. Prescribed burning in an aspen–mixed hardwood forest. Can. J. For. Res. 4:222–228.

Perala, D.A. 1974b. Repeated prescribed burning in aspen. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-171.

Perala, D.A. 1977. Manager's handbook for aspen in the north-central states. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-36.

Perala, D.A. 1978. Aspen sucker production and growth from outplanted root cuttings. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-241.

Perala, D.A. 1979. Regeneration and productivity of aspen grown on repeated short rotations. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Pap. NC-176.

Perala, D.A. 1981. Clone expansion and competition between quaking and bigtooth aspen suckers after clearcutting. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-201.

Perala, D.A. 1984. How endemic injuries affect early growth of aspen suckers. Can. J. For. Res. 14:755–762.

Perala, D.A. 1985. Using glyphosate herbicide in converting aspen to conifers. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Pap. NC-259.

Perala, D.A.; Alban, D.H. 1982a. Biomass, nutrient distribution and litterfall in *Populus*, *Pinus* and *Picea* stands on two different soils in Minnesota. Plant Soil 64:177–192.

Perala, D.A.; Alban, D.H. 1982b. Rates of forest floor decomposition and nutrient turnover in aspen, pine and spruce stands on two soils. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Pap. NC-227.

Perala, D.A.; Laidly, P.R. 1989. Growth of nitrogen-fertilized and thinned quaking aspen (*Populus tremuloides* Michx.). U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Pap. NC-286.

Perala, D.A.; Russell, A.J. 1983. Aspen. Pages 113–115 *in* R.M. Burns, comp. Silvicultural systems for the major forest types of the United States. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 445.

Perry, D.A.; Maghembe, J. 1989. Ecosystem concepts and current trends in forest management: time for reappraisal. For. Ecol. Manage. 26:123–140.

Person, R.A.; Hallgren, A.R.; Hubbard, J.W. 1971. Yields from short-rotation aspen suckers. Minn. For. Res. Notes 224.

Peterson, E.B. 1988. An ecological primer on major boreal mixedwood species. Pages 5–12 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Peterson, E.B.; Apps, M.J. 1989. Do ecosystem models such as FORCYTE-11 have a role in boreal mixedwood management? Pages 181–186 *in* E.N. Hogan, ed. Proc. Seventh Can. Bioenergy R & D Semin., April 24–26, 1989, Ottawa, Ontario. Energy, Mines Resour. Can., Ottawa, Ontario.

Peterson, E.B.; Chan, Y.-H.; Cragg, J.B. 1970. Aboveground standing crop, leaf area, and caloric value in an aspen clone near Calgary, Alberta. Can. J. Bot. 48:1459–1469.

Peterson, E.B.; Chan, Y.-H.; Peterson, N.M. 1988. Biomass and nutrient content of aspen ecosystems in Alberta, Canada. Pages 119–123 *in* C. Granger, ed. Proc. Sixth Can. Bioenergy R & D Semin., February 16–18, 1987, Richmond, British Columbia. Elsevier Science Publ. Co., N.Y.

Peterson, E.B.; Chan, Y.-H.; Peterson, N.M.; Kabzems, R.D. 1988. Calibration of FORCYTE-11 growth simulation model for aspen ecosystems in Alberta, Canada. Pages 151–154 *in* C. Granger, ed. Proc. Sixth Can. Bioenergy R & D Semin., February 16–18, 1987, Richmond, British Columbia. Elsevier Science Publ. Co., N.Y.

Peterson, E.B.; Chan, Y.-H.; Peterson, N.M.; Kabzems, R.D. (Western Ecological Services Ltd.) 1989. Data sources for a nominal dataset for Alberta aspen ecosystems of medium site quality. For. Can., North. For. Cent., Edmonton, Alberta.

Peterson, E.B.; Kabzems, A.; Kabzems, R.D.; Peterson, N.M. 1989a. Boreal mixedwood forest management challenges: a synopsis of opinions from 1988 interviews. For. Can., North. For. Cent., Edmonton, Alberta. ENFOR Proj. P-353. Unpubl. Rep.

Peterson, E.B.; Kabzems, A.; Kabzems, R.D.; Peterson, N.M. 1989b. Boreal mixedwood forest management challenges: a synopsis of opinions from 1988 interviews. For. Can., Can. For. Serv., North. For. Cent., Edmonton, Alberta. ENFOR Proj. P-353.

Peterson, E.B.; Kabzems, R.D.; Peterson, N.M. 1989. Hardwood management problems in northeastern British Columbia: an information review. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 66.

Peterson, E.B.; Levson, V.M.; Kabzems, R.D. 1982. Upper limits of standing crop density for woody species in the prairie provinces. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-243.

Peterson, N.M. 1990. Bibliography of recent North American literature on aspen and balsam poplar to 1989. Companion Dbase IV database to Peterson and Peterson (1992). For. Can., North. For. Cent., Edmonton, Alberta.

Petric, B. 1972. Utjecaj strukture na permeabilnost drva listaca. [Influence of wood structure on the permeability of hardwoods.] Sumarski List 96(9–10):364–373.

Petro, F.J. 1987. Some considerations in utilizing Alberta aspen for solid wood products. Pages 24–33 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Petrov, V.V. 1967. O biologii kornevych otpryskov osiny. [On the biology of aspen suckers.] Biol. Nauki (Mosc.) 4:76–79. Transl. from Russian by J. Seppala.

Pfaff, F. 1988. Status of balsam (black) poplar utilization in waferboard/OSB production. Summary Report. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Phillips, W.E.; Armstrong, G.W.; Beck, J.A., Jr.; Banskota, K. 1988. The opportunity cost of forested land losses to agricultural uses: an Alberta case study. For. Chron. 64:35–39.

Pierpoint, G.; Jones, R.K.; Jeglum, J.K.; Wickware, G.M.; Arnup, R. 1984. Characteristics and management implications of ecosystems with boreal hardwood components in the great Clay Belt, northern Ontario, Canada. Pages 17–28 *in* E.L. Stone, ed. Forest soils and treatment impacts. Proc. Sixth North Am. For. Soils Conf., June 1983, Knoxville, Tennessee. Dep. For. Wildl. Fish., Univ. Tennessee, Knoxville, Tennessee.

Plonski, W.L. 1956. Normal yield tables for black spruce, jack pine, aspen and white birch in northern Ontario. Ont. Dep. Lands For., Toronto, Ontario. Div. Timber Manage. Rep. 24.

Plonski, W.L. 1974. Normal yield tables (metric) for major forest species of Ontario. Ont. Minist. Nat. Resour., Toronto, Ontario.

Pollard, D.F.W. 1970. Leaf area development on different shoot types in a young aspen stand and its effect upon production. Can. J. Bot. 48:1801–1804.

Pollard, D.F.W. 1971. Mortality and annual changes in distribution of above-ground biomass in an aspen sucker stand. Can. J. For. Res. 1:262–266.

Pratt, R.H.M. 1965. Aerial spraying with 2,4-D to eliminate aspen. Pulp Pap. Mag. Can., Woodl. Rev. Sec. 67:460-462.

Presslee, D.J. 1989. Use of herbicides for site preparation and brushing and weeding in the sub-boreal spruce zone: a Northwood perspective. Pages 103–107 *in* B.A. Scrivener and J.A MacKinnon, eds. Learning from the past: looking to the future. Proc. North. Silvic. Comm. 1988 Winter Workshop, February 2–3, 1988, Prince George, British Columbia. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 30.

Prince Albert Pulp Company. 1983. Aspen cull study of the Prince Albert and Big River area. Prince Albert Pulp Company, Prince Albert, Saskatchewan. Unpubl. Rep.

Pringle, W.L.; Elliott, C.R.; Dobb, J.L. 1973. Aspen regrowth in pastures of the Peace River region. J. Range Manage. 26:260–262.

Pronin, D.; Lassen, L.E. 1970. Evaluating quaking aspen of Wisconsin for a site-quality to wood-quality relationship. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wisconsin. Res. Pap. FPL 141.

Pronin, D.; Vaughan, C.L. 1968. A literature survey of *Populus* species with emphasis on *P. tremuloides*. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wisconsin.

Puttock, G.D.; Smith, C.R. 1987. Evaluation of site preparation with Young's teeth on sites with dense residual poplars. Can. For. Serv., Great Lakes For. Cent., Sault Ste. Marie, Ontario. Inf. Rep. O-X-379.

Ramananskis, H. 1987. Aspen solid wood products. Pages 82–85 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Rauscher, H.M.; Perala, D.A.; Host, G.E. 1990. An aspen forest management advisory system. Pages 185–194 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Reade, A.E.; McQueen, R.E. 1983. Investigation of white-rot fungi for the conversion of poplar into a potential feedstuff for ruminants. Can. J. Microbiol. 29:457-463.

Renecker, L.A. 1988. Overview of game farming in Canada. Pages 47–62 *in* R. Valdez, ed. Proc. First Int. Wildl. Ranching Symp., May 16–21, 1988, Las Cruces, New Mexico. New Mexico State Univ., Las Cruces, New Mexico.

Renecker, L.A.; Hudson, R.J. 1986. Seasonal foraging rates of free-ranging moose. J. Wildl. Manage. 50:143–147.

Renewable Resources Sub-Committee, Public Advisory Committee to the Environment Council of Alberta. 1989. A place for wildlife. Environ. Counc. Alberta, Edmonton, Alberta.

Revel, J. 1983. The impact of some hardwoods on silviculture in the Prince George forest region. B.C. Minist. For., Prince George, British Columbia. Unpubl. Rep.

Revel, J.; Gray, R.; Spence, H.; Parminter, D.; MacLennan, D.; Delong, C.; Thorp, W. 1986. Interim strategies for the management of hardwoods in the boreal biogeoclimatic zone of the Prince George Forest Region. Final Report of the Task Force on Hardwoods. B.C. Minist. For., Victoria, British Columbia.

Reynolds, H.W.; Donahue, P.K. 1990. Opportunities for aspen for furniture. Pages 301–304 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Rice, E.L. 1984. Allelopathy. 2nd ed. Academic Press, Toronto, Ontario.

Riley, C.G. 1953. Hail damage in forest stands. For. Chron. 29:139–143.

Ritchie, J.C. 1964. Contributions to the Holocene paleoecology of west central Canada. I. The Riding Mountain area. Can. J. Bot. 42:181-196.

Ritchie, J.C.; de Vries, B. 1964. Contributions to the Holocene paleoecology of west central Canada. A late-glacial deposit from Missouri Coteau. Can. J. Bot. 42:677–692.

Roe, E.I. 1934. Natural classification of forest vegetation in the Lake States. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Unpubl. Rep.

Roe, E.I. 1935. Forest soils, the basis of forest management. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota.

Roe, E.I. 1958. Silvical characteristics of balsam poplar. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Stn. Pap. 65.

Rogers, L.L.; Wilker, G.A.; Allen, A.W. 1988. Managing northern forests for black bears. Pages 140–146 *in* Economic and social development: a role for forests and forestry professionals. Proc. Soc. Am. For. Natl. Conv., October 18–21, 1987, Minneapolis, Minnesota. Soc. Am. For., Bethesda, Maryland.

Rolley, R.E.; Keith, L.B. 1979. A review of moose habitat requirements. Alberta Environ., Res. Manage. Div., Edmonton, Alberta. AOSERP Proj. TF 1.1. RMD Rep. L;21.

Rolley, R.E.; Keith, L.B. 1980. Moose population dynamics and winter habitat use at Rochester, Alberta, 1965–1979. Can. Field. Nat. 94:9–18.

Ronald, W.G.; Lenz, L.M.; Cumming, W.A. 1973. Biosystematics of the genus *Populus* L. 1. Distribution and morphology of native Manitoban species and variants. Can. J. Bot. 51:2431–2442.

Rood, S.B.; Campbell, J.S.; Despins, T. 1986. Natural poplar hybrids from southern Alberta. I. Continuous variation for foliar characteristics. Can. J. Bot. 64:1382–1388.

Rouse, C. 1986. Fire effects in northeastern forests: aspen. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-102

Rowe, J.S. 1955. Factors influencing white spruce reproduction in Manitoba and Saskatchewan. Can. Dep. North. Aff. Natl. Resour., For. Branch, For. Res. Div., Ottawa, Ontario. Tech. Note 3.

Rowe, J.S. 1956. Uses of undergrowth plant species in forestry. Ecology 37:461–473.

Rowe, J.S. 1961. Critique of some vegetational concepts as applied to forests of northwestern Alberta. Can. J. Bot. 39:1007–1017.

Rowe, J.S. 1972. Forest regions of Canada. Can. Dep. Fish. Environ., Can. For. Serv., Ottawa, Ontario. Publ. 1300.

Ruark, G.A. 1990. Evidence for the reserve shelterwood system for managing quaking aspen. North. J. Appl. For. 7:58–62.

Ruark, G.A.; Bockheim, J.G. 1987. Below-ground biomass of 10-, 20-, and 32-year-old *Populus tremuloides* in Wisconsin. Pedobiologia 30:207–217.

Rudolph, P.O. 1956. Guides for selecting superior forest trees and stands in the Lake States. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Stn. Pap. 40.

Russell, C.W. 1988. Wood products marketing: can the old dog learn new tricks. Pages 132–137 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Rytz, A.A. 1980. Past utilization of hardwoods in Alberta—poplar as lumber or component stock. Pages 43–45 *in* J.A. McIntosh and M.N. Carroll, eds. Utilization of western Canadian hardwoods, Proc. Symp. November 21–22, 1979, Prince George, British Columbia. Forintek Can. Corp., West. For. Prod. Lab., Vancouver, British Columbia. Spec. Publ. SP-2.

Sachs, I.B.; Ward, J.C.; Kinney, R.E. 1974. Scanning electron microscopy of bacterial wetwood, sapwood, and normal heartwood in poplar trees. Pages 453–460 *in* Proc. Seventh Annu. Scanning Electron Microsc. Symp., April 8–11, 1974, Chicago, Illinois. IIT Res. Inst., Chicago, Illinois.

Safford, L.O.; Czapowskyj, M.M. 1986. Fertilizer stimulates growth and mortality in a young *Populus–Betula* stand. Can. J. For. Res. 16:807–813.

Sakai, A.S.; Burris, T.A. 1985. Growth in male and female aspen clones: a twenty-five-year longitudinal study. Ecology 66:1921–1927.

Sakai, A.S.; Weiser, C.J. 1973. Freezing resistance of trees in North America with reference to tree regions. Ecology 54:118–126.

Salt, W.R.; Salt, J.R. 1976. The birds of Alberta. Hurtig Publ., Edmonton, Alberta.

Samoil, J.K., ed. 1988. Management and utilization of northern mixedwoods. Proceedings of a Symposium held April 11–14, 1988, in Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Samoil, J.K.; Boughton, B., eds. 1987. Saskatchewan's forests. Can. For. Serv., North. For. Cent., Edmonton, Alberta. For. Rep. 33.

Sandberg, D. 1951. The regeneration of quaking aspen by root suckering. M.F. thesis, Univ. Minnesota, Minneapolis, Minnesota.

Sandberg, D.; Schneider, A.E. 1953. The regeneration of aspen by suckering. Minn. For. Notes 24.

Sanders, P. 1988. Growing stock of the future. Pages 69–78 *in* Forestry or agriculture: a case for diversification. Information Seminars sponsored by Canadian Forestry Service, Victoria, British Columbia. Presented by Northern Lights College, April 29, 1988, Dawson Creek, British Columbia and April 30, 1988 Fort. St. John, British Columbia. Can. For. Serv., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 42.

Santillo, D.J.; Brown, P.W.; Leslie, D.M., Jr. 1989. Response of songbirds to glyphosate-induced habitat changes on clearcuts. J. Wildl. Manage. 53:64–71.

Sauder, E.A.; Sinclair, A.W.J. 1989. Trial of a double-drum flail delimber/debarker processing small-diameter frozen timber: Phase I. For. Can., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. FERIC Unpubl. Spec. Rep. SR-59.

Schier, G.A. 1973a. Origin and development of aspen root suckers. Can. J. For. Res. 3:45–53.

Schier, G.A. 1973b. Seasonal variation in sucker production from excised roots of *Populus tremuloides* and the role of endogenous auxin. Can. J. For. Res. 3:459–461.

Schier, G.A. 1975. Deterioration of aspen clones in the middle Rocky Mountains. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Pap. INT-170.

Schier, G.A. 1976. Physiological and environmental factors controlling vegetative regeneration of aspen. Pages 20–23 *in* Utilization and marketing as tools for aspen management in the Rocky Mountains. Proc. Symp., September 8–9, 1976, Fort Collins, Colorado. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-29.

Schier, G.A. 1978. Vegetative propagation of Rocky Mountain aspen. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Gen. Tech. Rep. INT-44.

Schier, G.A. 1981a. Physiological research on adventitious shoot development in aspen roots. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Gen. Tech. Rep. INT-107.

Schier, G.A. 1981b. Aspen regeneration. Pages 15–21 *in* N.V. DeByle, ed. Proc. Symp. Situation Manage. Two Intermt. Species: Aspen and Coyotes. Vol. 1. Aspen. Utah State Univ., Logan, Utah.

Schier, G.A. 1982. Sucker regeneration in some deteriorating Utah aspen stands: development of independent root systems. Can. J. For. Res. 12:1032–1035.

Schier, G.A.; Campbell, R.B. 1978. Aspen sucker regeneration following burning and clearcutting on two sites in the Rocky Mountains. For. Sci. 24:303–308.

Schier, G.A.; Johnston, R.S. 1971. Clonal variation in total nonstructural carbohydrates of trembling aspen roots in three Utah areas. Can. J. For. Res. 1:252–255.

Schier, G.A.; Jones, J.R.; Winokur, R.P. 1985. Vegetative regeneration. Pages 29–33 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Schier, G.A.; Smith, A.D. 1979. Sucker regeneration in a Utah aspen clone after clearcutting, partial cutting, scarification and girdling. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Note INT-253.

Schier, G.A.; Zasada, J.C. 1973. Role of carbohydrate reserves in the development of root suckers in *Populus tremuloides*. Can. J. For. Res. 3:243–250.

Schipper, A.L., Jr. 1978. A *Hypoxylon mammatum* pathotoxin responsible for canker formation in quaking aspen. Phytopathology 68:866–872.

Schlaegel, B.E. 1972. Growth and yield of managed stands. Pages 109–112 *in* Aspen Symp. Proc. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-1.

Schlaegel, B.E.; Ringold, S.B. 1971. Thinning pole-sized aspen has no effect on number of veneer trees or total yield. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-121.

Schneider, B.B. 1988. Harvesting northern mixedwood forests in Alberta. Pages 110–113 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Schnekenburger, F.; Farmer, R.E., Jr. 1989. Genetic variance in growth of balsam poplar under 16- and 8-hour photosynthetic periods. For. Sci. 35:903–919.

Schopmeyer, C.S. 1974. Seeds of woody plants in the United States. U.S. Dep. Agric., Washington, D.C. Agric. Handb. 450.

Schultz, R.C.; Isebrands, J.G.; Kormanik, P.P. 1983. Mycorrhizae of poplars. Pages 17–28 *in* E.A. Hansen, comp. Intensive plantation culture: 12 years research. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-91.

Schwartz, C.C.; Regelin, W.L.; Franzmann, A.W. 1987. Protein digestion in moose. J. Wildl. Manage. 51:352–357.

Scoggan, H.J. 1978. The flora of Canada. Natl. Mus. Can., Ottawa, Ontario. Publ. Bot. 7.

Scott, V.E.; Crouch, G.L. 1987. Response of breeding birds to commercial clearcutting of aspen in southwestern Colorado. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Note RM-475.

Shands, W.E.; Hoffman, J.S. 1987. The greenhouse effect, climate change, and U.S. forests. Conserv. Found., Washington, D.C.

Shepard, R.K., Jr. 1975. Radial distribution of corticular photosynthesis in stems of bigtooth and trembling aspen. For. Sci. 21:370–372.

Shepperd, W.D. 1981. Stand characteristics of Rocky Mountain aspen. Pages 22–30 *in* N.V. DeByle, ed. Proc. Symp. Situation Manage. Two Intermt. Species: Aspen and Coyotes. Vol. 1. Aspen. Utah State Univ., Logan, Utah.

Shepperd, W.D. 1986. Silviculture of aspen forests in the Rocky Mountains and the Southwest. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. RM-TT-7.

Shepperd, W.D. 1987. Silviculture research in Rocky Mountain aspen. Pages 25–29 *in* C.A. Troendle, M.R. Kaufmann, R.H. Hamre, and R.P. Winokur, tech. coords. Management of subalpine forests: building on 50 years of research. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-1.

Shepperd, W.D.; Engelby, O. 1983. Rocky Mountain aspen. Pages 77–79 *in* R.M. Burns, comp. Silvicultural systems for the major forest types of the United States. U.S. Dep. Agric., For. Serv. Washington, D.C. Agric. Handb. 445.

Shepperd, W.D.; Jones, J.R. 1985. Nurse crop. Pages 181–184 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Shields, W.J.; Bockheim, J.G. 1981. Deterioration of trembling aspen clones in the Great Lakes region. Can. J. For. Res. 11:530–537.

Shirley, H.L. 1941. Restoring conifers to aspen lands in the Lake States. U.S. Dep. Agric., For. Serv., Washington, D.C. Tech. Bull. 763.

Shiue, C.-J.; Hossfield, R.L.; Ress, L.W. 1958. Absorption and translocation of 2,4,5-trichlorophenoxyacetic acid derivatives in quaking aspen. For. Sci. 4:319–324.

Shortreid, A., ed. 1991. Northern mixedwood '89, Proceedings of a symposium held at Fort St. John, British Columbia, September 12–14, 1989. For. Can., Pac. For. Cent., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 164.

Shoup, J.M. 1967. Effect of slash on aspen regeneration (winter cut) Hudson Bay, Saskatchewan. Can. Dep. For. Rural Dev., For. Branch, For. Res. Lab., Winnipeg, Manitoba. Unpubl. Intern. Rep. MS-50.

Shoup, J.M. 1968. Effect of slash on aspen regeneration (winter and summer cuts) Hudson Bay, Saskatchewan. Can. Dep. For. Rural Dev., For Branch, For. Res. Lab., Winnipeg, Manitoba. Unpubl. Intern. Rep. MS-73.

Shoup, J.M.; Nairn, L.D.; Pratt, R.H.M. 1968. Trembling aspen bibliography. Can. Dep. For. Rural Dev., For. Branch, For. Res. Lab., Winnipeg, Manitoba. Liaison Serv. Note MS-L-3.

Silvacom Ltd. 1988. Shingles and shakes from Alberta jack pine and aspen: a feasibility study. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta. For. Resour. Dev. Agreement. Unpubl. Rep.

Simkovic, I.; Ebringerova, A.; Antal, M.; Micko, M.M. 1987a. New aspects in the cationization of lignocellulose materials. VI. Modification of steam-exploded aspen wood chips with quaternary ammonium groups. J. Appl. Polymer Sci. 34:1779–1783.

Simkovic, I.; Ebringerova, A.; Antal, M.; Micko, M.M. 1987b. New aspects in the cationziation of lignocellulose materials. V. Modification of rotten aspen wood meal with quaternary ammonium groups. J. Appl. Polymer Sci. 33:1955–1961.

Sims, J. 1989. Alberta: from oil bust to pulp rush with a few bumps along the way. Pulp Pap. J. 42(10):44–48.

Singer, F.J.; Schrier, W.; Oppenheim, J.; Garton, E.O. 1989. Drought, fires, and large mammals: evaluating the 1988 severe drought and large-scale fires. BioScience 39:716–722.

Singh, T. 1982. Weight tables for important tree species in the prairie provinces. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. For. Manage. Note 14.

Singh, T. 1984. Variation in the ovendry wood density of ten prairie tree species. For. Chron. 60:217–221.

Singh, T. 1986. Generalizing biomass equations for the boreal forest region of west-central Canada. For. Ecol. Manage. 17:97–107.

Singh, T. 1987. Wood density variations in thirteen Canadian tree species. Wood Fiber Sci. 19:362–369.

Singh, T. 1988. Potential impacts of climatic change on forestry. Environ. Can., Can. Comm. Ecol. Land Classif., Ottawa, Ontario. Newsletter 17:4–5.

Singh, T.; Higginbotham, K.O. 1988. An overview of the effects of climatic change and climatic variability on forest vegetation in western Canada. Pages 255–273 in B.L. Magill and F. Geddes, eds. The impact of climate variability and change on the Canadian prairies. Proc. Symp. Workshop, September 9–11, 1987, Edmonton, Alberta. Alberta Environ., Edmonton, Alberta.

Singh, T.; Kostecky, M.M. 1986. Calorific value variations in components of 10 Canadian tree species. Can. J. For. Res. 16:1378–1381.

Singh, T.; Micko, M.M. 1984. Energy potential of aspen and other hardwoods in the prairie provinces of Canada. Pages 215–218 *in* F.A. Curtis, ed. Energy developments: new forms, renewables, conservation. Proc. ENERGEX '84, the Global Energy Forum, May 14–19, 1984, Regina, Saskatchewan Pergamon Press, Oxford, England.

Singh, T.; Powell, J.M. 1986. Climatic variation and trends in the boreal forest region of western Canada. Clim. Change 8:267–278.

Siren, G. 1979. Energy forestry in Sweden. Univ. Alberta. Agric. For. Bull. 2(4):3–7.

Skinner, D.L. 1984. Selection of winter food by beavers at Elk Island National Park. M.Sc. thesis, Univ. Alberta, Edmonton, Alberta.

Slabaugh, P.E. 1958. Silvical characteristics of bigtooth aspen (*Populus grandidentata*). U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Stn. Pap. 63.

Smith, C. 1987. Opening remarks. Pages 1–5 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Smith, C. 1988. Setting the stage. Unpublished chairman's comments. Management and Utilization of Northern Mixedwoods Symposium, April 11–14, 1988, Edmonton, Alberta. Unpubl. Rep.

Smith, D.W.; James, T.D.W. 1978a. Changes in the shrub and herb layers of vegetation after prescribed burning in *Populus tremuloides* woodland in southern Ontario. Can. J. Bot. 56:1792–1797.

Smith, D.W.; James, T.D.W. 1978b. Characteristics of prescribed bums and resultant short-term environmental changes in *Populus tremuloides* woodland in southern Ontario. Can. J. Bot. 56:1782–1791.

Smith, J.H.G. 1976. Methods for use of timber inventory data to estimate averages and upper limits to growth and yield of biomass. Pages 163–174 *in* IUFRO Oslo biomass studies. Working Party on Mensuration of Forest Biomass. XVI IUFRO Congress, June 21–27, 1976, Olso, Norway. College of Life Sciences and Agriculture, Univ. Maine, Orono, Maine.

Smith, K.E. 1988. Weyerhaeuser Canada starts up fine paper mill at Prince Albert. Pulp Pap. 62(11):88–93.

Smith, S.M. 1989. What did you expect? For. Chron. 65:28–30.

Sorensen, R.W. 1968. Size of aspen crop trees little affected by initial sucker density. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Res. Note NC-51.

Sourial, F.A. 1981. Economic feasibility study: integrated industrial complex for the utilization of aspen, birch and cottonwood in northeastern British Columbia. M.Sc. thesis. Univ. British Columbia, Vancouver, British Columbia.

Spurr, S.H.; Barnes, B.V. 1973. Forest ecology. 2nd ed. Ronald Press, N.Y.

Stanek, W.; State, D. 1978. Equations predicting primary productivity (biomass) of trees, shrubs, and lesser vegetation based on current literature. Environ. Can., Can. For. Serv., Pac. For. Res. Cent., Victoria, British Columbia. Inf. Rep. BC-X-183.

Stanosz, G.R.; Patton, R.F. 1987a. Armillaria root rot in aspen stands after repeated short rotations. Can. J. For. Res. 17:1001–1005.

Stanosz, G.R.; Patton, R.F. 1987b. Armillaria root rot in Wisconsin aspen sucker stands. Can. J. For. Res. 17:995–1000.

Stelfox, J.G. 1981. Effects on ungulates of clear-cutting in western Alberta: the first 25 years. Environ. Can., Can. Wildl. Serv., Edmonton, Alberta.

Stelfox, J.G. 1984. Effects of clear-cut logging and scarification on wildlife habitats in west-central Alberta. Environ. Can., Can. Wildl. Serv., Edmonton, Alberta.

Stelfox, J.G. 1988. Forest succession and wildlife abundance following clear-cut logging in west-central Alberta. Environ. Can., Can. Wildl. Serv., Edmonton, Alberta.

Stelfox, J.G.; Telfer, E.S.; Lynch, G.M. 1973. Effects of logging on wildlife. Fish and Game Sports (Fall 1973):1–4.

Steneker, G.A. 1963. Results of a 1936 release cutting to favour white spruce in a 50-year-old white spruce–aspen stand in Manitoba. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Dep. For. Publ. 1005.

Steneker, G.A. 1964. Ten-year results of thinning 14-, 19- and 23-year-old aspen to different spacings. Can. Dep. For., For. Res. Branch, Ottawa, Ontario. Dep. For. Publ. 1038.

Steneker, G.A. 1966. Thinning aspen Riding Mountain. Can. Dep. For., For. Res. Lab., Winnipeg, Manitoba. Inf. Rep. MS-X-2.

Steneker, G.A. 1967a. Growth of white spruce following release from trembling aspen. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ontario. Dep. Publ. 1183.

Steneker, G.A. 1967b. Management of aspen stands in Manitoba. Pages 36-41 *in* Trembling aspen in Manitoba. Papers presented at the 1965 Annu. Meet., Manit. Sect., Can. Inst. For. Can. Dep. For. Rural Dev., Inf. Tech. Serv. Div. Unpubl. Rep.

Steneker, G.A. 1969. Multiple thinning in fourteen-year-old poplar, Porcupine Provincial Forest, Saskatchewan. Can. Dep. Fish. For., For. Branch, For. Res. Lab., Winnipeg, Manit. Inf. Rep. MS-X-17. Unpubl. Rep.

Steneker, G.A. 1972. Suckering and soluble sugars in trembling aspen root cuttings. Can. For. Serv. Bi-Mon. Res. Notes 28:34.

Steneker, G.A. 1973. The size of trembling aspen (*Populus tremuloides* Michx.) clones in Manitoba. Can. J. For. Res. 3:472–478.

Steneker, G.A. 1974a. Factors affecting the suckering of trembling aspen. For. Chron. 50:32–34.

Steneker, G.A. 1974b. Thinning of trembling aspen (*Populus tremuloides* Michaux) in Manitoba. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-122.

Steneker, G.A. 1976a. Early performance of poplar clones in Manitoba. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-156.

Steneker, G.A. 1976b. Guide to the silvicultural management of trembling aspen in the prairie provinces. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-164.

Steneker, G.A.; Jarvis, J.M. 1966. Thinning in trembling aspen stands, Manitoba and Saskatchewan. Can. Dep. For., Ottawa, Ontario. Dep. For. Publ. 1140.

Steneker, G.A.; Wall, R.E. 1970. Aspen clones: their significance and recognition. Can. Dep. Fish. For., Can. For. Serv., For. Res. Lab., Winnipeg, Manit. Liaison Serv. Note MS-L-8.

Sterner, T.E.; Davidson, A.G. 1983. Forest insect and disease conditions in Canada 1982. Environ. Can., Can. For. Serv., For. Insect Dis. Surv., Ottawa, Ontario.

Stevenson, S. 1990. With a zero-effluent mill Millar Western will meet the stringent Saskatchewan standards. Pulp Pap. Can. 91(4):16–18.

Stiell, W.M.; Berry, A.B. 1986. Productivity of short-rotation aspen stands. For. Chron. 62:10–15.

Stoeckeler, J.H. 1960. Soil factors affecting growth of quaking aspen forests in the Lake States. Minn. Agric. Exp. Stn. Tech. Bull. 233.

Stoeckeler, J.H.; Macon, J.W. 1956. Regeneration of aspen cutover areas in northern Wisconsin. J. For. 54:13–16.

Strain, B.R. 1966. The effect of a late spring frost on the radial growth of variant quaking aspen biotypes. For. Sci. 12:334–337.

Strong, W.L.; La Roi, G.H. 1983a. Root-system morphology of common boreal forest trees in Alberta, Canada. Can. J. For. Res. 13:1164–1173.

Strong, W.L.; La Roi, G.H. 1983b. Rooting depths and successional development of selected boreal forest communities. Can. J. For. Res. 13:577–588.

Strong, W.L.; La Roi, G.H. 1985. Root density—soil relationships in selected boreal forests of central Alberta, Canada. For. Ecol. Manage. 12:233–251.

Strothmann, R.O. 1960. Evaluating the growth potential of aspen lands in northern Minnesota. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Res. Pap. 86.

Strothmann, R.O.; Heinselman, M.L. 1957. Five-year results in an aspen sucker density study. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Tech. Notes 490.

Strothmann, R.O.; Zasada, Z.A. 1962. Silvical characteristics of quaking aspen (*Populus tremuloides*). Rev. ed. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Stn. Pap. 49.

Sucoff, E. 1982. Water relations of the aspens. Minn. Agric. Exp. Stn. Tech. Bull. 338.

Sutton, R.F. 1986. Hexazinone Gridballs applied with concurrent underplanting of white spruce in boreal mixedwood forests: 7-yr results. For. Chron. 62:226–232.

Svoboda, F.J.; Gullion, G.W. 1972. Preferential use of aspen by ruffed grouse in northern Minnesota. J. Wildl. Manage. 36:1166–1180.

Swanson, J.S.; Hailey, J.R.T. 1987. Scanning and imaging techniques for assessing wood decay and wood quality in logs and standing trees. Pages 128–132 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton Canada–Alberta For. Resourc. Dev. Agreement. Unpubl. Rep.

Swanson, R.H.; Stevenson, D.R. 1971. Managing snow accumulation and melt under leafless aspen to enhance watershed value. Pages 63–69 *in* Proc. 39th West. Snow Conf., April 20–22, 1971, Billings, Montana. Colorado State Univ., Fort Collins, Colorado.

Tappeiner, J.C. 1982. Aspen root systems and suckering in red pine stands. Am. Midl. Nat. 107:408–410.

Taylor, B.R.; Parkinson, D. 1988a. Aspen and pine leaf litter decomposition in laboratory microcosms. II. Interactions of temperature and moisture. Can. J. Bot. 66:1966–1973.

Taylor, B.R.; Parkinson, D. 1988b. Does repeated freezing and thawing accelerate decay of leaf litter? Soil Biol. Biochem. 20:657–665.

Taylor, B.R.; Parkinson, D. 1988c. Does repeated wetting and drying accelerate decay of leaf litter? Soil Biol. Biochem. 20:647–656.

Taylor, B.R.; Parkinson, D. 1988d. Respiration and mass loss rates of aspen and pine leaf litter decomposing in laboratory microcosms. Can. J. Bot. 66:1948–1959.

Taylor, B.R.; Parsons, W.F.J.; Parkinson, D. 1989. Decomposition of *Populus tremuloides* leaf litter accelerated by addition of *Alnus crispa* litter. Can. J. For. Res. 19:674–679.

Taylor, R.L.; MacBryde, B. 1977. Vascular plants of British Columbia: a descriptive resource inventory. Univ. British Columbia Press, Vancouver, British Columbia. Univ. B.C. Bot. Gard. Tech. Bull. 4.

Teachman, G.E.; Frederick, D.J.; Perkis, W.E.; Jurgensen, M.F. 1980. Effects of fertilization on Hypoxylon canker of trembling aspen. Plant Dis. 64:284–286.

Telfer, E.S. 1969. Weight-diameter relationships for 22 woody plant species. Can. J. Bot. 47:1851–1855.

Telfer, E.S. 1970. Winter habitat selection by moose and white-tailed deer. J. Wildl. Manage. 34:553–559.

Telfer, E.S. 1974. Vertical distribution of cervid and snowshoe hare browsing. J. Wildl. Manage. 38:944–946.

Telfer, E.S. 1978. Habitat requirements of moose—the principal taiga range animal. Pages 462–465 *in* D.N. Hyder, ed. Proc. First Int. Rangeland Congr., August 14–18, 1978, Denver, Colorado. Soc. Range Manage., Denver, Colorado.

Telfer, E.S. 1984. Circumpolar distribution and habitat requirements of moose (*Alces alces*). Pages 145–182 *in* R. Olson, R. Hastings, and F. Geddes, eds. Northern ecology and resource management. Univ. Alberta Press, Edmonton, Alberta.

Telfer, E.S.; Cairns, A. 1978. Stem breakage by moose. J. Wildl. Manage. 42:639–642.

Telfer, E.S.; Scotter, G.W. 1975. Potential for game ranching in boreal aspen forests of western Canada. J. Range Manage. 28:172–180.

Teske, E. 1989. Mixedwood symposium drew international delegates. Information Forestry (Pac. For. Cent.) 16(3):7.

Tew, R.K. 1967. Soil moisture depletion by aspen in central Utah. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Note INT-73.

Tew, R.K. 1968. Properties of soil under aspen and herb–shrub cover. U.S. Dep. Agric., For. Serv., Intermt. For. Range Exp. Stn., Ogden, Utah. Res. Note INT-78.

Tew, R.K. 1970a. Root carbohydrate reserves in vegetative reproduction of aspen. For. Sci. 16:318–320.

Tew, R.K. 1970b. Seasonal variation in the nutrient content of aspen foliage. J. Wildl. Manage. 34:475–478.

Tew, R.K.; DeByle, N.V.; Schultz, J.D. 1969. Intraclonal root connections among quaking aspen trees. Ecology 50:920–921.

Thibault, J.R.; Jobidon, R.; Younger, P. 1983. Allelopathic relationships of alders and poplar. Pages 19–21 *in* J.A. Fortin, L. Chatarpaul, and A. Carlisle, eds. The role of nitrogen fixation in intensive forestry in Canada. Part II. Environ. Can., Can. For. Serv., Petawawa Natl. For. Inst., Chalk River, Ontario. Inf. Rep. PI-X-29.

Thom, G. 1988. High-yield pulps from Canadian hardwoods. Pages 119–128 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11–14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Thomas, G.P. 1966. Decay as a limiting factor on poplar utilization. Pages 49–51 *in* The future for poplar utilization in Alberta, Canada. Proc. Ind. Wood Prod. Semin., November 8–9, 1966, Edmonton, Alberta. Can. Dep. Ind., Wood Prod. Branch, Ottawa, Ontario.

Thomas, G.P.; Etheridge, D.E.; Paul, G. 1960. Fungi and decay in aspen and balsam poplar in the boreal forest region, Alberta. Can. J. Bot. 38:459–466.

Thomas, J.W., tech. ed. 1979. Wildlife habitats in managed forests: the Blue Mountains of Oregon and Washington. U.S. Dep. Agric., Washington, D.C. Agric. Handb. 553.

Thomas, P.R. 1987. Preparation of pulps from sound Alberta aspen and balsam poplar by various processes. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Thompson, C.F. 1989. Developing herbicide efficacy tables for the southern interior. For. Can., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 96.

Thompson, D.C.; Ealey, D.M.; McCourt, K.H. (McCourt Management Ltd.) 1980. A review and assessment of the baseline data relevant to the impacts of oil sands developments on large mammals in the AOSERP study area. Alberta Oil Sands Environ. Res. Prog., Edmonton, Alberta. AOSERP Rep. 64.

Thompson, G.E. 1939. A canker disease of poplars caused by a new species of Neafabraea. Mycologia 31:455–465.

Thompson, I.D.; Vukelich, M.F. 1981. Use of logged habitats in winter by moose cows with calves in northeastern Ontario. Can. J. Zool. 59:2103–2114.

Thorp, W. 1988. Industrial perspective: the deciduous resource in the Peace River Land District. Pages 13–22 *in* Forestry or agriculture: a case for diversification. Information Seminars sponsored by Canadian Forestry Service. Northern Lights College, Dawson Creek, British Columbia. Can. For. Serv., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For., Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 42.

Thorp, W. 1989. Hardwood conversion—how much is required? Pages 48–49 *in* B.A. Scrivener and J.A. MacKinnon, eds. Learning from the past: looking to the future. Proc. North. Silvic. Comm. 1988 Winter Workshop, February 2–3, 1988, Prince George, British Columbia. Can. For. Serv., Pac. For. Cent., Victoria, British Columbia and B.C. Minist. For. Victoria, British Columbia. Canada/B.C. For. Resour. Dev. Agreement Rep. 30.

Timmer, V.R.; Savinsky, H.N.; Marek, G.T. 1983. Impact of intensive harvesting on nutrient budgets of boreal forest stands. Pages 131–147 *in* R.W. Wein, R.R. Riewe, and I.R. Methven, eds. Resources and dynamics of the boreal zone. Proc. Conf., August 1982, North Bay, Ontario, Assoc. Can. Univ. North. Stud., Ottawa, Ontario.

Timmermann, H.R.; McNicol, J.G. 1988. Moose habitat needs. For. Chron. 62:238–245.

Tiren, L. 1949. On natural regeneration in unburnt cutting areas in Norrland spruce forests. Abridgement. Medd. Statens Skogsforskningsinst. 38(9):119–176.

Tonan Commerce Ltd. 1987. Demand for disposable aspen chopsticks (waribashi). Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Troth, J.L.; Deneke, F.J.; Brown, L.M. 1976. Upland aspen/birch and black spruce stands and their litter and soil properties in interior Alaska. For. Sci. 22:33–44.

Tryon, P.R.; Chapin, F.S., III. 1983. Temperature control over root growth and root biomass in taiga forest trees. Can. J. For. Res. 13:827–833.

Turlo, J.B. 1963. An ecological investigation of *Populus tremuloides* at two elevational levels in the Medicine Bow National Forest of Wyoming. M.S. thesis, Univ. Wyoming, Laramie, Wyoming.

Turskij, M. 1904. Lesovodstvo. [Forest science]. 3rd ed. Moskva. Translated from the Russian by J. Seppala.

U.S. Department of Agriculture, Forest Service. 1972. Aspen: symposium proceedings. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 434.

U.S. Department of Agriculture, Forest Service. 1976. Utilization and marketing as tools for aspen management in the Rocky Mountains. Proc. Symp., September 8-9, 1976, Fort Collins, Colorado. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-29.

Usher, R.G. 1978. The response of moose and woody browse to clearing in the boreal mixed-wood zone of Alberta. M.Sc. thesis, Univ. Calgary, Calgary, Alberta.

Usher, R.G. (International Environmental Consultants Ltd.) 1981. Ungulate use and habitat capability of recently clear-cut forest blocks in the Sand River area of Alberta, and of different-aged stands in the Cold Lake region. Esso Resour. Can. Ltd., Calgary, Alberta.

Vaartaja, O. 1960. Ecotypic variation of photoperiodic response in trees especially in two *Populus* species. For. Sci. 6:200–206.

Valentine, K.W.G.; Sprout, R.N.; Baker, T.E.; Lavkulich, L.M., eds. 1978. The soil landscapes of British Columbia. B.C. Minist. Environ., Resour. Anal. Branch, Victoria, British Columbia.

Vallee, G. 1979. Recherches et développement en populiculture au Ministère des terres et forêts du Québec. Pages 2-1 to 2-10 *in* D.C.F. Fayle, L. Zsuffa, and H.W. Anderson, eds. Poplar research, management and utilization in Canada. Proc. North Am. Poplar Counc. Meet. September 6–9, 1977, Brockville, Ontario. Ont. Minist. Nat. Resour., Ottawa, Ontario. For. Res. Inf. Pap. 102.

van Buijtenen, J.P.; Einspahr, D.W.; Joranson, P.N. 1959. Natural variation in two *Populus tremuloides* Michx. Tappi (Tech. Assoc. Pulp Pap. Ind.) 42:819–823.

van Buijtenen, J.P.; Joranson, P.N.; Einspahr, D.W. 1957. Naturally occurring triploid quaking aspen in the United States. Soc. Am. For. Proc. 1957:62–64.

van Buijtenen, J.P.; Joranson, P.N.; Einspahr, D.W. 1958. Diploid versus triploid aspen as pulpwood sources with reference to growth, chemical, physical and pulping differences. Tappi (Tech. Assoc. Pulp Pap. Ind.) 41:170–175.

Van Cleve, K. 1973. Short-term growth response to fertilization in young quaking aspen. J. For. 71:758–759.

Van Cleve, K. 1974. Organic matter quality in relation to decomposition. Pages 311–324 *in* A.J. Holding, O.W. Heal, S.F. MacLean, Jr., and P.W. Flanagan, eds. Soil organisms and decomposition in tundra. Tundra Biome Steering Comm., Stockholm, Sweden.

Van Cleve, K.; Moore, T.A. 1978. Cumulative effects of nitrogen, phosphorus, and potassium fertilizer additions on soil respiration, pH, and organic matter content. Soil Sci. Soc. Am. J. 42:121–124.

Van Cleve, K.; Noonan, L.L. 1971. Physical and chemical properties of the forest floor in birch and aspen stands in interior Alaska. Soil Sci. Soc. Am. Proc. 35:356–360.

Van Cleve, K.; Noonan, L.L. 1975. Litterfall and nutrient cycling in the forest floor of birch and aspen stands in interior Alaska. Can. J. For. Res. 5:626-639.

Van Cleve, K.; Oliver, L.; Schlentner, R.; Viereck, L.A.; Dyrness, C.T. 1983. Productivity and nutrient cycling in taiga forest ecosystems. Can. J. For. Res. 13:747-766.

Van Cleve, K.; Oliver, L.K. 1982. Growth response of postfire quaking aspen (*Populus tremuloides* Michx.) to N, P, and K fertilization. Can. J. For. Res. 12:160-165.

Van Cleve, K.; Viereck, L.A. 1981. Forest succession in relation to nutrient cycling in the boreal forest of Alaska. Pages 185-211 *in* D.C. West, H.H. Shugart, and D.B. Botkin, eds. Forest succession: concepts and application. Springer-Verlag, N.Y.

Van Wagner, C.E. 1990. Six decades of forest fire science in Canada. For. Chron. 66:133-137.

Verry, E.S. 1987. The effect of aspen harvest and growth on water yield in Minnesota. Pages 553-562 *in* R.H. Swanson, P.Y. Bernier, and P.D. Woodard, eds. Forest hydrology and watershed management. Proc. Symp., August 1987, Vancouver, British Columbia. Int. Assoc. Hydrol. Sci., Wallingford, England. IAHS/AISH Publ. 167.

Verry, E.S.; Lewis, J.R.; Brooks, K.N. 1983. Aspen clearcutting increases snowmelt and storm flow peaks in north central Minnesota. Water Resour. Bull. 19:59-67.

Verry, E.S.; Timmons, D.R. 1976. Elements in leaves of a trembling aspen clone by crown position and season. Can. J. For. Res. 6:436-440.

Vicars, M. 1988. Agriculture and forestry: co-operation and competition. Univ. Alberta Agric. For. Bull. 11(1):15-17.

Vitt, D.H. 1973. Distributional studies on bryophytes of Alberta. Bryologist 76:505-510.

Voigt, G.K.; Heinselman, M.L.; Zasada, Z.A. 1957. The effects of soil characteristics on the growth of quaking aspen in northern Minnesota. Soil Sci. Soc. Am. Proc. 21:649-652.

Volney, W.J.A. 1988. Insects and diseases of the mixedwood forest: problems or opportunities? Pages 99-109 *in* J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11-14, 1988, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-296.

Volney, W.J.A. 1989. The aspen leaf beetle. Pages 3-4 *in* Forest insect and disease notes, A-013. For. Can., North. For. Cent., Edmonton, Alberta. Unpubl. Rep.

Volney, W.J.A. 1990. Artificial intelligence for forest pest management. Pages 50-54 *in* B.J. Boughton and J.K. Samoil, eds. Forest modeling symposium. Proc. Symp., March 13-15, 1989, Saskatoon, Saskatchewan. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-308.

Waddington, J.; Bittman, S. 1987. Control of brush regrowth in northeastern Saskatchewan by several concentrations of herbicides applied with a roller. Can. J. Plant Sci. 67:467-475.

Waldron, R.M. 1961. Girdling, basal spraying and frilling of mature aspen. Timber Can. 22(12):34-35.

Waldron, R.M. 1963. Observations on aspen suckering in Manitoba and Saskatchewan. Can. Dep. For. Rural Dev., For. Branch, For. Res. Lab., Winnipeg, Manitoba. Unpubl. Rep.

Waldron, R.M.; Dyck, J.R. 1975. Trees and shrubs on residential lots in Edmonton, 1973. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-143.

Waldron, R.M.; Hildahl, V. 1974. Deterioration of shelterbelts in southwestern Saskatchewan. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-127.

Walker, C. 1980. Hybrid poplar mycorrhizae and endogenous spores in Iowa. Ph.D. thesis, Iowa State Univ., Ames, Iowa.

Walker, J. 1989. A British Columbia perspective. Panel on integrated management on Crown lands. Pages 42-48 *in* Trans. 53rd Fed.-Prov. Wildl. Conf., June 20-23, 1989, St. John's, Newfoundland. Environ. Can., Can. Wildl. Serv., Ottawa, Ontario.

Wall, G.; Sanderson, M., eds. 1990. Climate change: implications for water and ecological resources. Proc. Int. Symp. Workshop. March 15-16, 1990, Waterloo, Ontario. Univ. Waterloo, Dep. Geog., Waterloo, Ontario. Occas. Pap. 11.

Wall, R.E. 1969. Distribution of *Fomes igniarius* in aspen stands as affected by clonal variation. Can. For. Serv. Bi-Mon. Res. Notes 25(1):5.

Wall, R.E. 1971. Variation in decay in aspen stands as affected by their clonal growth pattern. Can. J. For. Res. 1:141-146.

Wall, R.E.; Kalra, Y.P.; Prasad, R. 1971. Concentration of micronutrients in foliage of aspen (*Populus tremuloides* Michx.) in Manitoba. Can. Dep. Fish. For., Can. For. Serv., For. Res. Lab., Edmonton, Alberta. Inf. Rep. A-X-47.

Wallin, W.B. 1954. Wetwood in balsam poplar. Minn. For. Notes 28.

Walters, D.K.; Ek, A.R. 1990. Recent progress of the Great Lakes Forest Growth and Yield Cooperative. Pages 331-335 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25-27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Walters, J.W.; Hinds, T.E.; Johnson, D.W.; Beatty, J. 1982. Effects of partial cutting on diseases, mortality, and regeneration of Rocky Mountain aspen stands. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Res. Pap. RM-240.

Wang, E.I.C.; Micko, M.M. 1985. Some strength properties of aspen wood affected by varying degrees of heart rot. For. Prod. J. 35(2):53-57.

Wann, S.R.; Einspahr, D.W. 1986. Reliable plantlet formation from seedling explants of *Populus tremuloides* (Michx.) Silvae Genet. 35:19-23.

Wann, S.R.; Wyckoff, G.W.; Wyckoff, J.L. 1988. A tissue culture solution to a forestry problem—the propagation of a tetraploid European aspen. Tree Plant. Notes 39(1):28–30.

Ward, J.C. 1986. The effect of wetwood on lumber drying times and rates: an exploratory evaluation with longitudinal gas permeability. Wood Fiber Sci. 18:288–307.

Ward, J.C.; Pong, W.Y. 1980. Wetwood in trees: a timber resource problem. U.S. Dep. Agric., For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oregon. Gen. Tech. Rep. PNW-112.

Ward, J.C.; Zeikus, J.G. 1980. Bacteriological, chemical and physical properties of wetwood in living trees. Pages 133–165 *in* J. Bauch, ed. Natural variations of wood properties. Proc. IUFRO Working Party S.5.01-02, April 8–16, 1980, Oxford, U.K. Kommissionsverlag Buchhandlung Max Wiedebusch, Hamburg, Germany.

Waring, R.H.; Schlesinger, W.H. 1985. Forest ecosystems: concepts and management. Academic Press, Orlando, Florida.

Weatherill, R.G.; Keith, L.B. 1969. The effect of livestock grazing on an aspen forest commmunity. Alberta Dep. Lands For., Fish Wildl. Div. Edmonton, Alberta. Tech. Bull. 1.

Webb, F.E. 1967. The implications of insect attack on aspen. Pages 21–26 *in* Trembling aspen in Manitoba. Papers presented at the 1965 Annu. Meet., Manit. Sect., Can. Inst. For. Can. Dep. For. Rural Dev., Inf. Tech. Serv. Div. Unpubl. Rep.

Weber, M.G. 1990a. Forest soil respiration after cutting and burning in immature aspen ecosystems. For. Ecol. Manage. 31:1–14.

Weber, M.G. 1990b. Response of immature aspen ecosystems to cutting and burning in relation to vernal leaf-flush. For. Ecol. Manage. 31:15–33.

Wedgwood, J.A. 1989. Largest cottonwood in Saskatchewan? Blue Jay 47:140–143.

Weetman, G.F.; Krause, H.H.; Koller, E.; Veilleux, J.-M. 1987. Interprovincial forest fertilization trials: 5- and 10-year results. For. Chron. 63:184–192.

Weingartner, D.H. 1980. The effects of scarification on trembling aspen in northern Ontario: a preliminary report. For. Chron. 56:173–175.

Weingartner, D.H. 1981. Forest management and research needs in the boreal mixedwood forest of Ontario: a problem analysis summary. Pages 209–210 *in* R.D. Whitney and K.M. McClain, eds. Boreal mixedwood symposium. Proc., September 16–18, 1980, Thunder Bay, Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. COJFRC Symp. Proc. O-P-9.

Weingartner, D.H.; Doucet, R. 1990. The quest for aspen management in eastern Canada. Pages 61–71 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Weinstein, J. 1980. The condition and trend of aspen along Pacific Creek in Grand Teton National Park. Pages 79–82 *in* M.S. Boyce and L.D. Hayden-Wing, eds. North American elk: ecology, behaviour and management. Univ. Wyoming, Laramie, Wyoming.

Welsh, D.A. 1981. Impact on bird populations of harvesting the boreal mixedwood forest. Pages 155–167 *in* R.D. Whitney and K.M. McClain, eds. Boreal mixedwood symposium. Proc., September 16–18, 1980, Thunder Bay, Ontario. Environ. Can., Can. For. Serv., Great. Lakes For. Res. Cent., Sault Ste. Marie, Ontario. COJFRC Symp. Proc. O-P-9.

Wengert, E.M. 1976. Some properties and characteristics of aspen that affect utilization in the Rocky Mountains. Pages 62–67 *in* Utilization and marketing as tools for aspen management in the Rocky Mountains. Proc. Symp., September 8–9, 1976, Fort Collins, Colorado. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-29.

Wengert, E.M. 1986. Evaluation of kiln drying characteristics of 8/4 Canadian aspen lumber in a commercial kiln. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Wengert, E.M. 1988. Utilization and marketing opportunities for Alberta aspen solid wood products. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Wengert, E.M.; Donnelly, D.M; Markstrom, D.C.; Worth, H.E. 1985. Wood utilization. Pages 169–180 *in* N.V. DeByle and R.P. Winokur, eds. Aspen: ecology and management in the western United States. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Fort Collins, Colorado. Gen. Tech. Rep. RM-119.

Westfield, L. 1987. Remote sensing techniques for forest species identification, a Minnesota–Alberta cooperative. Pages 43–54 *in* Proc. Aspen Quality Workshop, February 12, 1987, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Wheaton, E.E.; Singh, T.; Dempster, R.; Higginbotham, K.O.; Thorpe, J.P.; Van Kooten, G.C.; Taylor, J. 1987. An exploration and assessment of the implications of climatic change for the boreal forest and forestry economics of the prairie provinces and Northwest Territories: phase one. Sask. Res. Counc., Saskatoon, Saskatchewan. SRC Tech. Rep. 211.

Whitney, R.D.; McClain, K.M., eds. 1981. Boreal mixedwood symposium. Proc. September 16–18, 1980, Thunder Bay, Ontario. Environ. Can., Dep. Environ., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ontario. COFJRC Symp. Proc. O-P-9.

Widman Management Ltd. 1987. Canada's forest industry markets, 87–90. Widman Manage. Ltd., Vancouver, British Columbia.

Wilde, S.A.; Paul, B.H. 1959. Growth, specific gravity, and chemical composition of quaking aspen on different soil types. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wisconsin. Rep. 2144.

Wilde, S.A.; Pronin, D.T. 1949. Growth of trembling aspen in relation to ground water and soil organic matter. Soil Sci. Soc. Am. Proc. 13:345–347.

Wilde, S.A., Steinbrenner, E.C.; Pierce, R.S.; Dosen, R.C.; Pronin, D.T. 1953. Influence of forest cover on the state of the groundwater table. Soil Sci. Soc. Am. Proc. 17:65–67.

Williams, B.D.; Johnston, R.S. 1984. Natural establishment of aspen from seed on a phosphate mine dump. J. Range Manage. 37:521–522.

Williams, G.D.V. 1985. Estimated bioresource sensitivity to climatic change in Alberta, Canada. Clim. Change 7:55–69.

Winandy, J.E.; LeVan, S.L.; Schaffer, E.L.; Lee, P.W. 1988. Effect of fire-retardant treatment and redrying on the mechanical properties of Douglas-fir and aspen plywood. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wisconsin. Res. Pap. 485.

Winternitz, B.L. 1980. Birds in aspen. Pages 247–257 *in* R.M. DeGraff and N.G. Tilghman, comps. Management of western forests and grasslands for nongame birds. U.S. Dep. Agric., Proc. Workshop, February 11–14, 1980, Sault Lake City, Utah For. Serv., Internnt. For. Range Exp. Stn., Ogden, Utah. Gen. Tech. Rep. INT-86.

Winton, L.L. 1968. Plantlets from aspen tissue cultures. Science 160:1234–1235.

Winton, L.L.; Einspahr, D.W. 1970. Tetraploid aspen production using unreduced triploid pollen. For. Sci. 16:180–182.

Wippermann, J. 1984. Trends and prospects in timber harvesting, transport and conversion. Pages 165–174 *in* T.J. Corcoran and D.R. Gill, eds. Proc. Symp. Counc. For. Eng./Int. Union For. Res. Organ., August 11–18, 1984, Orono and Bangor, Maine. Univ. Maine, Orono, Maine and Univ. New Brunswick, Fredericton, New Brunswick. Soc. Am. For., Orono, Maine.

Wollenweber, E. 1973. Methylated flavonols from buds of several species of *Populus*. Phytochemistry 13:760–761.

Wong, A. 1987. Some papermaking properties of bleached neutral sulphite-anthraquinone aspen pulp. Pages 164–171 *in* A. Wong and T. Szabo, eds. Proc. Workshop on Aspen Pulp, Paper and Chemicals. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Wong, A.; Szabo, T., eds. 1987. Proceedings of the Workshop on Aspen Pulp, Paper and Chemicals. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Canada–Alberta For. Resour. Dev. Agreement. Unpubl. Rep.

Wood, R.S. 1967. The promotion and utilization of poplar in western Canada. Pages 73–78 *in* The future for poplar utilization in Alberta, Canada. Proc. Ind. Wood Prod. Semin., November 8–9, 1966, Edmonton, Alberta. Can. Dep. Ind., Wood Prod. Branch, Ottawa, Ontario.

Woodard, P.M.; Delisle, G.P. 1987. Biomass regression equations for common tree seedlings and shrubs in Jasper National Park, Alberta. Univ. Alberta, Dep. For. Sci., Edmonton, Alberta. For. Notes 1.

Woodbridge, Reed and Associates Ltd. 1981. Aspen for high quality chemi-mechanical pulps: overview for Alberta. For. Prod. Working Group, Ind. Eng. Div., Alberta Res. Counc., Edmonton, Alberta.

Woodbridge, Reed and Associates Ltd. 1982. Market mechanical and chemi-mechanical pulp: a growth opportunity for Canada. Can. Dep. Supply Serv., Ottawa, Ontario.

Woodbridge, Reed and Associates Ltd. 1985. Utilization of hardwoods in northern Alberta. Vol. 1. Alberta Dev. Counc., Peace River, Alberta.

Woodward, F.I. 1987. Climate and plant distribution. Cambridge Univ. Press, Cambridge, U.K.

Wright, H.A. 1974. Range burning. J. Range Manage. 27:5–11.

Wright, H.A.; Bailey, A.W. 1982. Fire ecology: United States and southern Canada. John Wiley, N.Y.

Wright, L.L.; Graham, R.L.; Turhollow, A.F. 1990. Short-rotation woody crop opportunities to mitigate carbon-dioxide buildup. North Am. Conf. For. Responses to Clim. Change, May 15–17, 1990, Washington, D.C.

Wyckoff, G.W.; Einspahr, D.W.; Benson, M.K. 1990. Development of an aspen sucker stand following irrigation and fertilization. Pages 195–203 *in* R.D. Adams, ed. Aspen symposium '89. Proc. Symp., July 25–27, 1989, Duluth, Minnesota. U.S. Dep. Agric., For. Serv., North Cent. For. Exp. Stn., St. Paul, Minnesota. Gen. Tech. Rep. NC-140.

Wyckoff, G.W.; Stewart, B. 1977. Procedures for growing aspen and aspen hybrids from seed. Inst. Pap. Chem., Appleton, Wisconsin.

Yanchuk, A.D. 1982. Clonal variation of wood density and fibre length of trembling aspen (*Populus tremuloides* Michx.) in north-central Alberta. M.Sc. thesis, Univ. Alberta, Edmonton, Alberta.

Yanchuk, A.D.; Dancik, B.P.; Micko, M.M. 1983. Intraclonal variation in wood density of trembling aspen in Alberta. Wood Fiber Sci. 15:387–394.

Yanchuk, A.D.; Dancik, B.P.; Micko, M.M. 1984. Variation and heritability of wood density and fibre length of trembling aspen in Alberta, Canada. Silvae Genet. 33:11–16.

Yanchuk, A.D.; Spilda, I.; Micko, M.M. 1988. Genetic variation of extractives in the wood of trembling aspen. Wood Sci. Technol. 22:67–71.

Yarie, J. 1981. Fire cycles and life tables—a case study from interior Alaska. Can. J. For. Res. 11:554–562.

Young, H.E.; Carpenter, P.N. 1967. Weight, nutrient element and productivity studies of seedlings and saplings of eight tree species in natural ecosystems. Maine Agric. Exp. Stn. Tech. Bull. (Orono) 28.

Young, H.E.; Gammon, C.B.; Ashley, M. 1964. Potential fiber from balsam fir, white pine, hemlock, white birch, and aspen logging residue. Tappi (Tech. Assoc. Pulp. Pap. Ind.) 47:555–557.

Younger, P.D.; Koch, R.G.; Kapustka, L. A. 1980. Allelochemic interference by quaking aspen leaf litter on selected herbaceous species. For. Sci. 26:429-434.

Zackrisson, O. 1985. Some evolutionary aspects of life history characteristics of broadleaved tree species found in the boreal forest. Pages 17–36 *in* B. Hagglund and G. Peterson, eds. Broadleaves in boreal silviculture—an obstacle or an asset? Swed. Univ., Agric. Sci. Dep. Silvic. Rep. 14.

Zahner, R.; Crawford, N.A. 1965. The clonal concept in aspen site relations. Pages 229–243 *in* C.T. Youngberg, ed. Forest-soil relationships in North America. Proc. Second North Am. For. Soils Conf., August, 1963, Corvallis, Oregon. Oregon State Univ. Press, Corvallis, Oregon.

Zahner, R.; DeByle, N.V. 1965. Effect of pruning the parent root on growth of aspen suckers. Ecology 46:373–375.

Zak, J.B. 1990. Changing our views on aspen acceptance. Can. For. Ind. 110(3):46–49.

Zalasky, H. 1970. Disease problems of poplar in the western interior of Canada. Can. Dep. Fish. For., Can. For. Serv., For. Res. Lab., Edmonton, Alberta. Inf. Rep. A-X-39.

Zalasky, H. 1976. Frost damage in poplar on the prairies. For. Chron. 52:61–64.

Zasada, J.C.; Argyle, D. 1983. Interior Alaska white spruce–hardwoods. Pages 33–35 *in* R.M. Burns, comp. Silvicultural systems for the major forest types of the United States. Rev. ed. U.S. Dep. Agric., For. Serv., Washington, D.C. Agric. Handb. 445.

Zasada, J.C.; Norum, R.A.; Teutsch, C.E.; Densmore, R. 1987. Survival and growth of planted black spruce, alder, aspen and willow after fire on black spruce/feather moss sites in interior Alaska. For. Chron. 63:84–88.

Zasada, J.C.; Norum, R.A.; Van Veldhuizen, R.M.; Teutsch, C.E. 1983. Artificial regeneration of trees and tall shrubs in experimentally burned upland black spruce/feather moss stands in Alaska. Can. J. For. Res. 13:903–913.

Zasada, J.C.; Schier, G.A. 1973. Aspen root suckering in Alaska: effect of clone, collection date, and temperature. Northwest Sci. 47:100–104.

Zasada, J.C.; Van Cleve, K.; Werner, R.A.; McQueen, J.A.; Nyland, E. 1977. Forest biology and management in high-latitude North American forests. Pages 137–195 *in* North American forest lands at latitudes north of 60 degrees. Proc. Symp., September 19–22, 1977, Fairbanks, Alaska.

Zasada, J.C.; Viereck, L.A.; Foote, M.J.; Parkenson, R.H.; Wolff, J.O.; Lankford, L.A., Jr. 1981. Natural regeneration of balsam poplar following harvesting in the Susitna Valley, Alaska. For. Chron. 57:57–65.

Zasada, Z.A. 1952. Does it pay to thin young aspen? J. For. 50:747–748.

Zehngraff, P.J. 1947. Possibilities of managing aspen. U.S. Dep. Agric., For. Serv., Lake States For. Exp. Stn., St. Paul, Minnesota. Aspen Rep. 21.

Zehngraff, P.J. 1949. Aspen as a forest crop in the Lake States. J. For. 47:555–565.

Zimmermann, M.H.; Brown, C.L. 1971. Trees: structure and function. Springer-Verlag, N.Y.

Zoltai, S.C. 1988. Ecoclimatic provinces of Canada and man-induced climatic change. Can. Comm. Ecol. Land Classif. Newsl. 17:12–15.

Zsuffa, L. 1979. A breeding program for short rotation poplar biomass production in Ontario, Canada. Pages 247–259 *in* Proc. IUFRO Working Parties on Poplar Provenances and Breeding Poplars S2-02-10 and S2-03-07, September 17–22, 1979. Dorschkamp Research Institute for Forestry and Landscape Planning, Wageningen, Netherlands.

APPENDIX 1. GLOSSARY

Alluvium (alluvial): Material such as clay, silt, sand, and gravel deposited by modern rivers and streams.

Allelopathy (allelopathic): The term allelopathy (= harmful to the other) refers to a form of antibiosis in which chemicals produced by one plant species inhibit the germination, growth, or occurrence of other species.

Ament: A pendulous, spike-like cluster of flowers as in aspen, poplars, willows, and birches. Aments are also referred to as catkins.

Annual allowable cut: The calculation of the amount of forest produce (the yield) that may be harvested annually from a specified area over a stated period, in accordance with the objects of management.

Apical dominance: The upward growth of terminal shoots at the expense of lateral buds below the terminal shoot.

Autecology (also referred to as ecophysiology): The study of physiological functions of individual organisms in field environments and communities; life history studies of species or ecotypes.

Auxin: A plant hormone that controls the growth of plants through its effects on cell elongation.

Basal area: The area of the cross section of a tree at breast height usually expressed as the summation of the basal area of trees in a stand per unit area of land.

Biogeoclimatic zones: The delineation of biotic regions or zones on the basis of vegetation, soils, topography, and climate.

Biomass: The living matter of a given habitat, expressed as fresh or dry weight of living matter per unit area of habitat.

Bole: The unbranched trunk or stem of a tree.

Browse (browsing): As a noun, browse refers to twigs or shoots, with or without attached leaves, of shrubs, trees, or woody vines that are eaten by wildlife or livestock; as a verb, browse refers to the grazing of shrubby or woody material.

Callus: A thickened tissue that develops after the wounding of a plant.

Calorific value: The heat produced by the complete combustion of a unit of weight of a fuel.

Cambium: A single layer of cells between the woody part of the tree and the bark. Division of these cells results in diameter growth of the tree through formation of wood cells (xylem) and inner bark (phloem).

Canker: A relatively localized, necrotic lesion, primarily of the bark and cambium.

Canopy: The more or less continuous cover of branches and foliage formed collectively by the crowns of adjacent trees and other woody growth. Layers of canopy may be distinguished by the terms overstory and understory.

Capsule: A dry fruit, the product of a compound pistil, splitting along two or more lines.

Cation: An ion carrying a positive charge such as calcium, sodium, and hydrogen.

Cation exchange capacity: A measure of the total quantity of exchangeable cations that a soil can adsorb.

Cellulose (hemicellulose): Cellulose is a fibrous carbohydrate, having the formula $(C_6H_{10}O_5)n$, and is the main structural material of cell walls of plants. The chief sources of cellulose are wood pulp and cotton. Hemicellulose is a noncellulosic polysaccharide contained in intercellular layers and cell walls.

Chlorophyll: A green pigment found in chloroplasts in plant cells; chlorophyll is essential for photosynthesis and is formed only in the presence of light.

Chlorosis (chlorotic): An abnormal condition in plants characterized by the absence of green pigments; chlorotic plants are yellowish white to white and poorly developed.

Chromosome: The threadlike or rodlike bodies that bear genes in the cells of plants and animals. Chromosomes are formed from chromatin during the process of cell division.

Clear-cutting: The harvesting of all trees from an area of forest land in a single cut.

Clone (clonal): Any group of plants derived from a single individual by vegetative reproduction. All members of a clone have the same genetic makeup and consequently tend to be uniform.

Conifer: Cone-bearing tree that has needles or scale-like leaves, usually evergreen. The wood of conifers is known commercially as softwoods.

Conk: A hard, spore-bearing structure that projects outwards from the bark of a tree, caused by wood-destroying fungi.

Crown: The upper part of a tree carrying the main branch system and foliage.

Cull: Any item of production (trees, logs, lumber) that is rejected because it does not meet certain specifications. The unusable, decayed portions of stems are referred to as cull.

Culture, tissue: A laboratory method in which small portions of embryos, roots, leaves, stems, or fruits are grown on appropriate nutrient media until they develop into whole organisms.

Cytokinin: A plant hormone that regulates the distribution of root and stem cells in plants.

Deciduous: Applied to trees, commonly broadleaf, that usually shed their leaves annually. The wood of deciduous trees is known as hardwood.

Defoliator: An insect or other agent that consumes foliage.

Density, stand: A quantitative measure of tree stocking, expressed as number of stems per unit area.

Density, wood: Weight of wood per unit volume. As the moisture content of wood affects its weight and volume, it is necessary to specify the moisture condition of the wood, as in air-dry density or oven-dry density.

Dieback: A diseased condition in woody plants in which peripheral parts are killed either by parasites or by other agencies such as winter injury. Also refers to the dying back from bud tip to branch.

Dioecious: Plants in which pistillate (female) and staminate (male) flowers occur in separate individuals. If both male and female flowers occur on the same plant it is monoecious.

Diploid: The presence of chromosomes in pairs or in two sets.

Dominant: A crown class referring to trees that have free-growing crowns in the uppermost layers of the forest canopy.

Ecosystem: The interacting system of a biological community and its nonliving surroundings.

Ecotone: A transition area between two communities which has characteristics of both kinds of neighboring vegetation as well as characteristics of its own.

Ectomycorrhiza: A mycorrhiza in which fungal hyphae grow only on the surface of roots and between the cells (intercellularly).

Edaphic: Referring to the soil. The influence of the soil upon plant growth is referred to as an edaphic factor.

Endomycorrhiza: A mycorrhiza in which fungal hyphae penetrate inside the root cells.

Endosperm: The nutritive tissue that surrounds the growing embryo, and which is present in the mature seeds of many species of plants. Endosperm provides food for the embryo during germination and early development.

Epicormic branches: A type of branch or shoot arising from an adventitious or dormant bud on a stem or branch of a woody plant.

Epiphytes: A plant growing upon or attached to another plant, or often on some non-living support, but not parasitic upon the plant or support to which it is attached.

Evapotranspiration: The loss of water from a given area during a specified time by evaporation from the soil surface and by transpiration from the plants (*see* transpiration).

Fiberboard: A generic term for a panel manufactured from fibers (as opposed to wood particles, strands, or flakes as in particleboard) which are bonded together with synthetic resin or other binders under heat and pressure.

Flushing: The fresh growth of foliage or blossoms, immediately following the bursting of buds in spring.

Free-growing: A height class that refers to young trees that are as high or higher than competing brush vegetation. An example of a precise definition of "free-growing" specifies that there should be a 1-m radius of free space surrounding the growing tip of a young tree. When this condition prevails, the tree is classified as free-to-grow.

Gall: A tumor made up of greatly modified tissue structure, often in response to damage by an insect or some other agent.

Game ranching: The use of wild animals, in place of domesticated livestock, in ranching operations.

Genetics: The branch of biology dealing with heredity and variation in organisms.

Genotype: The entire genetic constitution, or the sum total of genes, of an organism.

Girdle (girdling): To kill a tree by severing or damaging the cambium layer and interrupting the flow of food between the leaves and the rest of the tree.

Hardwood: The wood of a deciduous species of tree in contrast to softwood of conifers.

Heartwood: The inner core of a woody stem composed of non-living cells and usually differentiated by its darker color than the outer wood layer (sapwood).

High-grading: The harvest removal of only the best trees, often resulting in a poor-quality residual stand.

Humus: The fraction of the soil organic matter that remains after most of the added plant and animal residues have decomposed. It is usually dark colored. It may also refer to all the dead organic material on and in the soil that undergoes continuous breakdown, change, and synthesis.

Hybrid (hybridization): 1) Genetic—an organism resulting from a cross between parents with different genotypes; 2) Taxonomic—a cross between parents of different species.

Hydric: A hydric habitat is characterized by very poorly drained soils in which the water is removed so slowly that the water table is at or above the soil surface all year. These soils are usually gleyed mineral or organic.

Hygric: A hygric habitat is characterized by soils that are moist because of abundant input of water by soil seepage. The soils are imperfectly-to-poorly drained.

Isotherm: A line drawn on a map or chart connecting places with the same temperature at a particular time or the same mean temperature over a period of time.

Kraft pulping: This pulping process, also known as the sulfate process, uses an alkaline cooking liquor comprised of sodium hydroxide and sodium sulfide in the approximate proportions of two to one. The term "kraft" refers to strength and the main products of this process are strong wrapping papers, paper bags, and cardboard boxes. It is the standard chemical pulping used commercially in Canada to date.

Landing: The area where logs are collected for loading.

Leaching (leachates): The removal by percolating water of soluble constituents (leachates) from humus, soil, or other parent materials.

Leader: The leading shoot; the terminal or topmost shoot of a tree (*see* also shoot, terminal).

Leaf area index: A measure of the amount of foliage per unit area of habitat, commonly expressed as m^2 of foliage surface area (either one side or both sides of flat leaves) per m^2 of land area.

Litter: The uppermost slightly decayed layer of organic matter on the forest floor.

Lignin: A complex polymeric substance which, with cellulose, causes the thickening and strengthening of plant cell walls and forms the bulk of the woody structure of plants.

Luvisolic: An order of soils that have eluvial (Ae) horizons and illuvial (Bt) horizons in which silicate clay is the main accumulation product. The soils developed under forest or forest–grassland transition in a moderate to cool climate.

Mean annual increment (MAI): The average annual increase in volume of individual trees or stands up to a specified point in time. The MAI changes with different growth phases in a tree's life, being highest in the middle years and then slowly decreasing with age. The point at which the MAI peaks is commonly used to identify the biological maturity of a stand and its readiness for harvesting. Usually expressed in cubic meters of wood increment per hectare per year.

Meiosis: The sequence of complex nuclear changes resulting in the production of cells (as gametes) with half the number of chromosomes present in the original cell and typically involving an actual reduction division in which the chromosomes without undergoing prior splitting join in pairs with homologous chromosomes of maternal or paternal origin associated and then separate so that one member of each pair enters each daughter nucleus and a second division not involving reduction.

Mensuration: The branch of mathematics concerned with measuring lengths, areas, and volumes.

Merchantable: Commercial, marketable, saleable.

Mesic: A habitat that is medium in moisture supply. The water is removed somewhat slowly in relation to supply; soil may remain moist for a significant, but sometimes short period of the year. Sites that are moister than mesic but not as moist as hygric are termed subhygric.

Mixedwood: A forest composed of trees of two or more species. Usually at least 20% of the trees are other than the leading species.

Monoculture: Raising crops of a single species, generally even-aged.

Morphology: The study of the form, structure, and development of organisms.

Mycorrhizae (mycorrhizal): The symbiotic relationship between certain fungi and the roots of certain plants, in which the fungus grows on the outside of the root or in the outer root tissues, taking on the function of root hairs. It is an association between hyphae of certain fungi and roots of higher plants.

Organosolv pulping: A pulping process that use aqueous solutions of organic solvents such as ethanol, methanol, or ethylacetate to delignify wood.

Oriented strandboard (OSB): A type of particleboard in which logs are processed by cutting strands tangentially from the longitudinal face of the log so that the grain of the wood runs the length of the strand. As with other kinds of particleboard, strands are bonded together with synthetic resins or binders under heat and pressure.

Overstory: Those trees that form the upper canopy in a multi-layered forest, with smaller trees and shrub layers referred to as the understory.

Particleboard: A generic term for a panel manufactured from woody particles (as distinct from fibers used in production of fiberboard) which are bonded together with synthetic resin or other binders under heat and pressure, and to which other materials may have been added during manufacture to improve certain properties. Flakeboard, waferboard, and oriented strandboard are examples of particleboard.

Pathology: The study of diseases. Pathogens are agents such as viruses, bacteria, or fungi which transmit or cause diseases.

Pathological rotation age: The age at which a decay-prone forest stand should ideally be harvested to maximize annual wood production and to minimize annual wood losses from stem decay.

Periderm: The layers that replace the epidermis as the impermeable covering of older stems, roots, and branches, typically consisting of cork and cork cambium.

Petiole: The stalk of a leaf.

Phloem: A layer of tree tissue just inside the bark that conducts food from the leaves to the stem and roots.

Photoperiod: The relative duration of periods of light and dark in a 24-hour period as these affect the growth or behavior of plants and animals.

Photosynthesis: The synthesis of carbohydrates from carbon dioxide and water by chlorophyll using light as energy with oxygen as a by-product. Photosynthates are the carbohydrate products of photosynthesis.

Physiology (physiological): The branch of biology that deals with the functions and processes carried on by plants and animals.

Pioneer: A plant capable of invading newly exposed soil surfaces and persisting there until supplanted by successor species. A species that can serve as a nurse crop because it will tolerate planting on a bare site where it can prepare the site for successor species.

Pith: The central core of a stem and some roots, consisting mainly of soft tissue.

Polyploid (tetraploid, triploid): An organism or cell that contains more than the normal double (diploid) number of chromosomes per cell. A triploid organism has three times the single number of chromosomes in a cell and a tetraploid has four times the single number.

Prescribed fire: Controlled application of fire to fuels in either their natural or modified state under such conditions of weather, fuel moisture, soil moisture, etc. as allow the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to further certain planned objectives of silviculture, wildlife management, grazing, fire-hazard reduction, etc.

Production (productivity): Production refers to the total quantity of organic material produced within a given period by organisms, or the energy that this represents such as gram–calories per square centimeter per year. Productivity is a more general term referring to the innate capacity of an environment to produce plant and animal biomass, or the capacity of the soil to produce a certain crop under a defined set of management conditions.

Propagation: The increase of the number of plants either through seed production or vegetatively by cuttings of stems, roots, or other asexual organs.

Provenance: The geographic place of origin of seeds or other plant materials used for propagation.

Reforestation: The natural or artificial restocking (planting, seeding) of an area with forest trees. Also called forest regeneration.

Regeneration: The renewal of a tree crop by natural or artificial means. Regeneration also commonly refers to the young crop itself.

Regression (regression equation): A statistical method for the study and expression of the change in one variable associated with and dependent upon changes in another related variable or group of variables.

Respiration: The complex series of chemical reactions in the cells of all living organisms by which energy in foods is made available for use through the biological oxidation of certain materials, especially sugars.

Root, adventitious: A root that has developed at a location other than the usual or expected, such as roots growing from leaves or from aboveground stems.

Root, lateral: A root that extends more or less horizontally from the central vertical axis of a root system.

Root, sinker: A root that extends vertically from lateral roots or from the central part of a root system.

Root, primary: The first root of a germinating seed usually grows directly downward and is known as the primary root.

Rotation: The planned number of years between the regeneration of a stand of trees and its final cutting at a specified stage of maturity.

Rotation age: The age at which a stand is considered to be ready for harvesting.

Saprophyte (saprophytic): A plant that obtains food from dead or decaying organic material, in contrast to a parasite that obtains its food from another living organism.

Sapwood: The light-colored wood that appears on the outer portion of a cross-section of a tree stem. These more recently formed annual rings are usually more active physiologically than the inner (heartwood) portion of the stem.

Scarification: A method of seedbed preparation that consists of exposing patches of mineral soil through mechanical treatment with heavy equipment.

Selective (selection) harvesting: A silvicultural system in which trees are removed periodically in small groups, resulting in openings of 1 ha or less in area. This leads to the formation of an uneven-aged stand in the form of a mosaic of age-class groups in the same forest.

Sere: This term is related to the concept of succession, the sequence of plant, animal, and microbial communities that successively occupy an area over a period of time; succession is the process of change and sere refers to the product of succession. Sometimes sere is used in a more restrictive sense, as in "seral aspen stands" to refer to a particular early stage of a successional sequence, but generally sere refers to the entire series of stages that follow one another in ecological succession on a given habitat.

Shade tolerant (intolerant): The capacity (incapacity) of a tree or plant to develop and grow in the shade of other trees or plants.

Shelterwood: Harvest removals from a stand by a series of partial cuttings, resembling thinnings, that remove the entire stand within a period of years which is a small fraction of the rotation age. The goal of this silvicultural system is to encourage natural reproduction under the protection of the residual older stand, with gradual release of the regeneration from this shade and protection when it is able to endure the exposure.

Shoot, short: Aspen shoots that show no growth in length after the burst of leaf buds in spring.

Shoot, long: Lateral aspen shoots that continue to elongate during the growing season, long after the initial flushing of leaves in spring.

Shoot, terminal: If in reference to the vertically-growing stem tip of a tree, this term is synonymous with leader; if in reference to a branch, it is the youngest (outermost) leaf- or needle-bearing shoot at the branch tip.

Silviculture: Theory and practice of controlling forest establishment, composition, and growth.

Silvicultural system: A process whereby forests are tended, harvested, and replaced, resulting in a forest of distinctive form. Silvicultural systems are classified according to various methods of carrying out the fellings that remove the harvestable crop with a view to regeneration and according to the type of forest thereby produced.

Site: An area delimited by fairly uniform climatic and soil conditions, essentially equivalent to habitat.

Site index: A numerical evaluation of the productivity of forest land, commonly expressed as the average height of several dominant trees in a stand, on a species by species basis, at some index age such as 50, 70, or 100 years.

Slash: The residue left on the ground after harvest removal, including unused logs, uprooted stumps, broken tops, and branches.

Snag: A standing dead tree from which most of the branches have fallen.

Softwood: The wood of a conifer, in contrast to the commercial designation of hardwood for the wood from deciduous species of trees.

Soil horizon: A layer of the soil, approximately parallel to the soil surface, with distinctive characteristics produced by soil-building processes.

Specific gravity: The numerical ratio between the weight of a given volume of a substance (under specified conditions such as green, fresh weight, air-dry, or oven-dry) and the weight of an equal volume of water at 4°C.

Sprouts, root collar: A sprout that arises from the transitional area, generally just below the soil surface, where the stump of a tree flares into recognizable root segments.

Sprouts, stump: A sprout that arises from a tree stump above the root-collar zone, commonly at or above the humus layer.

Stand: A community of trees sufficiently uniform in species, age, arrangement, or condition to be distinguishable as a group from other groups of trees in a forest.

Stand breakup: The stage at which significant numbers of mature trees in a stand are recycled to the forest floor by death, decay, or windfall.

Standing crop: This term is synonymous with biomass.

Stocking (understocking, overstocking): Stocking is a measure of stand density, usually expressed as number of tree stems per hectare, although it is sometimes estimated by crown closure on aerial photographs. When a site is not occupied by as many trees as it could support for maximum productivity, it is called understocked; if there are too many trees per unit area to allow their development to harvestable size, the stand is classified as overstocked.

Stomates (stomata): A stomate is a pore in a plant leaf that controls gaseous exchange between leaves and the atmosphere. Stomata is plural for stomate.

Succession (successional): The gradual replacement of one plant community by another in a naturally occurring, progressive development toward climax vegetation.

Succession, decadent: Characterized by low levels of aspen stocking, high stem mortality, little sucker regeneration, and no replacement by conifers, ultimately succeeding to brush, forbs, or grasses.

Succession, stable: Characterized by high levels of aspen stocking, no unusual mortality, no or few conifers, and evidence of successive generations of aspen.

Succession, seral: Characterized by high levels of aspen stocking after a disturbance, but with conifers increasing, aspen mortality increasing, and aspen regeneration decreasing as the stand develops.

Sucker (suckering): A shoot arising from a root system or from the underground part of a stem.

Sulfite pulp: A pulping process applied to woods that have a low resin content, using an acid solution of calcium or magnesium bisulfite in the cooking liquor. When mixed with groundwood pulp, sulfite pulp is used for production of cheap paper (newsprint, tissue, and writing paper).

Sustainable development: Sustainable development of the forests and their multiple environmental values involves fostering, without unacceptable impairment, the productivity, renewal capacity, and species diversity of forest ecosystems.

Sustained yield: A method of forest management that calls for an approximate balance between net growth and the amount harvested over the rotation age on a management area.

Synecology (also referred to as habitat science or ecosystem research): The study of habitat factors and the physiological response of species and species groups to these factors; study of community functioning and niche functions of plant populations in an ecosystem context.

Taxonomy: The science of classification of organisms; the arrangement of organisms into systematic groupings such as species, genus, family, and order.

Tension wood: Abnormal wood that is typically formed on the upper sides of branches and the upper sides of leaning or crooked stems of trees, characterized anatomically by a lack of cell-wall lignification and often by the presence of an internal gelatinous layer in the fibers.

Terminal: *See* shoot, terminal.

Tetraploid: *See* polyploid.

Thinning: Removal of selected trees from a stand for the purpose of improving the growth and value of the remaining crop trees.

Translocation: The movement of material in solution from one part of a plant to another part.

Transpiration: The loss of water in vapor form from a plant, mostly through stomates.

Tree breeding: The application of genetics to the systematic improvement of a tree species or population.

Triploid: *See* polyploid.

Tylosis: An outgrowth from an adjacent ray or axial parenchyma cell through a pit cavity in a vessel wall, partially or completely blocking the vessel lumen.

Understory: Those trees or other vegetation in a forest stand below the main canopy level, which is referred to as overstory.

Ungulate: Any of the many hoofed animals such as deer, elk, or bison.

Vessel elements: A series of cells that form a tube-like structure in the stems of plants to conduct water and other substances in solution.

Volume, merchantable: The amount of sound wood in a single tree or stand that is suitable for processing into specified products. The gross (total) volume of a tree stem is commonly reduced by the amount of cull in the stem to arrive at an estimate of merchantable (net) volume of usable wood in the stem.

Weathering: Natural processes involving the physical and chemical disintegration of rocks and minerals.

Wetwood: Wood, particularly heartwood, with an abnormally high water content and a translucent, glassy appearance, a condition that develops in the living stem, unrelated to soaking of the stem in water.

Windthrow: Trees uprooted by wind.

Xeric: A xeric habitat is characterized by soils that are well to rapidly drained and low or deficient in moisture that is available for the support of plant life.

Xylem: Complex tissues in the stems of plants that provide strength to the stem and also serve as the main water-conducting tissue from the roots through the stem to the photosynthetic system in the foliar canopy.

SUBJECT INDEX