COFRDA REPORT 3306

Short-rotation Culture of *Populus* and *Larix*: a Literature Review

C.L. Palmer
School of Forestry, Lakehead University
Thunder Bay, Ontario

1991

Canada-Ontario
Forest Resource Development Agreement
Entente sur la mise en valeur de la ressource forestière

Catalogue No. Fo 29-25/3306E
ISBN 0-662-18194-8
ISSN 0847-2866

Copies of this publication are available at no charge from:
Communications Services
Great Lakes Forestry Centre
Forestry Canada, Ontario Region
P.O. Box 490
Sault Ste. Marie, Ontario
P6A 5M7

Microfiches of this publication may be purchased from:
Micro Media Inc.
Place du Portage
165, Hôtel-de-Ville
Hull, Québec
J8X 3X2

This report was produced in partial fulfillment of the requirements of Project 33020, "Development of Short-rotation Silvicultural Systems for Selected *Populus* and *Larix* in Northwestern Ontario", under the Research, Development and Applications Sub-program of the Canada-Ontario Forest Resource Development Agreement. The views, conclusions and recommendations contained herein are those of the authors and should be construed neither as policy nor endorsement by Forestry Canada or the Ontario Ministry of Natural Resources.

Palmer, C.L. 1991. Short-rotation culture of *Populus* and *Larix*: a literature review. For. Can., Ont. Region, Sault Ste. Marie, Ont. COFRDA Rep. 3306. 66 p.

ABSTRACT

A detailed literature review of short-rotation intensive culture forestry as a method of management and the potential of this approach for *Populus* and *Larix* are presented. The review was prepared as a guideline for the development of the COFRDA research project "Development of short-rotation silvicultural systems for selected *Populus* and *Larix* in northwestern Ontario". It provides a background for the development of many of the materials used in the project, the history of their previous use in North America, the potential for their future use in the wood-products industry, and methods that have been used for their successful establishment under short-rotation intensive culture. Particular areas that need further investigation for the successful management of these species under the short-rotation intensive culture system are addressed.

RÉSUMÉ

Les auteurs présentent une synthèse bibliographique sur la foresterie intensive à courte révolution à titre d'outil d'aménagement et le potentiel qu'offre cette approche pour la culture de *Populus* et de *Larix*. Cette synthèse a été préparée pour orienter l'élaboration du projet de recherche portant sur l'établissement de régimes sylvicoles à courte révolution pour certaines essences de *Populus* et de *Larix* dans le nord-ouest de l'Ontario dans le cadre de l'Entente Canada-Ontario concernant la mise en valeur de la ressource forestière. Elle fournit des données de base qui ont permis de mettre au point bon nombre des matériels utilisés lors du projet, de connaître l'histoire de leur utilisation antérieure en Amérique du Nord ainsi que leur potentiel d'utilisation future par l'industrie des produits du bois et les méthodes d'implantation qui se sont avérées fructueuses dans le cadre d'une culture intensive à courte révolution. Les auteurs abordent les domaines particuliers qui exigent des recherches plus approfondies en vue d'assurer le succès de l'aménagement de ces essences dans le cadre d'un système de culture intensive à courte révolution.

TABLE OF CONTENTS

POTENTIAL OF HYBRID POPLARS FOR SHORT-ROTATION FORESTRY

(cont'd)

POTENTIAL OF LARCH FOR SHORT-ROTATION FORESTRY

SHORT-ROTATION CULTURE OF *POPULUS* AND *LARIX*: A LITERATURE REVIEW

INTRODUCTION

A 4-year research project was begun in 1986 to develop short-rotation silvicultural systems for selected *Populus* and *Larix* in the Fort Frances area of northwestern Ontario. Cooperators in the project included Boise-Cascade Canada Ltd. of Fort Frances, Lakehead University in Thunder Bay, and the Ontario Ministry of Natural Resources.

The long-term goal of the project was to develop poplar (*Populus* spp.) and larch (*Larix* spp.) materials suitable for relatively short rotations under site conditions existing in the vicinity of Fort Frances, and plantation systems that will promote the rapid growth of these materials. The impetus for the project came from Boise-Cascade's interest in exploring alternatives to the traditional sources of pulpwood, primarily jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*), that were used in its Fort Frances mill. These traditional species are currently obtained more than 100 km from the mill. Since the mill employs the kraft and groundwood pulping processes, it could utilize hardwood and softwood species such as poplar and larch. These materials could be managed under short-rotation silvicultural systems on the large agricultural land base immediately surrounding Fort Frances.

As the first phase of the research project, a detailed literature review of short-rotation intensive-culture (SRIC) forestry was conducted to evaluate the potential of this management method for use with *Populus* and *Larix* and to guide the research. The review provides background on the development of many of the *Populus* and *Larix* materials that were used in the program, the history of their previous use in North America, the potential for their future use in the wood-products industry, and methods that have been employed for their successful establishment under SRIC. The review also points out areas that need further investigation for the successful management of these species under SRIC.

SHORT-ROTATION FORESTRY: AN OVERVIEW

During the past several decades, intensive culture of forest trees has attracted a great deal of interest in North America because of projected fiber shortages and competing demands for forest land. The concept of short-rotation forestry borrows its main ideas from agriculture, and offers a means of growing increased amounts of wood fiber through intensive culture.

There are several definitions of "short-rotation" forestry, depending on the rotation length and size of the crop trees at the time of harvest. Short-rotation forestry, as referred to in this report, involves intensive management of even-aged plantations of fast-growing, genetically improved trees under short rotations, and where the trees have been established at close spacings through site preparation, weed control and fertilization for the purpose of pulpwood production. Depending on the species, rotation age may range from 6 to 15 years for plantations in some locations in the United States, southern Ontario and Quebec, at which point the resulting timber, 20 to 25 cm in diameter, can be harvested and processed with standard equipment and facilities (Schreiner 1970, Zobel and Kellison 1972). Investigators throughout the United States and Canada have studied this system for a variety of species of hardwoods and conifers (Schreiner 1970, Zobel and Kellison 1972, Schmidt and Debell 1973, Smith and

Debell 1973, Dawson 1976, Vallee 1977, Raitanen 1978, Hansen et al. 1983).

The advantages that are combined in the short-rotation forestry system have been summarized by Ribe (1974). They include: (1) reduction of costs because of the production of several crops in the time that would ordinarily be required to produce a single crop; (2) increased fiber production on a smaller area; (3) economical use of highly productive land; (4) early amortization of the costs of site preparation, planting and early culture; (5) harvest of smaller, cleaner clearcut areas similar to the harvest of agricultural crops, which may be more acceptable to the public than a conventional clearcutting operation; (6) rapid growth, clonal propagation, and early maturation of trees grown under a short rotation permit rapid genetic improvements; and (7) greater uniformity of the physical properties of the trees within a species.

The ultimate success of the short-rotation forestry concept hinges on the amount of usable fiber produced per unit area of land in a reasonable length of time and at an acceptable cost. The determination of yield values is very complex, and involves many factors such as site, planting methods, planting stock, spacing, cultural treatments, fertilization, length of rotation, and others, since any factor affecting the growth of the trees will necessarily affect fiber production (Steinbeck et al. 1972). To implement a successful short-rotation forestry program it is necessary to examine these factors for the particular species being worked with, and eventually to determine the economics of the system.

POTENTIAL OF HYBRID POPLARS FOR SHORT-ROTATION FORESTRY

The Genus *Populus*

Populus is one of the oldest of the modern angiosperm genera and is believed to have originated in China and Japan (Khosla and Khurana 1982). Subsequent migration was characterized by widespread introgression that has left a fossil record of more than 125 species. Today, the genus is characterized by a relatively high degree of genetic diversity and includes approximately 30 species (Rehder 1947). These species are placed taxonomically in five sections: *Turanga, Leuce, Aigeiros, Tacamahaca* and *Leucoides* (Pourtet 1979). *Populus* species are distributed throughout the temperate and subtropical regions of the northern hemisphere from about 22°N to 70°N latitude. Only members of the collective species *P. euphratica* of the section *Turanga* are found in their natural state outside of this zone (Muhle Larson 1970). There are numerous subspecies within species, and many provenance differences exist. There are also numerous cultivars, especially since poplars are usually propagated readily by stem cuttings, thereby permitting the cultivation of clones (Anon. 1958). Table 1 indicates the species and the sections to which they belong. The economically most important species are in the sections *Leuce, Tacamahaca* and *Aigeiros*.

Because of the wide geographic distribution of some species, the frequent introgressive hybridization, and the extensive cultivation and vegetative propagation of poplars, much confusion has arisen about the nomenclature of poplar species. Several "species" have been described under both specific and varietal names, so that it is sometimes difficult to decide whether such names refer to real species differences or only to varieties, races, or ecotypes within the same species. However, recent studies of wild populations have added to our knowledge of races and ecotypes within various species (Hamaya and Inokuma 1957, Papaioannou 1963, Brayshaw 1965, Erdesi 1965). Large clonal variations in both morphological and physiological characteristics often occur within the same species of poplar.

Poplar Breeding and Culture

Poplars have many features that make them attractive for breeding. Because *Populus* is a widely distributed and variable genus, poplar

Table 1. Classification of *Populus* species.

SECTION Species	Geographic distribution
TURANGA	
euphratica	West and Central Asia, North Africa
pruinoca	Central Asia
LEUCE	
adenopoda	China
alba	Europe, Asia, North Africa
davidiana	Northeast Asia
grandidentata	North America
sieboldii	Japan, Korea
tomentosa	Asia
tremula	Europe, Asia
tremuloides	North America
LEUCOIDES	
ciliata	Central Asia
heterophylla	Southeast U.S.A.
lasiocarpa	China
wilsonii	China
TACAMAHACA	
angustifolia	North America
balsamifera	North America
cathayana	Korea
laurifolia	Siberia
maximowiczii	Northeast Asia, Japan
simonii	Asia
suaveolens	Asia
szechuanica	China
trichocarpa	North America
yunnanensis	China
AIGEIROS	
deltoides	North America
fremontii	North America
nigra	Europe, Asia, North Africa
sargentii	North America
wislizenii	North America

species and hybrids are adaptable to a broad range of sites. This range of adaptability and other features, such as relatively fast growth, the desirability of fiber and wood properties for a variety of products, ease of hybridization and vegetative propagation of some sections, and early flowering, have contributed to significant amounts of plantation culture of *Populus* throughout the world. In fact, poplars are probably the most intensively domesticated of all forest trees (Mohrdiek 1983). Forest plantations have been established around the world for fuelwood, pulpwood, lumber, veneer and other products, as well as for windbreaks, stabilization of slopes, riverbanks and roadbeds, reclamation of stressful sites such as surface-mined lands and former sea beds, and aesthetic improvement. Nearly 1.5 million ha of poplar plantations in Europe, Asia, Africa, the Middle East, North and South America, Australia and New Zealand supplement an estimated 20 million ha of natural *Populus* forests, located primarily in North America (Viart 1979). The area occupied by *Populus* plantations has been increasing steadily; in 1979, close to 150,000 ha of new plantations were established throughout the world (Anon. 1979a).

History of Poplar Breeding and Culture

Poplar hybrids were already under cultivation by the end of the seventeenth century. The first clone to be mentioned in the literature is "Serotina" (Houtzagers 1937). In the eighteenth and nineteenth centuries, the first selections were made in Europe from natural hybrids that had originated from aspen pollinations between *P. deltoides* and *P. nigra* (Mohrdiek 1983). Clones from that era such as "Robusta" are still used today. In about 1784, the Lombardy poplar (*P. nigra* var. *italica*) was introduced to North America and was planted across the continent (Schreiner 1970). The first artificial crosses reported in the literature were made in 1910 at the University of Dublin between *P. angulata* (Syn. *P. deltoides* var. *deltoides*) and *P. trichocarpa* (Henry 1914). Since then, poplars have been bred with increasing intensity in many countries of the world.

Interspecific breeding, combined with vegetative propagation of the selected ortets, has been a powerful tool used in producing poplar strains and clones with vigorous growth and improved resistance to disease, and stem cuttings with better rooting ability. By interspecific breeding, hybrids can also be produced for different ecological environments and with a wider tolerance for site conditions. The first program of interspecific poplar breeding aimed at producing hybrid varieties for commercial timber was initiated by Stout and Schreiner of the Oxford Paper Company in 1924. Stout and Schreiner (1933) conducted a crossing program with 34 parent trees. Three clones of these crosses, originating from species of the sections *Tacamahaca* and *Aigeiros*, are still in use almost everywhere in the world. The work of Stout and Schreiner led to further crossing and selection work in many other countries. Soon poplar breeding began in Austria (Wettstein 1930), the USSR (Albenskiy and Delcina 1934), Canada (Heimberger 1936) and Italy (Piccarolo 1948). After the Second World War, poplar breeding programs sprang up in many countries.

The major interest in poplar breeding has been in the sections *Aigeiros, Tacamahaca* and *Leuce*. Most of the intersectional crosses have been between *Aigeiros* and *Tacamahaca* species because of the ease of hybridization between species of these sections. It has been estimated that more than 90% of the poplar cultivation throughout the world is concentrated on species of the section *Aigeiros* (Pourtet 1979), primarily because of the broad adaptability of these species and hybrids to sites in temperate and subtropical zones, their ready vegetative propagation by stem cuttings and the ease of hybridization between species of this section. European reports have been published concerning the breeding of *Aigeiros* poplars by Kopecky (1956), Langner (1962), Muhle Larson (1963, 1964, 1967) and Frohlich (1965), who has also dealt with poplars of the section *Tacamahaca*.

For the *Leuce* section, reports on breeding have been published in France by Bouvarel and Lemoine (1957), in Canada by Heimberger (1958), in Germany by Seitz (1954, 1963), in Italy by Sekawin (1962) and in the Netherlands by van Vloten (1955) and Hellinga (1957). In Norway, the breeding of aspen has been discussed by Borset and Haugberg (1960). The discovery of a natural triploid "gigas" aspen clone (Muntzing 1936, Nilsson-Ehle 1936) led to a great emphasis in the field of polyploidy, which has recently declined. The most successful results have been obtained with F1 hybrid progeny of *P. tremula* and *P. tremuloides* (Melchior and Seitz 1966, Hattemer and Seitz 1967, Einspahr and Winton 1976, Johnsson 1976) as well as with hybrid clones of *P. alba* and aspen species (Benson 1972, Hyun and Son 1976, Zsuffa 1976).

Intersectional *Leuce-Aigeiros* and *Leuce-Tacamahaca* crosses have been more difficult to achieve successfully than crosses between the sections *Aigeiros* and *Tacamahaca* (Stettler 1968, Zufa 1968). These crosses with the section *Leuce* often result in dead seed or dwarfed seedlings (Johnsson 1956, Kopecky 1962). However, promising single hybrids are reported occasionally. Some success with difficult crosses has been achieved by using mixed pollen of viable incompatible and inviable compatible pollen (Stettler 1968, Knox et al. 1972). In addition, by using interspecific hybrids instead of pure species as parents, some difficult crosses have become feasible (Zufa 1968). Little work has been carried out on the crossability of poplars belonging to the sections *Turanga* and *Leucoides* (Zsuffa 1973a).

Poplar Breeding and Culture in Ontario

The purposes behind breeding programs differ from one country to another, since an optimal economic profit depends on the best balance between the genetic constitution of the trees and all environmental influences (Muhle Larson 1970). In Canada, poplar breeding was initiated regionally in Quebec, Ontario, the Prairie Provinces and British Columbia with poplars that had local economic importance or other desired characteristics.

Several poplar species grow in Ontario, and constitute a significant part of the hardwood timber. Ontario's poplar breeding program was developed to satisfy the needs created by a large number of plantations established for intensive management on marginal, sub-marginal and good farmlands, and for extensive management on forest soils (Zsuffa et al. 1977). The objectives of poplar breeding and culture in the province were to select and produce poplar clones with (1) good rooting ability, (2) resistance to frost, (3) resistance to diseases and insects, (4) fast growth, (5) desired site tolerance, (6) positive reactions to intensive site management, (7) desired wood quality, and (8) other desired biomass characteristics.

Experience with poplar breeding in Ontario has been accumulated with *P.* x *euramericana* clones of European origin, *P. deltoides* and *P.* x *jackii* selections from Ontario, and *P. alba* interspecific hybrids of Ontario and European origin. Breeding has also concentrated on *P. deltoides* x *tacamahaca, P. deltoides* x *trichocarpa, P. deltoides* x *maximowiczii, P. deltoides* x *nigra*, and *P. tremuloides* x *tremula* crosses. Selected trees of native species have been used in these crosses, and pollen from exotic parents has been obtained either from other countries or from Ontario arboreta. Progenies of exotic species have been established in the province to provide a rich gene pool for further selection and breeding work.

For regular, intensively managed poplar plantations, *P. deltoides* crosses are the most important. In southern Ontario, clones of *P. deltoides* x *nigra*, and crosses of *P. deltoides* and various *Tacamahaca* species, can have success. For northern Ontario, clones developed from crosses between local *P. balsamifera* and either *P. deltoides* varieties or other *Tacamahaca* species of good timber quality are promising, as are trembling aspen selections and hybrids and other *Tacamahaca* hybrids (Zsuffa 1979).

Growth and Yield of Hybrid Poplar

The products of efforts in cross-breeding among the major poplar species have been established in plantations throughout the world to produce crops of high-quality cellulose under short rotations. High growth rates have frequently been reported for these intensively managed hybrid poplar plantations (Anon. 1958, Heimberger 1958, Schreiner 1959). Productivity rates of 12 to 15 tonne/ha/yr have been reported from many studies of SRIC of hybrid poplar (Zavitkovski and Isebrands 1983).

Extensive experimentation with short-rotation hybrid poplar plantations has occurred at many American and Canadian research centers since these hybrids were first developed in North America. In many of the early plantings, established in the 1930s and 1940s, disease was found to be a major problem (Jensen and Harrington 1930, Rudolf 1948, Cram 1960). Diseases such as *Melampsora* spp. leaf rust (Gruschow 1939) and *Septoria* spp. canker (Bier 1939), as well as winter injury (Anon. 1939), were common. The occurrence of diseases and frost damage on many of the early hybrid poplar plantings in the United States and Canada limited widespread planting of hybrid poplars, and initiated the testing of clones for resistance to these injurious agents, as well as an evaluation of growth. Subsequent research has indicated that insect and disease resistance vary from clone to clone (Bagley 1972). Differences in the anatomy of the stem affect the rate of moisture loss and, therefore, susceptibility to some diseases (Bloomberg 1962a,b)

In the United States, selections of "Oxford Paper Company" clones produced from the initial crossing work carried out by Stout and Schreiner (1933) in Maine, U.S.A. were established and evaluated for growth at various locations. McKee (1931) reported yields of 80 cords per acre (approximately 729.6 m^3/ha) from these plantings, for which close spacing and heavy thinning had been applied. The Lake States Forest Experiment Station and several other agencies in the Lake States received clonal stock from this early work, and tested many of these clones in Michigan, Wisconsin, Minnesota, and North Dakota from 1935 to 1941 (Rudolf 1948). The results of most of these trials were not promising, since most of the clones were not suitable for the region. Exceptions were five of the Oxford paper hybrids and one hybrid "Henry" poplar (*P.* x *generosa*) from Denmark, all of which usually appeared superior. On the basis of these early trials, it was suggested that species native to the Lake States region, such as the aspens and cottonwood, should be used in poplar hybrids planted in these areas, since the Oxford Paper hybrids included mostly species foreign to the region along with many of the balsam poplar group (Rudolf 1948). A cooperative research program was subsequently initiated in the Lake States to produce and test aspen hybrids containing native aspens and *P. tremula* from Europe (Einspahr and Benson 1964). Results of tests of these hybrids indicated that triploid aspen showed great promise in the area as a result of its rapid early growth and high specific gravity (Benson and Einspahr 1967) and investigations of hybrid aspen performance in the Lake States have continued since that time.

More recently, research on intensively cultured hybrid poplar plantations in Wisconsin began at the North Central Forest Experiment Station in 1970 (Hansen et al. 1983). From the results of clonal tests, it has been found that, in general, northeastern clones grow better in northern Wisconsin than do *P. euramericana* clones, although there is not yet enough information to recommend particular clones for specific sites with guaranteed success. Instead, recommendations have been made that local trials should be established to select fast-growing clones that root easily, are resistant to insects and diseases, and are adapted to the local climate and soils (Hansen et al. 1983).

Fifty of the northeastern Oxford Paper clones developed by Stout and Schreiner (1933) were planted in West Virginia and their performance was evaluated at the end of 20 years (Wendel 1972). At that time, several of the clones had attained an average diameter of more than 9 inches (24 cm) and heights of more than 70 feet (21 m). Results of the study indicated that rotations may be limited to 20 years as a result of the occurrence of stem cankers caused by *Fusarium solinia*. The Northeastern Forest Experiment Station of the USDA Forest Service also tested 199 of these northeastern clones at locations in Pennsylvania and Maryland (Demeritt 1981). Average 4-year height of the clones ranged from 5.1 to 26.0 feet (1.5 to 8 m) in Pennsylvania, and 5.6 to 22.7 feet (1.7 to 7 m) in Maryland, with significant differences in height among clones both within and between locations. Twelve of these clones ranked in the upper 12.5% for height at both locations and grew at the rate of 4 to 6 feet (1.2 to 1.8 m) per year. Similar growth rates were achieved by hybrid poplars growing on a reclaimed strip mine in Pennsylvania, where they maintained an average growth rate of 4 feet (1.2 m) per year and reached 65 feet (19.8 m) in height after 16 growing seasons (Davidson 1979).

Further west, Jensen and Harrington (1930) reported survival of 2% and height of 13 feet (4 m) for 11-year-old plantings of a "Northwest" poplar clone from an early planting in Montana, whereas George (1936) reported survival of 88% and height of 12 feet (3.7 m) for Northwest poplar grown under a seasonal precipitation of 11 inches (27.9 cm) for 6 years in North Dakota. Plantations of selected poplar hybrids and of *Populus deltoides* were also established in Nebraska in 1961 to examine survival, growth and pest resistance (Bagley 1972). Results indicated that certain clones are not high in vigor and performance on all sites, but rather are more site specific. In addition, certain clones had a greater ability than others to establish themselves from cuttings or rooted seedlings. Differences in performance can be expected among clones on a specific site, since each has inherent characteristics that interact with environmental conditions to affect its growth and development (Schreiner 1959, Merritt and Bramble 1966, Read 1967).

In Canada, plantations of various hybrid poplars were established from the 1940s to the 1970s in several provinces, primarily with the intent to select fast-growing clones for fiber production. Testing of hybrid poplars was initiated in Saskatchewan to provide shelterbelts for the prairies, since hybrid poplars have rapid early growth. Since 1942, various poplar clones were tested at the Forest Nursery Station in Indian Head, Saskatchewan, for winter hardiness, drought tolerance, and resistance to prevailing diseases (Cram 1960). Of 17 of the most promising of these clones, survival of the most outstanding clone, *Populus* 44-52, was 75% and height was 17 feet (5.2 m) after 6 years. The superior characteristics of this clone resulted in its wide distribution for prairie shelterbelt planting and it was suggested for use in tree-improvement programs.

The growth performance of 28 poplar clones established in field trials in Manitoba was studied between 1965 and 1973 by Steneker (1976) with the intention of identifying suitable hybrids for fiber production and amenity use. The superior *Populus* 44-52 clone from Indian Head, Saskatchewan, was included in these studies. Five clones, including clone 44-52, were selected as potential candidates for fiber production and amenity uses within the province. Growth performance of clone 44-52 was evaluated further on provincial sample plots (Segaran and Rathwell 1978). These additional studies indicated differential growth rates in diameter and height for various site conditions. Segaran and Rathwell suggested that careful site selection should be a major priority in the establishment of future trials of this clone.

In British Columbia, various poplar hybrids have been established and evaluated by several forest-products companies (Smith and Blom 1966), as well as at the University of British Columbia (Walters 1963). A private tree farm, West Tree Farms Ltd., was established to study growth, spacing, thinning and weed control in local and hybrid poplars. The hybrids tested included several Euro-American hybrids supplied from Ontario's poplar breeding program at Maple, as well as hybrids containing interior and coastal *Populus trichocarpa* that had been tested in Belgium for 20 years. After only 11 years in the field, many of these hybrids averaged 8 inches (20.3 cm) in diameter (DBH) and 70 feet (21.4 m) in height (Smith and Blom 1966). The hybrid *P.* x *robusta* was the most successful and was widely planted after initial testing (Smith 1980). Since, by comparison with conifers in British Columbia, hybrid poplars can achieve large diameters and heights under short rotations, they have an important role where quick growth of large trees in a short time is required. Therefore, further research and operational trials on a range of sites have been recommended throughout the range of poplar species in the province (Smith 1980).

In Quebec, 53 experimental trials with 68 hybrid poplar clones were established between 1963 and 1974 throughout the province for the purpose of selecting clones suitable for timber and pulpwood production (Popovich 1982). The poplar hybrids used were northeastern clones obtained from the Northeastern Forest Experimental Station in the United States that were originally produced by Stout and Schreiner (1933). After 10 years of growth, eight clones were selected as the best performers and were considered for use in further studies. As in other studies, the results indicated that careful site selection should be a major priority in establishing hybrid poplar plantations. The best sites were bottomlands. The most promising clone, NE-56, produced mean heights of 12.6 and 9.9 m on good and average sites, respectively, and had excellent survival rates and very good stem form.

Extensive test plantations of hybrid poplar throughout southern Ontario have shown fast growth and high yields on many sites (Zsuffa 1973b). The average annual height increment of hybrid aspen after 7 to 15 years ranged from 1 to 1.7 m and diameter (DBH) ranged from 1.3 to 1.6 cm. Mean annual increments attained between 7 and 15 years of age were between 7 and 20 m^3/ha. These results compared favorably with yields of native aspen on site class 1; the average DBH of 9- to 15-year-old hybrid plantations was similar to that of 35- to 50-year-old natural stands, and the average height of the hybrids equaled that of 30-year-old trees in natural stands. Hybrid cottonwood plantations showed similar yields. The excellent growth obtained in these early trials in southeastern Ontario justified the initiation of large-scale pulpwood production trials in that area. A technology-development group was established in the Ontario Ministry of Natural Resources' Brockville District in 1976 to develop technologies for poplar management in Eastern Region. By 1981, 388 *Populus* clones of varying origin and parentage were being tested in the region (Anon. 1983). The best hybrid poplar varieties in these trials grew to 12.5 m in height and 16.5 cm in diameter (DBH) in 7 years and were 17.4 m high and 18.8 cm in DBH at age 12; they also achieved mean annual increments of 8 m^3/ha at age 7 and 29 m^3/ha at age 12 (Zsuffa et al. 1977). These values are excellent in comparison with the MAI of native poplar stands on Ontario, which even on site class 1 reach a maximum of only 6.3 m^3/ha at 50 years of age (Plonski 1960). Growth of a number of hybrid poplar clones in southwestern Ontario was studied by von Althen (1981b), who found that the height and diameter of 5-year-old clones varied widely, and therefore suggested that, to obtain the highest possible yield from a given site, only clones that have grown well on similar sites should be planted.

Recent studies by Khalil (1984a,b) investigated the performance of 32 hybrid poplar clones of various species in the boreal region of Newfoundland. Clones were tested on four different sites, and the results provided guidelines for the selection of clones best suited to the boreal environments represented at these sites. Significant variation occurred among clones and locations 4 years after outplanting. Superior clones have been identified for the environmental conditions represented by each test site on the basis of genetic stability and productive quality. The results confirm those from many other trials, which indicated that poplar clones vary in their growth characteristics and site requirements, and therefore clonal selection decisively influences the success of hybrid poplar management.

Physiology of Yield in Hybrid Poplar Plantations

In recent years, many studies of yield physiology have been carried out in SRIC hybrid poplar plantations. These investigations of yield were intended to provide baseline morphological and physiological information on tree growth that could then be applied to increase the productivity of plantations by deliberate manipulation of selected stages of the tree's growth (Larson 1969, 1972).

At the North Central Forest Experiment Station in Rhinelander, Wisconsin, a research program was initiated in 1978 to provide physiological criteria for improving SRIC plantations (Isebrands et al. 1983). Integrated studies of crown morphology, photosynthesis, and photosynthate distribution have been conducted in relation to biomass yield, as expressed by traditional growth analysis. In SRIC poplars, leaf characteristics such as age, structure and size, orientation, type of shoot on which the leaf is located, and distance from main stem have important effects on both photosynthetic rate and on the distribution of photosynthesis within the tree (Isebrands and Nelson 1980, Michael et al. 1980, Nelson and Ehlers 1981, Isebrands 1982, Nelson and Michael 1982, Isebrands and Michael 1985).

It is now recognized that biomass productivity in poplars is closely related to total leaf area (Larson and Isebrands 1972, Zavitkovski et al. 1974, Isebrands and Nelson 1982). Aspects of leaf growth have been studied as they relate to stem growth (Ridge et al. 1986), since a detailed knowledge of the relationship between the components of leaf growth and tree productivity would assist efforts to increase the productivity of hybrid poplar plantations (Heilman and Stettler 1985, Weber et al. 1985). Ridge et al. (1986) found that stem growth was correlated with individual leaf area and leaf growth rate.

Several investigators have found differences among hybrid poplar clones in terms of partitioning of dry matter, photosynthetic and respiration rates, and various gas-exchange parameters (Fasehun 1978, Pallardy and Kozlowski 1979, Ceulemans et al. 1980). Cain and Ormrod (1984) used growth analysis to compare the early growth of two hybrid *P.* x *euramericana* clones and a clone of each of *Populus deltoides* and *Populus nigra*. The hybrid clones grew more vigorously than did the species clones with regard to most of the measured parameters, including plant dry weight, leaf dry weight, leaf area and root dry weight.

Species and clonal differences in the time of bud-set and the time and extent of leaf abscission have been observed in hybrid poplars (Isebrands 1982). These differences greatly affect both the quantities and distribution patterns of exported photosynthate within the tree.

The results of the many yield-physiology studies on SRIC hybrid poplars suggest that cooperative efforts among silviculturists, physiologists and geneticists toward establishing a physiological basis for intensive culture of these hybrids should provide new strategies for increased yields in hybrid plantations.

Utilization of Hybrid Poplar

The utilization of short-rotation, fast-growing hybrid poplars as a wood supply for the wood-products industry has aroused much interest in the past decade. However, SRIC material differs from conventional fiber in that it is both juvenile and rapidly grown, and these conditions affect wood properties, which in turn affect wood-product quality.

It has been demonstrated that numerous *Populus* hybrids produced by SRIC systems do have potential for use as a wood source to produce kraft pulp for some paper grades (Einspahr et al. 1968, Marton et al. 1968, Laundrie and Berbee 1972, Cheng and Bensend 1979, Zarges et al. 1980). In a study of the kraft-pulping qualities of four hybrid poplars from a plantation on Manitoulin Island, Ontario, the hybrids were comparable to or better than those of either select fresh-cut or seasoned native poplar obtained from the Thunder Bay region (Holder et al. 1977). Three of these hybrids also showed potential for chemi-refiner mechanical pulp. Similarly, pulp yields produced by the magnesium-bisulfite and refiner-groundwood processes from trials in southeastern Ontario proved to be similar or superior in quality to locally grown poplar and mixed hardwoods (Zsuffa 1973b). Phelps et al. (1985) found that wood chips from SRIC hybrid poplar plantations mixed with conifer chips to supplement the furnish for kraft pulping produced paper of acceptable quality. Additional studies have also indicated the suitability of various poplar hybrids for use in other products, including structural flakeboard (Geimer and Crist 1980) and hardboard (Hutchinson 1981, Myers and Crist 1986).

Factors Affecting Pulpwood Suitability

The reported studies confirm that although the properties of SRIC hybrid poplars are those of juvenile and fast-grown wood, they are still suitable for producing pulp products of acceptable quality. The anatomical characteristics of wood are closely related to the quality of pulp and paper produced from it. Wood with long fibers, low percentages of vessels, ray cells and gelatinous fibers, and a high percentage of thin-walled fiber cells is most desirable for the paper industry (Dadswell and Wardrop 1959, Dadswell et al. 1959). The relative amounts of holocellulose and alpha-cellulose, and to some extent the specific gravity, are also important in determining the pulpability of wood (Murphey et al. 1979).

The strength of paper is controlled primarily by the strength of interfiber bonds produced by the crossing of fibers. Long wood fibers result in a greater number of interfiber bonds, thus increasing paper strength. Although juvenile materials have shorter fibers than mature materials, the average cell-wall thickness of juvenile material is less than that of older material. These thin-walled cells collapse readily into the desired ribbon shape to provide a large surface for bonding and are pliable, so the fibers can conform to each other and form strong bonds. Consequently, although there are less interfiber bonds with the short fibers, the bonds present are strong enough that the resulting strength properties of the paper are acceptable and within most product standards (Crist 1983).

Contrary to popular belief, the rapid growth of hybrid poplars does not detrimentally affect the mechanical strength properties of their wood, but rather prolongs juvenility (Crist 1983). In fact, Marton et al. (1968) observed, for four hybrid poplar clones, that not only did increased growth rate not decrease pulp quality, but that the faster-growing trees within a clone actually gave the best pulp quality. Based on these results, the authors suggested that forest managers be advised to grow selected poplar material at the maximum rate possible in production plantations.

High bark contents are generally not desirable in pulpwood production. Although SRIC hybrid poplars have high bark contents because of their small-diameter, branchy stems, the bark is not as detrimental as that from older stems. The abundance of the cell types in bark that decrease paper quality increases with increasing age. Young stems harvested from short-rotation plantations have not developed many of these cells (Crist 1983).

It is well known that in *Populus* species, the formation of tension wood is common, especially in young poplars grown under intensive culture (Isebrands and Parnham 1974, Anderson and Zsuffa 1975) since tension wood has been associated with rapid growth (Berlyn 1961, Correns 1961, White and Robards 1965, Isebrands and Bensend 1972). Tension wood is not a desirable component in chemical and semichemical pulping; although it increases yield, it decreases strength properties of the paper produced (Panshin and de Zeeuw 1949). In a study of the effects of pulp containing tension wood produced from the hybrid poplar clone "Tristis No. 1" (Parnham et al. 1977), although the pulp was inferior to that of normal wood, it compared favorably with that obtained from conventional pulps of other young or mature hardwoods (Barker 1974). Thus, Parnham et al. (1977) stated that even with a high percentage of tension wood in its fast-growth juvenile stems, this clone, and perhaps similar ones, may hold promise as a valuable source of hardwood fiber.

A number of genetic and cultural factors can affect the quality of wood that can be produced from intensively cultured hybrid poplar plantations. Clonal variation in several properties that influence wood quality (e.g., fiber length, specific gravity, lignin, tension wood, and extractive content) has been demonstrated for various hybrid poplar clones (Cheng and Bensend 1979, Crist 1980), indicating that these properties are probably under strong genetic control and that part of the selection criteria for clonal use should be based on the quality of the raw material. Blankenhorn et al. (1985) also demonstrated that site, rotation length, and tissue age and parentage can affect the chemical-content values (e.g., extractives, lignin, holocellulose, alpha-cellulose) of hybrid poplar clones. These results suggest that cultural and harvesting decisions can influence selected chemical properties of wood produced in short-rotation hybrid poplar plantations. No effects on wood properties of hybrid poplar clones under SRIC have been observed as a result of spacing (Holt and Murphey 1978, Murphey et al. 1979, Phelps et al. 1982). Thus, planting to maximize biomass per hectare is the criterion to be applied for such short-rotation stands.

Vegetative Propagation

The advantages of autovegetative propagation of poplars have long been known. Propagation techniques that depend on the inherent biology of the species or hybrid have been developed for various poplars. Through vegetative propagation, large numbers of poplar species and hybrids are reproduced each year in many countries and made available for practical cultivation.

Hardwood Stem Cuttings

Many hybrid poplars can be successfully established from dormant stem (hardwood) cuttings (Farmer 1973, Fege 1983) and, as a result, a great deal of knowledge has accumulated concerning the collection, storage and planting of poplar hardwood cuttings. The rooting of such cuttings provides a convenient and relatively inexpensive means of establishing fast-growing, intensively cultured clonal poplar plantations.

One-year-old stems and some older woods of poplars from the sections *Aigeiros* and *Tacamahaca* contain preformed root primordia that generally originate in ray tissue of the secondary phloem (Shapiro 1958, Braun 1963, Smith and Wareing 1972a, Haissig 1974, Hartman and Kester 1975). Rooting of such stems directly in field plantations is relatively easy, since these root primordia need only to increase in length and size. Bloomberg (1963) observed for several poplar hybrids that adventitious roots develop first along the cutting and then later at the basal end during the rooting process. It has also been shown that physiologically mature dormant cuttings from older trees can be rooted under greenhouse conditions after treatment with indole-butyric acid (IBA) (Farmer 1966).

Cutting orchards (stool beds) of poplar clones are commonly managed in nurseries for the production of dormant, unrooted hardwood cuttings from 1-year-old stump sprouts. Numerous cuttings for plantations of hybrid poplar (Anon. 1983, Hansen et al. 1983) and cottonwood (McKnight 1970) have been produced in this way. In this system, the stool beds are established by planting high-quality, disease-free hardwood cuttings at regularly spaced intervals in site-prepared nursery beds. Cultural practices such as weed control, fertilization, irrigation and pest eradication are employed throughout the growing season to maximize the production of cutting material. Maintenance of healthy plants is essential, since vigor of cuttings has been related to nutrition of the parent shoot (Anon. 1979b, Hartman and Kester 1975). The shoots that sprout from the clonal stools are generally allowed to grow for two seasons so that a strong root system can develop (Hansen et al. 1983). At this point, there are generally 4 to 10 sprouts (whips) per rootstock, from which 5 to 8 cuttings (each 20 to 25 cm long) can usually be harvested, depending upon the clone and the condition of the shoots (Fege 1983). The rootstocks are usually cut back to within 15 cm of the ground every 1 or 2 years during the dormant season, and the resultant coppice growth is harvested annually from this point on for cuttings. Rootstocks can usually be harvested for 4 to 8 years, until sprouting vigor is reduced to a degree at which cuttings can no longer be produced (Fege 1983). Various factors that affect the regeneration of rootstocks have been studied, including season of harvest and cutting method. Several studies indicated that the sprouting vigor of coppice shoots is greatest when harvests are made during the dormant season (Debell and Alford 1972, Lee and McNabb 1979, Strong and Zavitkovski 1983) and that stems should be severed as close to the ground as possible during harvest to prevent decay and loss of biomass (Lust and Mohammady 1973, Crist et al. 1983, Strong and Zavitkovski 1983).

Dormant hardwood cuttings may also be rooted and planted as container stock rather than being planted directly in the field. The advantages of this approach (Hansen et al. 1983) are that (1) even small-diameter cuttings survive and grow well, (2) the planting season may be extended, and (3) survival may be improved on harsh sites. These advantages make the use of containerized rooted cuttings especially useful for research purposes, where high survival rates are required to obtain accurate trial results.

Factors Affecting Rooting of Cuttings

Success in the establishment of hybrid poplar plantations depends on a variety of factors that affect the ability of the cuttings to develop early, vigorous root systems. Genetic variation in rooting characteristics has been reported both among and within various poplar species (Cunningham 1953, Bloomberg 1963, Wilcox and Farmer 1968, Ying and Bagley 1977). Other factors such as collection time, stem dimensions and physiological quality of cuttings, as well as environmental factors that affect cutting vigor, must be considered in order to produce high-quality propagation materials.

Hardwood cuttings must be collected after the shoots have achieved some degree of dormancy in the fall, and before dormancy has ended in the spring (Fege 1983). Investigations of the effects of collection time on cutting performance after planting were made by Allen and McComb (1956) and Farmer (1966); rooting performance was better for cuttings harvested during the dormant season. For each of these studies, cuttings were planted under greenhouse conditions immediately after their collection, which, for practical purposes, would not really be possible on an operational planting scale.

Most commercial nurseries that produce hardwood poplar cuttings store them after collection at near-freezing temperatures for some period of time, often up to 4 months, before planting. The temperature and conditions at which dormant cuttings are stored have a strong influence on their vigor after outplanting (Fege 1983). Smith and Wareing (1972b) found that bud development and rooting of dormant hybrid poplar cuttings were significantly affected by certain constant or variable temperature regimes, and Bloomberg (1963) observed that the number, length and weight of root initials emerging from cuttings increased with temperature for several poplar hybrids. Although most nurseries store cuttings at temperatures between -2 and 2°C (Fege 1983), acceptable survival of hybrid poplar cuttings stored at temperatures well below 0°C has been reported (Cram and Lindquist 1981, Phipps and Netzer 1981). Fege and Phipps (1983) studied the storage of seven hybrid poplar clones for 5 to 9 months at a range of temperatures from 2°C to -20°C. They found no significant differences in the height of cuttings stored at all temperatures regimes at the end of the first growing season. The results suggest that nursery managers could successfully store hardwood cuttings at any of the evaluated temperatures so long as the cuttings have been collected after the plant material has achieved the required degree of dormancy. However, since shoots and roots were seen to emerge at the end of the storage period from cuttings held at -3°C and 2°C, it was suggested that more flexibility in scheduling planting could be gained by storing cuttings at lower temperatures, since such flushing did not occur. It has also been shown that the incidence of blackstem fungus, a disease that commonly develops during storage of cuttings, was lower and survival of hybrid poplar clones was higher when cuttings were stored at -3°C rather than 1°C (Ostry and McNabb 1982).

Environmental factors such as light (Shapiro 1958) and moisture (Allen and McComb 1956, Bloomberg 1963) are also known to have a major influence on the rooting ability of cuttings. It has been shown that there is a correlation between soil moisture content and root production in poplar cuttings (Allen and McComb 1955, Larsen 1957). Several studies have indicated that warming and soaking cuttings prior to planting increases subsequent survival and growth, particularly under dry conditions (Edwards and Kissock 1975, Petersen and Phipps 1976, Phipps 1978, Krinard and Randall 1979). Various planting guides have recommended soaking as a procedure in establishing plantations with unrooted cuttings (McKnight 1970, Phipps et al. 1977). A recent study of the relationship between soil moisture tension and early growth of hybrid poplar cuttings indicated that, for all clones studied, rooting and shoot growth increased with increasing soil moisture, and warming and soaking cuttings to the point of imminent root emergence accelerated early shoot growth (Hansen and Phipps 1983). Based on these results, the authors suggested that cuttings should be warmed and soaked to the point of root emergence and subsequently planted in moist soil. They also stated that warming and soaking can largely compensate for unavoidable situations in which soil moisture is less than desirable and irrigation is unavailable. Phipps et al. (1983) found that root length, root dry weight, percentage of bud flush and shoot length increased with soaking of cuttings, as soaking increases early root growth, which essentially extends the growing season. Fege (1983) recommended that cuttings be soaked in water at about 15°C for 7 to 10 days before planting, until root primordia begin to emerge from the bark and cuttings are fully imbibed. However, cuttings must not be soaked beyond the point of root emergence since subsequent planting will break off or damage many of these emerged initial roots. Removal of initial roots was found to decrease shoot growth and subsequent rooting of planted hardwood hybrid poplar cuttings (Bloomberg 1963).

Rooting success of cuttings is often related to the cutting's position on the shoot (Bloomberg 1959, Hartman and Kester 1975). The rooting capacity of several poplar clones increased with distance from the tip of the stem, and 3-mm basal cuttings produced significantly greater numbers, total length and weight of roots than cuttings taken from the second 15-cm length from the tip (Bloomberg 1963). Hansen and Tolsted (1981) found increases in rooting of poplar cuttings from the lower position of the stem for a difficult-to-root clone, and Ying and Bagley (1977) observed similar effects with cottonwood clones from a variety of geographic sources.

Another important measure of cutting quality is diameter. It has generally been observed that small-diameter cuttings from the tip portions of shoots have fewer preformed root primordia (Smith and Wareing 1974) and, as a result, do not root or grow as well as cuttings from basal stem portions. In addition, total carbohydrate reserves are greater in larger-diameter cuttings (Fege 1983). Dickman et al. (1980) found, for several hybrid poplar clones, that survival and growth of cuttings generally increases with increasing cutting diameter. These authors suggested that although clones differed in their response, cuttings less than 6 mm in diameter should not be used for field plantings. Bowersox (1970) found that height growth was correlated with cutting diameter for the first 2 years after outplanting, but this relationship no longer held by the third year after outplanting.

Cutting length is known to influence survival of outplanted cuttings. Although cuttings are commonly 20 to 25 cm in length and planted flush with the ground (Anon. 1983, Fege 1983), longer cuttings are better able to survive in the field than shorter cuttings under conditions such as moisture stress. McKnight (1970) recommended the use of 50-cm cottonwood cuttings planted with all but 5 cm beneath the soil for use in plantations in the southern United States. Allen and McComb (1956) observed that the survival, number of roots and shoot growth of 45-cm cuttings of cottonwood was at least double that of 15-cm cuttings. Thus, shorter cuttings are generally recommended for use on shallow soils, and 50- to 80-cm cuttings inserted to a depth of 30 to 40 cm are suggested for deeper soils to increase survival (Anon. 1979b).

Softwood Stem Cuttings

In addition to using hardwood cuttings, softwood or greenwood cuttings of poplar can also be used to propagate clones rapidly under mist (Randall and Miller 1971). This system is used by horticulturalists, and has been used successfully in experimental and production nurseries in the United States and Europe (Koster 1968). Phipps (1976) states that the rooting of softwood cuttings of some poplar clones in commercially manufactured containers has proven to be a reliable method for the establishment of research plots. However, the rooting performance of different clones is variable, and various rooting media have been found to affect both the rate and the form of rooting.

Root Cuttings

For poplars of the section *Leuce*, dormant stem cuttings are difficult to root since few to no preformed latent root primordia exist in the shoots (Frohlich and Weisgerber 1984). Thus, it has not been possible to achieve practical, large-scale propagation of aspens and their hybrids by means of rooting cuttings, although some rooting of stem cuttings treated with root-promoting growth regulators has been achieved (Schier

1980). However, vegetative propagation of young, succulent aspen root suckers that arise from excised roots is possible (Schier 1978). This propagation technique was developed in Europe for *Populus tremula* (Muhle Larson 1943) and various adaptions have been successfully applied for aspens and their hybrids in North America (Farmer 1963, Barry and Sachs 1968, Benson and Schwalbach 1970, Hicks 1971, Starr 1971, Zufa 1971, Schier 1978). Variation in rooting has been reported among clones of *P. tremuloides* under mist propagation (Barry and Sachs 1968) and Benson and Schwalbach (1970) reported much better rooting success with *P. tremuloides* than with *P. grandidentata*. However, Zufa (1971) found that rooting of *P. grandidentata* was comparable to that of *P. tremuloides*.

The misting method generally involves propagating root suckers from roots that have been placed horizontally and covered with some form of rooting media such as coarse and fine sands, vermiculite or mixtures of sand and vermiculite (Maini and Horton 1966, Barry and Sachs 1968, Benson and Schwalbach 1970, Tew 1970, Schier 1978). Root suckers are then placed in a medium such as coarse sand (Farmer 1963), sand and vermiculite (Benson and Schwalbach 1970) or perlite and vermiculite (Barry and Sachs 1968, Schier 1978) after having been treated with IBA in order to increase the percentage of cuttings that root and the number of roots produced (Farmer 1963). Cuttings are then subjected to mist for 2 to 3 weeks, by which time most clones will develop root systems (Schier 1978).

Tissue Culture

In recent years, the possibility of vegetatively propagating poplars by means of tissue culture has been investigated. The use of this technique for forestry has been stimulated by the success in autovegetative large-scale propagation by means of tissue culture that has been achieved throughout the world since the 1970s with many plant species in agriculture, fruit growing and horticulture (Morel 1960, Fast 1980). This technique could be especially useful for aspens, which are difficult to root from dormant stem cuttings, since it offers the possibility of fast and relatively unproblematic plant production. Consequently, the research on poplars to date has been concentrated principally upon the aspens *P. tremula* and *P. tremuloides* (Winton 1968, 1971; Christie 1978; Chalupa 1981; Schmid 1981; Ahuja 1983; Frohlich and Weisgerber 1984). The propagation method as applied to aspen has been described in detail by Barocka et al. (1984) and Frohlich (1982). The main steps in the procedure, as summarized by Frohlich and Weisgerber (1984), involve (1) gathering and treatment of meristematic tissues from the vegetative points of the plant shoot, (2) formation of callus and shoots, (3) shoot proliferation, (4) root proliferation, and (5) development of plantlets in the greenhouse and nursery.

Hybrid Poplar Establishment

The period of plantation establishment is that period of time from initial site preparation until the tree canopy closes (Hansen et al. 1983). During this period, several key steps must be taken to ensure that the establishment of an intensively cultured hybrid poplar plantation will be successful. This series of steps includes thorough site preparation, selection and matching of clones to the site, proper planting procedures and weed control. Initial spacing is an important factor that must also be considered in the establishment phase. Additional procedures may also include fertilization and irrigation.

Site Preparation

Initial site preparation is generally required to loosen the soil and control weeds that will compete with hybrid poplars (Hansen et al. 1983). It has long been recognized that newly planted hybrid poplars are very sensitive to competition from grasses and broadleaved weeds (Hesmer 1951), since early growth is directly correlated with the available area of grass-free and weed-free soil (Schreiner 1945). Controlled experiments have shown that the presence of weeds significantly decreases root, shoot and volume growth, the number and weight of leaves, and the foliar composition of poplars (Aird 1962).

Site preparation is an expensive procedure, and therefore is a substantial part of the investment in the establishment of a hybrid poplar plantation. However, once trees are planted, weed control becomes much more difficult and often results in some tree mortality or reduced growth. Thus, money spent on site preparation may be offset by even greater savings in the long run (Hansen et al. 1983). There are several methods that are commonly used to prepare sites for planting hybrid poplar: (1) plowing and disking, (2) fallowing (repeated tillage for a season before planting), and (3) no-till (treated with herbicides). These site-preparation methods may be used singly or in combination.

To reduce costs, site preparation has been tried only in strips or in plots where the trees are planted for various hardwoods including hybrid poplar (Lane and McComb 1953, Bey et al. 1975, von Althen 1981a). Because hybrid poplar grows fast, the lateral roots grow quickly and can reach 2.2 m in length by the end of the first growing season (Hansen 1981). As a result, if only partial site preparation is carried out, the poplar roots are quickly forced to compete with undisturbed weeds outside the prepared areas, even in widely spaced plantations. It has been shown that mechanical site preparation by plowing and disking of the entire site promotes the best growth of hybrid poplars (and other hardwoods) in southern Ontario (von Althen 1981b). This study also showed that reduced growth resulted when strips of only 1.2 to 2.7 m wide were plowed and disked, and growth was even poorer in no-till strips in which herbicides were applied. No poplars survived in strips without herbicide or tilling.

In a study of five site-preparation treatments consisting of combinations of tillage and contact (glyphosate) and pre-emergent (linuron) herbicide application, treatments had little effect on survival, but the effects on second-year height growth were significant and additive (Hansen et al. 1984a,b). Increasing the number and types of site preparation increased tree height and apparently had a cumulative effect on weed suppression. The best growth was obtained with a summer fallow-with-herbicide treatment consisting of two applications of glyphosate followed by plowing and repeated disking, plus spring disking and application of linuron at planting time. A comparable growth response was obtained from a less intensive fallow treatment consisting of one application of glyphosate followed by plowing and disking and subsequent spring disking and application of linuron at planting time. The results suggest that the combined site-preparation system of a contact herbicide plus tillage is desirable to control allelopathic vegetation such as quackgrass or fescue and their residual toxic effects. The herbicide kills the weed cover and tillage increases soil temperature and speeds up the microbial decomposition of residues and breakdown of allelopathic chemicals. The least effective treatment in the study was no tilling with one fall application of glyphosate.

This study confirms previous studies on the results of not tilling before planting hybrid poplars on imperfectly drained clay loam soils in southern Ontario. Hansen et al. (1984a,b) suggest that the no-till treatment for hybrid poplar is probably not as suitable as other site preparation methods involving tillage in more northerly latitudes, but more suitable in the longer and warmer growing seasons in the southern half of the corn belt and further south, as indicated by agricultural studies. No-till and other practices that leave soil residues on the soil surface result in higher soil moisture in the rooting zone and lower spring soil temperatures (Crosson 1981). These conditions are an advantage on droughty soils, but are disadvantageous on poorly drained soils, In contrast, McKittrick et al. (1986) found that 2-year results of no-till trials with two Euramerican hybrid poplar clones planted in southern New York State indicated that chemical competition control without exposing mineral soil was successful. These results suggest that the soil and climatic conditions of these more southerly hybrid poplar plantations may be more amenable to no-till site preparation.

Fall plowing is recommended as the most effective site-preparation treatment from an operational standpoint (Hansen et al. 1984a,b), since it does not require an idle growing season before planting as do fallow treatments and is not significantly different from them in terms of its effect on height growth. In addition, fall plowing requires less energy than deep plowing, which has not been shown to increase height growth significantly, or fallow treatments, which require repeated disking (Vaughan et al. 1978). A fall plowing treatment, recommended by Hansen et al. (1983), is similar to that recommended by von Althen (1979) for abandoned farmland in southern Ontario. The recommended schedule involves disking and then plowing during the fall before spring planting, after mowing heavy vegetation and applying a post-emergent herbicide such as glyphosate to resprouting vegetation and grass. In the spring, just before planting, it is recommended that the site be disked again and a pre-emergent herbicide such as linuron or diuron be applied to control germinating annual weeds and grasses for approximately 4 to 8 weeks.

In southeastern Ontario, two major chemical-mechanical site-preparation options are used for establishing hybrid poplar plantations (Anon. 1983). The first involves the application of glyphosate to the site, followed by plowing and disking several times in the summer before planting occurs. The second option involves plowing and disking of the site followed by incorporation of EPTC (a non-selective site-preparation chemical) into the soil during the summer before planting. For both methods, the site-preparation investment is protected by applying a pre-emergent herbicide (generally simazine) to the site in the fall before planting.

Clonal Selection

Studies have shown that significant clone-site interactions exist (Randall and Mohn 1969; Demeritt 1979; Hansen et al. 1984a,b; Rogers 1986). Individual clones tend to have a unique set of highly specific site requirements, needing large volumes of water but also good soil aeration. Hybrids of the balsam poplars tend to be relatively tolerant of extremes of site conditions, such as poor aeration. Aspen hybrids favor drier sites because their root systems tend to be quite extensive, with many deeply penetrating sinker roots.

Because of the specific site requirements of hybrid poplar clones, they must be carefully matched to sites to ensure good survival and growth. Information concerning the growth of hybrid poplar clones on specific sites has been obtained from clonal trials that have been established on a variety of site types (Anon. 1983; Hansen et al. 1984a,b). It has been suggested that such trials should last for many years because the clonal ranking changes as diseases or unusual frosts slow the growth of some previously fast-growing clones (Schreiner 1972) and since the importance of various pests also changes with tree age (Hansen et al. 1984a,b). Evaluations made closer to the anticipated rotation age will therefore provide a better basis for clonal selection (Wilkinson 1974, Hansen et al. 1983).

Planting

Dormant hybrid poplar hardwood cuttings are usually planted vertically, with the soil packed firmly around the cutting. Good contact between the cutting and the soil is necessary to eliminate air pockets and ensure good rooting. In addition, the top ends of the cuttings must not be damaged during planting or the resulting callus tissue will produce multiple shoots rather than one main shoot (Barkley 1983). Horizontal planting of cuttings has also been evaluated for various species, but is generally not recommended for poplars. Bloomberg (1963) found that significantly more roots were produced by cuttings of two hybrid poplar clones when they were planted upright and vertically instead of vertically inverted or horizontally. However, there was no effect on *P. trichocarpa* cuttings as a result of planting position.

Generally only 1 or 2 cm of the top of the cutting is left exposed (Fege 1983) and cuttings are often planted flush with the ground (Barkley 1983). However, in the southern states, cottonwood cuttings have been planted with 5 cm exposed (McKnight 1970). In studies to determine the effects of planting depth, Hansen et al. (1983) found that the fewest main shoots were produced when 20-cm cuttings were planted flush with the ground surface in a silt loam; however, first-year shoot height was less than that of cuttings planted at shallower depths (either 10 or 15 cm).

In southern Ontario, it has been recommended that dormant cuttings be planted in early spring for hybrid poplar plantation establishment (Anon. 1983, Barkley 1983), as soon as frost leaves the soil, since cool weather and wet soil reduce the risk of seedling desiccation at that time. Based on this guideline, planting time may be as early as March in warmer climates, and as late as early June in the northern United States and Canada. Hansen et al. (1983) found that in studies over 3 years, dormant hybrid poplar cuttings planted in mid-May grew consistently more during the growing season than those planted in April, but that differences between planting dates from April to early June were slight for plantations in Wisconsin. In these studies, it was observed that fall planting was successful in only one of the three years as a result of frost heaving, most probably because of light snowpacks during the years of plantation failure.

In a more recent study, Hansen (1986a) investigated the effects of planting dates from mid-April to mid-November for soaked versus unsoaked hybrid poplar cuttings under irrigated versus unirrigated and weedy versus weed-free conditions in northern Wisconsin. Survival was good for all planting dates at the end of the first growing season, but cuttings planted from July through to mid-November showed greatly reduced survival by the end of the second growing season. The tallest trees after two growing seasons were those planted in mid-May, regardless of clone, soaking, irrigation or weed treatments. These results indicate that the best growth is not achieved if cuttings are planted immediately after frost leaves the ground in northern Wisconsin. Since the actual optimum planting date would change with location and local climatic conditions, the author recommended that a soil temperature of 10°C may be used as a first approximation of the optimum time to plant hybrid poplar cuttings.

Weed Control

Weed control in intensively cultured hybrid poplar plantations must be maintained until the plantation is "free to grow". This condition is reached when the plantation is above the minimum stocking standard and is judged to be free from competing vegetation (Armson et al. 1980). Achievement of this state may require several years, depending upon growth of the trees and other factors including plantation spacing.

Control of competing vegetation in hybrid poplar plantations can be done chemically, mechanically, or by means of cover crops. Each of these approaches, used singly or in various combinations, has been successful in establishing intensively cultured hybrid poplar plantations at various locations. However, under certain conditions, each method also has drawbacks (Hansen et al. 1983). The ultimate success of various weed-control measures depends on the specific site and climatic conditions (Hansen 1984).

Netzer and Noste (1978) conducted a study in Wisconsin to evaluate the effects of 12 herbicide treatments on competing vegetation and the growth of the hybrid poplar clone "Tristis #1" on three sites. The herbicides tested included linuron, dichlobenil, simazine, paraquat and glyphosate, at various rates, which were applied in either the first, second, or both growing seasons. The sites included a clearcut forested site, an abandoned farm field with established sod, and a well cultivated field. Results of the trials indicated that herbicide treatments improved survival and growth on the sodded site, but had no effect on the clearcut area and may have had an adverse effect on the well cultivated field, where little vegetation was present to begin with. Three treatments, involving moderate application rates of linuron alone and in combination with paraquat or glyphosate, showed promise for eventually improving biomass production.

A study by von Althen (1981a) gave slightly better results for hybrid poplar after rototilling than with the application of the herbicide simazine at various rates and suggested that it is advisable to apply this chemical only in the second and later years after planting, when the trees have rooted and become more tolerant of the herbicide. Cunningham and Sowers (1965) found that simazine was no substitute for cultivation in hybrid poplar plantations because application rates of 2.2 kg/ha or more greatly reduced the survival of the poplar clones. Polyethylene mulch has been tested as an alternative to mechanical weed control for establishing hybrid poplar (Bowersox and Ward 1970). Although establishment success with this method was found to equal or exceed that achieved by mechanical weed control, the material is expensive and its application is labor-intensive.

Danfield et al. (1983) tested the effects of several herbicides (glyphosate, linuron, pronamide and dichlorbenil) at several rates and on several spray dates on 1-year-old hybrid poplar. Their results indicated that all herbicides controlled weeds and did not seriously injure the trees when applied in early spring or late fall, but applications earlier in the fall or later in the spring caused various amounts of injury and reduced height growth, depending on the herbicide and its application rate. Since herbicide injury increased as the number of leaves on the developing terminal shoot increased, the number of leaves may be a better indicator than date for determining when herbicides may be safely applied to hybrid poplar plantations in the spring. Further testing is required for various herbicides to determine the exact physiological stage of tree development at which they can be safely applied.

Hansen et al. (1984a,b) compared the effects of various weed-control methods, including herbicides, cultivation and leguminous cover crops, on survival and height growth of 2-year-old hybrid poplars. These authors found that cultivation and herbicides used singly or in combination gave consistently better results than the other treatments tested and they recommended using a pre-emergent herbicide at the time of planting, possibly followed in midsummer on some sites with cultivation or a contact herbicide. The best herbicide treatment tested was a pre-planting application of linuron followed by a midsummer application of glyphosate. Linuron is a safe herbicide for poplars since it is applied just before planting and prevents germination of weed seeds for 4 to 6 weeks. It also allows glyphosate application to be delayed until the trees are bigger and hardier, which reduces damage to them. Glyphosate is very difficult to apply after planting without causing damage. It has been shown that actively growing young poplars are easily damaged by even small amounts of glyphosate spray drift when less than 1 year old (von Althen 1979, Akinyemiju et al. 1982), although clonal variation in toxicity has been observed (Akinyemiju and Dickman 1982a,b). Cultivation alone resulted in generally good tree survival and height growth, although a herbicide treatment (linuron) followed by cultivation resulted in slightly better tree growth and survival. The use of a legume gave good first-year height growth and survival, but by the end of the second growing season, when the legume had become more established, the results were not as good. The question of the effect of a cover crop on hybrid poplar growth was studied earlier by Ford and Williamson (1952), who found that tree growth was significantly better with certain leguminous cover crops than with non-leguminous cover crops, possibly because of nitrogen provided by the legumes. However, although all cover crops established at the time of planting excluded weeds from the site, these crops seriously inhibited tree growth. Tree growth in cultivated plots was much superior to that of trees grown in association with legumes.

Spacing

There is no one spacing that is best for the establishment of an intensively cultured hybrid poplar plantation. A particular spacing will not affect the biomass ultimately obtained from a plantation, so long as the principle of harvesting when the mean annual biomass increment reaches a peak is observed (Hansen et al. 1983). However, the selection of a particular initial spacing is very important, as it affects the physical characteristics of the crop trees and the time and cost required to produce them.

Plantation establishment and harvesting costs are higher in dense plantations than in more widely spaced plantations, since more materials are required for planting, planting costs are higher and harvesting is less efficient. Logging and processing costs have been shown to decrease rapidly in trees above 25 cm DBH (Krinard and Johnson 1975). However, the duration of weed control required is shorter in dense plantations, where canopies close rapidly (often by the second growing season) and thus shade out weeds. In more widely spaced plantations, weed control may be required for several years (Barkley 1983).

Rotation length generally increases with spacing for specific site conditions and cultural treatments applied. Ek and Dawson (1976) indicated that, in dense plantings (0.23 x 0.23 m), mean annual biomass increment culminates at an age of approximately 3 years. In more open stands, the maximum mean annual increment was not reached until age 9 (Zavitkovski, unpublished data). In southeastern Ontario, intensively cultured hybrid poplar plantations are established at a spacing of 3 x 3 m, and rotation length is expected to be 10 years for most clones and site conditions (Anon. 1983).

Studies have shown that wider spacings and longer rotations drain less nutrients from a site than do closer spacings and shorter rotations (Hansen and Baker 1979). The removal of nitrogen, in particular, and to a lesser extent of phosphorus and potassium, can be reduced with longer rotations.

It is well known that the spacing of trees has a major influence on crown architecture in SRIC hybrid poplar plantations (Dawson et al. 1976, Nelson et al. 1981) and crown architecture in turn has a major influence on forest productivity and yield (Pollard and Wareing 1968, Larson and Gordon 1969, Zavitkovski et al. 1974, Farmer 1976, Isebrands and Nelson 1979). Spacing influences the photosynthetic rate of leaves and the leaf area available for intercepting the light falling upon the tree canopy (Dickman 1979). In poplars, it is known that there is a close correlation between productivity, in terms of wood yield, and leaf area (Larson and Isebrands 1972, Larson et al. 1976). It is also well known that an increase in spacing increases the crown surface (and probably root surface) of individual trees, and therefore causes an increase in the proportion of branchwood produced (Ek and Dawson 1976). In other words, spacing changes affect biomass distribution throughout a tree. As a result, maximum wood fiber production per unit area is achieved at very close spacings (1.2 m or less), which allow early increases in leaf-area index (Dickman 1979). Leaf-area index expresses the total leaf area of a plant canopy per unit of land area covered. At wider spacings, leaf-area index builds up slowly to low levels; however, leaf area per tree is much greater than in closely spaced plantations and, therefore, growth of individual trees is fostered, producing larger trees for a given rotation length (Dickman 1979).

The physiological effects caused by spacing changes have been observed in several spacing studies of hybrid and other poplars. In a spacing study of hybrid poplar and cottonwood, Smith and Blom (1970) observed that close spacings (1.8 m) produced the highest yields under short rotations, but that growth of individual trees increased up to very wide spacings (9.8 m). At this very wide spacing, the hybrid *P. grandis* produced three times the average basal area of trees at the 1.8-m spacing after only 2 years. These authors recommended a minimum spacing of 3.7 m for this hybrid and for cottonwood when planting costs and net yields, which increase rapidly with tree size, are considered. At this spacing, yields of 15-year-old cottonwood exceeded yields of natural cottonwood, observed by Mahon (1966) in the Lower Fraser River Valley, in one-fifth the time. Thus, it was concluded that the selection of a proper spacing can enhance yield per unit area.

Krinard and Johnson (1975) reported 10-year results of spacing trials on cottonwood in the southeastern United States. For conditions in that area, they found that there is no apparent best spacing, but that certain spacings appear best for a particular endproduct. Consequently, these authors recommended that the forest manager should decide on the endproduct before planting. From the results of these spacing trials it was observed that a minimum 2.4- x 2.7-m spacing would be best if the trees are to be harvested and pulped at an age of 8 or 9 years, since this spacing produced as much volume as trees spaced at 1.2- x 2.37-m spacing, but required less planting and harvesting. As well, larger trees with less bark were produced. If only trees ≥ 13 cm DBH are to be pulped, Krinard and Johnson recommended a spacing of either 2.4 x 2.7 m or 3.7 x 3.7 m, since, although the 2.4- x 2.7-m spacing produced 9% more volume in 44% more trees than the 3.7- x 3.7-m spacing, there were three times as many unmerchantable trees in the more closely spaced plots. For other products such as sawtimber, for which larger trees are required, they recommended wider spacings (e.g., 4.9 x 5.5 m) for 10-year rotations. If mixed products such as pulpwood and sawtimber are desired, the authors suggested a 3.7- x 3.7-m spacing, since flexibility is provided for harvesting pulpwood at only slightly less production than at the best pulpwood spacing, and subsequent production can be extended into sawtimber with only a slightly longer rotation and somewhat better bole quality than at the 4.9- x 5.5-m spacing.

In southeastern Ontario, spacings for intensively managed clonal plantations are chosen to allow the optimum growth of trees to the desired size and to maximize yield while ensuring that the site is fully utilized. Plantations established at a range of spacings from 1.8 x 3.7 m to 6.1 x 6.1 m indicated that, after the fourth year of growth, the closer spacings restricted diameter growth, although tree height appeared to be unaffected (Zsuffa et al. 1977). Smith and Blom (1970) observed that, for hybrid poplar spaced at 1.8 m, trees grew faster in height for the first few years after planting than did those at wider spacings, but that eventually height became fairly uniform in all spacings.

Fertilization and Irrigation

Research into fertilization and its application in forestry has progressed greatly in recent decades (Hansen 1986b). At the same time, there has been increasing interest in irrigating forests to increase tree growth (Debell et al. 1977, Hansen 1978). The general relationships between nutrient and moisture effects on plant growth are well established. Plant growth usually increases with an increasing supply of moisture, to some optimum level (Hansen 1976). Plants respond to fertilization in a similar way as to water (Morrison 1974): there is an area of deficiency, an optimum range, and an area of excess. Thus, for maximum fiber production, it is necessary to define the combinations of fertilizer and water that are necessary for optimum growth. Results of early studies in Wisconsin have shown that fertilization and irrigation of SRIC hybrid *Populus* greatly enhances growth and yield, by as much as six times the yield of natural aspen stands (Ek and Dawson 1976).

Several short-rotation hybrid poplar systems, representing a likely range of spacings, rotations, and various cultural practices including fertilization and irrigation, have been evaluated by means of discounted cash-flow models (Ferguson et al. 1981, Lothner et al. 1981, Rose et al. 1981). The results of these studies have been mixed. Systems that include both irrigation and fertilization have shown negative returns, with irrigation being the most uneconomic operation. No systems with fertilization alone have been evaluated. Detailed information and analyses are required to determine whether fertilization will pay for itself by increasing yield enough that the returns will be greater than the cost (Lothner 1986).

1. Fertilization:

Nutrient requirements are very high in SRIC plantations, and there are high nutrient removals from the site during harvesting. Applications of fertilizers may be necessary to achieve optimum production by genetically improved tree varieties. Near-optimum nutrient levels for volume production have been determined for some hybrid poplars (Einspahr 1971). Several studies on the foliar nutrient levels required for maximum growth showed little difference among the *Populus* species tested (Bonner and Broadfoot 1967; Einspahr 1968, 1969). However, it is possible that nutrient and water requirements for maximum growth may vary among clones, and it may therefore be possible to select clones with efficient nutrient utilization. A comparison of *P. deltoides* clones from three geographic sources showed that trees from one source utilized nitrogen and potassium 50 and 100% more efficiently, respectively, than trees from the other sources (Blackmon et al. 1979). In another study, a comparison of 50 clones of *Populus trichocarpa* and its hybrids showed significant differences among clones in nitrogen, phosphorus and calcium within the aboveground biomass (Heilman and Stettler 1985).

The importance of adequate nutrient levels has been studied in terms of the effects of certain nutrient concentrations on wood properties of several poplar species and hybrids. Foulger and Hacskaylo (1968) found that when seedlings of *P. deltoides* were deprived of potassium, their lower stems had shorter, narrower fibers and narrower annual rings, and upper stems had narrower vessel elements than did controls. Foulger et al. (1971) found that fiber length in the same species was greatest when nutrients included about 17 ppm nitrogen and 53.1 ppm potassium, but other nutrient relationships were not clearly established. Cutter and Murphey (1978) investigated the wood anatomy of a hybrid poplar clone in relation to the concentration of potassium in solution. Their results showed that stems grown in 2 and 50 ppm potassium solutions were taller and heavier than stems grown in 10-, 100- and 150-ppm solutions. Percentages of wood and pith in stem cross sections varied among treatments, but the percentage of bark remained the same. Both vessel element and fiber lengths and diameter were affected by potassium levels, as was vessel-element cell-wall thickness. Fiber cell-wall thickness, however, was not affected by treatment.

The major questions concerning fertilization of plantations are (1) whether or not to fertilize, and, if so, (2) when fertilization should take place (Lothner 1986). The main objective of fertilization is to maintain or enhance site productivity. Fertilization is generally concentrated on the one nutrient (or the few) that is deficient and that limits growth thereby. Nitrogen is the nutrient generally most deficient for poplar and most likely for other species (Hansen 1986b). Hansen and Tolsted (1985) found that fertilizing hybrid poplar with nitrogen for the first 5 years increased growth by from 50 to 400% depending upon the site and level of nitrogen applied. Optimum fertilization rates are generally about 110 to 168 kg/ha/year (Hansen 1986b). Weber et al. (1985) applied nitrogen fertilizer (ammonium nitrate) twice during a 4-year test of the productivity of *P. trichocarpa* and its hybrids on a plantation site, considered low in fertility, in western Washington. Nitrogen was applied at rates of 150 and 75 kg/ha in the third and fourth growing seasons, respectively. Phosphorus was not applied to the site because relatively high levels were already present in the foliage of the clones.

Yield gains are also related to site fertility. In the study by Hansen and Tolsted (1985), fertilization produced large gains on a sandy-loam site with annual applications of N up to 168 kg/ha/year, but little growth increase occurred after the first 3 years on a more fertile silt-loam site. The study also showed that fertilizing with phosphorus and potassium alone did not improve biomass yields above what could be obtained with nitrogen alone.

Several studies of various types and rates of fertilizer have been carried out on planted hybrid poplars in Quebec. Menetrier (1979) found that phosphorus was the most important nutrient for hybrid poplar growth at the time of establishment, but that nitrogen became most important later on. Menetrier and Vallee (1980) found that application of 28 kg/ha of nitrogen in 0.6-m-wide strips 3 weeks after planting, followed by the application of 112 kg/ha nitrogen on 1-m-wide strips after 1 year, gave the best cost/yield ratio after 3 growing seasons. In this study, as in the previous one, the application of phosphorus alone was better than that of nitrogen alone at the time of planting. Levels of foliar phosphorus were better correlated with height and diameter growth than were levels of foliar nitrogen. There was no significant difference between the fertilizer types used at planting after one growing season, but after 3 years, NH_4NO_3 + triplesuperphosphate + K_2SO_4 (with supplementary nitrogen in the second year) gave the best results. In a subsequent study, Sheedy (1982) fertilized two hybrid poplar clones with various combinations of nitrogen, phosphorus and potassium (as urea, triplesuperphosphate and K_2SO_4, respectively) immediately after planting, and measured growth over a 4-year period. Growth of both clones was increased by fertilization. Length, width and mass of leaves were increased by up to 58, 68 and 145% respectively. Nitrogen, phosphorus and potassium concentrations in the leaves increased, and the number and length of branches increased by up to 50 and 162%, respectively. Height growth was increased by up to 72%, total height by up to 29%, and diameter by up to 69%. The strongest response was to nitrogen, and the most effective treatment consisted of 150 g urea, 354 g triple-superphosphate, and 150 g K_2SO_4 per tree. It was also noticed that although both clones sustained high levels of frost mortality, damage was generally less in the fertilized trees.

There are biologically and economically optimum times to fertilize during a rotation. Fertilization at planting time may not be as beneficial as originally thought, because nutrient availability from exposed soil is often sufficient for good plant growth on all but the most impoverished soils, and early fertilization often increases competition from weeds (Hansen 1986b). Therefore, it has been suggested that perhaps fertilization should be delayed until crown closure, when weeds are shaded out. Conversely, in SRIC plantations, weeds are controlled by cultivation or herbicides and nutrient demands are high, so early fertilization may be necessary (Hansen 1986b). Studies in forestry have shown that the continual addition of nutrients, in balance with tree nutrient uptake, results in superior tree growth (Ingestad 1970). In any case, trees should be fertilized only when they need additional nutrients for growth, and this involves determination of the most appropriate time to fertilize on the basis of soil and plant tissue samples (Hansen 1986b). Agricultural research indicates that fertilizer recovery is usually greatest when the fertilizer is applied at the beginning of the period of greatest plant growth. This time might be in June for poplars.

Mineral fertilizers have been the predominant material used in forest fertilization, and they will probably continue to be (Mayer-Krapoll 1956; Anon. 1968, 1973). However, other methods of fertilization have also been tried. Effluents and sludges from municipal and industrial sources provide potential sources of nutrients for fast-growing tree crops (Urie 1975). Using such material takes advantage of the needs to both dispose of wastes safely and to provide nutrients to crops. Irrigating hybrid poplar with paper-mill effluent has produced good tree growth (Hansen et al. 1980). The trees removed essentially all nitrogen and phosphorus from the effluent, which helped to clean it. The disadvantage of this approach was that most sodium, chlorine, and SO_4 in the effluent reached the water table, posing potentially serious aquifer contamination.

Nitrogen-fixing plants have also been used to maintain or improve forest productivity. Tests with various combinations of nitrogen-fixing species and crop trees have shown that the nitrogen-fixers can increase tree growth as much as mineral fertilizer (Haines and DeBell 1979). However, there are presently only limited applications possible for this approach, and further research is required (Hansen 1986b).

Certain methods of decreasing nutrient removal and loss from a site are known. Harvesting plantations younger than 7 years old results in greatly decreased nutrient-use efficiency. Hansen and Baker (1979) observed that nitrogen-utilization efficiency was three to six times greater in 7- to 20-year-old than in 1- and 2-year-old intensively cultured poplar plantations. The longer rotation results in both lower nutrient concentrations and a smaller proportion of the total biomass in high-nutrient-concentration components. Removing only the tree components that contain the lowest nutrient concentrations also increases nutrient-utilization efficiency. It was found that harvesting only bolewood, which has the lowest nutrient component, from a 7-year-old cottonwood plantation removed 69% of the aboveground biomass, but only 23% of the nitrogen (Carter and White 1971). However, the foliage added only 5% to the aboveground harvested biomass, but accounted for 34% of the total nitrogen in the aboveground components. Thus, the nitrogen-utilization efficiency of the bolewood was 20 times that of the foliage. Some potential exists for increasing nutrient-utilization efficiency if harvesting is done in the early fall, before major nutrient translocation from leaves to wood and bark occurs, although this approach could result in some loss of wood and bark production (Hansen and Baker 1979). Increased nutrient utilization through this method would be possible only if leaves are left on the site.

2. Irrigation:

Irrigation of forests is generally done to increase yields on sites where the addition of moisture would increase tree growth. Thus, irrigation may be thought of as a substitute for insufficient soil moisture-storage capacity. Hansen (1983) classifies sites and the associated yield response as a result of irrigation into the following three categories:

1) Very droughty soils on which there is no tree growth or the existing trees are noncommercial. Irrigation of such sites creates new commercial forest land, and a maximum gain in wood production.

2) Land with chronic soil-moisture deficits, which depress tree growth and may result in substantial mortality as a result of infrequent droughts. Irrigation of these sites increases the probability of producing a commercial forest crop.

3) Land that is nearly certain to have sufficient soil moisture to produce a forest crop. Irrigation under these conditions would slightly increase yields.

Although irrigation increases yields in all three categories, the magnitude of the increases differs greatly.

Irrigation of forest trees usually increases tree growth (Hansen 1978). Zahner (1968) stated that even small decreases in soil moisture tension will increase the growth of forest trees. Irrigation research with hybrid poplars supports these conclusions. In a study of hybrid poplar planted at a 1- x 1-m spacing in Wisconsin and irrigated for three consecutive years, irrigation consistently increased tree growth (Hansen 1983). The wettest irrigation treatment, which produced a soil moisture tension of -0.3 bar, produced yields 76 and 44% greater than those of unirrigated controls at the end of the second and third growing seasons, respectively. Irrigation increased yield by about the same amount (1.5 tonne/ha/year) in both years. The study also showed that, although irrigation increased yields, it was not necessary for growing trees on the site (which would probably fall into category 3).

Hansen et al. (1983) stated that soil moisture tension should be -0.2 bar or more at the time of planting. A growth-room study indicated that the early shoot growth of unrooted hardwood hybrid poplar cuttings increased as soil moisture tension increased to at least -0.05 bar, indicating that new plantations should be kept moist (Hansen and Phipps 1983). These results agree with the conclusions of Stanhill (1957) and Zahner (1968) that yields are greater with wetter soil moisture regimes. However, it may not always be necessary to irrigate newly established plantations, especially if weed control is good, since soil moisture tensions in weedy plantations are severe, and can therefore be reduced if weeds are eliminated. Hansen (1983) found that unirrigated, newly planted hybrid poplars, which had little weed competition after weed control, survived and grew satisfactorily even though there was exceptionally low rainfall in July and August of the year of establishment. Because good weed control is much less expensive than irrigation, it may therefore be an alternative solution in some situations. However, if drought occurs earlier in the season (May and June), it may increase the need for irrigation during plantation establishment. Soil moisture can also be conserved by soaking plantings prior to planting to compensate for dry (-0.6 bar) soil moisture conditions (Hansen and Phipps 1983). Thus, whether or not irrigation is necessary for successful plantation establishment depends on the conditions during the growing season and on the condition of the cuttings themselves (if dormant hardwood cuttings are used), as well as on the degree of weed control achieved.

It is also very important to maintain high levels of soil moisture after the trees begin to grow. Hansen (1983) found that tree volume of hybrid poplar was greatest at the wettest soil moisture (-0.3 bars), almost double that of unirrigated trees, during the first 2 years of growth. The results indicated that the management objective should be to maintain high soil moisture levels by irrigation whenever possible. Heilman and Stettler (1985) used a tensiometer to determine the need for irritation, throughout several consecutive growing seasons, for hybrid poplar trial plantations in Washington.

Because irrigation is very expensive, it may not be economically justified on the basis of increased yields alone (Hansen 1983). The justification for irrigation must also rely to a large extent on (1) bringing previously unproductive land to higher levels of production, and (2) the insurance value of greatly reducing the risks of growth or mortality losses from drought, or secondary damage by insect and diseases. Trees under water stress are more susceptible to diseases (Haywood and McNabb 1979) and insect pests (Stark 1965), which can contribute to tree decline or death even after moisture is restored. It may also be possible to use sewage or industrial effluent for the common objectives of tree irrigation, fertilization, and waste disposal, as investigated by Hansen et al. (1980) and discussed in the section on fertilization. This approach would be more economical, since it would provide additional benefits beyond fiber production alone, thus making irrigation a feasible option. Further research on this approach is required.

POTENTIAL OF LARCH FOR SHORT-ROTATION FORESTRY

The Genus *Larix*

The larches are tall, deciduous, coniferous trees with spreading branches, and all are shade-intolerant, pioneer species noted for exceptionally vigorous growth. Although there have been difficulties with the taxonomy of genus *Larix*, there are 10 species that are generally recognized, as well as several varieties (Dallimore and Jackson 1948, Rehder 1954, Genys 1960, Carlson and Blake 1966). These species are distributed in cooler regions and on mountains throughout the northern hemisphere. Four of these species are located in Southeast Asia, three are in North America, two are in the Soviet Union, and one is in Europe. The species are classified in the sections *Multiseriales* and *Pauciseriales* on the basis of the length of bracts on the cones in relation to the length of the cone scales (Patschke 1912). Species in section *Multiseriales* have bracts that are longer than the cones, giving the cones a spiny or hairy appearance. Species in section *Pauciseriales*

Table 2. *Larix* species and their distribution.

SECTION Species or variety	Geographical distribution
MULTISERIALES	
Larix occidentalis (Western larch)	North America
Larix lyallii (Alpine Larch)	North America
Larix potaninii (Chinese larch)	Asia
Larix mastersiana (Master's larch)	Asia
Larix griffithii (Himalayan or Sikkim larch)	Asia
PAUCISERIALES	
Larix laricina (Tamarack)	North America
Larix decidua var. *decidua* (European larch, Alpine variety)	Europe
Larix decidua var. *polonica* (European larch, Carpathian variety)	Europe
Larix siberica (Siberian larch)	Europe and Asia
Larix gmelini var. *gmelini* (Dahurian larch, Dahurian variety)	Asia
Larix gmelini var. *olgensis* (Dahurian larch, Olga variety)	Asia
Larix gmelini var. *principis rupprechtii* (Dahurian larch, Prince Rupprecht variety)	Asia
Larix gmelini var. *japonica* (Dahurian larch, Kurile variety)	Asia
Larix leptolepis (Japanese larch)	Asia

have bracts that are shorter than the cone scales, which gives the cones a smooth appearance. In addition, species belonging to section *Multiseriales* generally have strongly keeled leaves, whereas species in section *Pauciseriales* are generally flat, or at most only slightly keeled (Schoenike 1961). Table 2 presents the species and varieties and indicates their ranges. In addition to the 10 recognized species, the larch found in the northeastern part of the European portion of the Soviet Union and the Urals was assigned to a separate species in 1947 by Dylis, which he called the Sukachev larch (*Larix sukaczewii*). This classification is currently disputed by Bobrovy (1982) after studies in 1973 and 1978.

It is believed that the larches are closely related, and that most interspecific crosses are possible (MacGillivray 1969). Natural interspecific hybrids of alpine larch and western larch have been reported in areas where the ranges of the two species overlap (Carlson and Blake 1966); the same is true for Chinese larch and Master's larch (Wright 1962), and for Dahurian larch and Siberian larch (Syrach-Larsen 1937). In addition, various larch species under cultivation have been known to cross spontaneously, including Japanese larch and European larch (Henry and Flood 1919), Japanese larch and Siberian larch (Dallimore and Jackson 1954), and tamarack and European larch (Rehder 1954).

Genetics and Breeding of *Larix*

The larches have been of great interest to foresters and geneticists throughout the world because of the potential of many of the species for reforestation and tree improvement. Tree improvement research can take advantage of the early flowering habit, rapid juvenile growth, and wide spectrum of adaptability of *Larix* species and hybrids to maximize wood production under short rotations (MacGillivray 1969).

Variation

Provenance studies of several larch species have indicated significant amounts of variation in a wide range of characteristics both within and among species. There are also appreciable differences in site requirements for optimal growth and development, which include, for some species, a strong adaptation to the broad climatic conditions that prevail over their natural range (Rauter and Graham 1983). The International Union of Forest Research Organizations (IUFRO) initiated an international larch provenance study in 1940 (Genys 1960). Seedlots of 55 provenances, including 51 of European larch, 2 of Siberian larch, 1 of Japanese larch, and 1 that originated from spontaneous European and Japanese larch hybrids, were distributed to 11 different countries in Europe and North America. European provenance trials containing European larch indicate that there are significant differences between four isolated geographical regions (Alpen, Sudeten, Tatra and Polen) of this larch, and significant differences within the Alpen region (McComb 1955). Provenance trials of European larch in the United States have shown similar results: the Sudeten provenance grows the fastest and the Alpine provenance the slowest (Giertych 1979). Results from trials in Canada at the Petawawa National Forestry Institute (PNFI) further substantiate the European and American findings, and also indicate that Sudetan sources that have gone through at least one generation of selection and improvement in Denmark are even better than material from the original source (Calvert and Rauter 1978).

Japanese larch has a limited range in central Japan, where the rugged topography has lead to the development of distinct populations through geographic isolation. Interest in Japanese larch increased greatly after World War II, and in 1955, a worldwide program of provenance studies was initiated, which included tests in Canada and the United States (Toda and Mikami 1976). These and additional provenance studies in New York (Stairs 1966), Maryland (Genys 1972), Wisconsin (Lester 1964), Michigan (Lee 1976), Minnesota (Pauley et al. 1965) and the Midwest (Farnsworth et al. 1972) in the United States and in New Brunswick (Park and Fowler 1983) in Canada have indicated that provenance variation in this species is not geographically related, but is instead random. Thus, the growth behavior of a provenance in one area will not necessarily be the same under different conditions (Wright 1962).

Studies of the variation of tamarack in North America have been undertaken, and have indicated that individuals are highly variable (Rehfeldt 1970). In contrast to both European and Japanese larch, tamarack has a more or less continuous transcontinental distribution from Newfoundland to Alaska. Genetic variation across the range of the species is expected to be clinal, with gradual changes occurring along environmental gradients (Rauter and Graham 1983). A range-wide provenance study of tamarack was initiated in 1977 in Canada at PNFI, although difficulties in obtaining adequate supplies of seed slowed implementation of the trial (Murray 1982).

Breeding

Breeding work has been carried out for a considerable time for *Larix*, especially in the European and Japanese larch species. A great deal of the early breeding work was done in Denmark by Syrach-Larsen (1934) in the early 1930s on these and other larch species. Much of this work concentrated on self-pollination as a means of inbreeding to evaluate selected trees by studying the variation within families and the eventual emergence of deleterious genes (Syrach-Larsen 1956). Inbreeding and outcrossing work with these two larches and with the hybrid *L. eurolepis* was continued by Keiding (1967) to select vigorous individuals for the purpose of establishing seed orchards.

Interspecific hybridization of *Larix* has been carried out with many species in an attempt to obtain genetic improvement of the resulting hybrids. Many known larch hybrids are valuable because they combine desirable characteristics of both parents and they also exhibit hybrid vigor (MacGillivray 1969). Thus, the greatest genetic improvement in larch will probably occur through hybridization (MacGillivray 1969, Jeffers and Isebrands 1974).

Because of the close relationship of many larches, all natural crosses that have occurred between species in the wild and under cultivation have been repeated by artificial pollination, with the possible exception of crosses between Chinese larch and Master's larch (MacGillivray 1969). Japanese larch has been very widely used in interspecific hybridization. Hybrids from natural or controlled pollination have been made with Japanese larch and *L. decidua*, *L. gmelini*, *L. gmelini* var. *japonica*, *L. gmelini* var. *olgensis*, *L. gmelini* var. *principis rupprechtii*, *L. occidentalis*, *L. sibirica* and *L. laricina* (Dimpflmuir 1959, Fairbairn 1959, Schoenike 1961, MacGillivray 1967, Wang 1971). All interspecies crosses made within the section *Pauciseriales* have been successful (Wang 1971), but the cross between *L. decidua* (section *Pauciseriales*) and *L. occidentalis* (section *Multiseriales*) produced only one triploid hybrid (Syrach-Larsen and Westergaard 1938). Artificial crosses have also been made between European larch and Dahurian larch (Al'benski 1940), European larch and Western larch (Wright 1962), European larch and Siberian larch (Syrach-Larsen 1956, Fowler et al. 1973), European larch and tamarack, tamarack and Siberian larch, and a cross of tamarack and Japanese larch with European larch (Fowler et al. 1973).

The best known larch hybrid is the "Dunkeld" larch, which is the result of a cross between Japanese larch and European larch. The cross has been given the scientific name of *L.* x *eurolepis*. The parents of this very vigorous hybrid were Japanese larches from the estate of the Duke of Atholl at Dunkeld, Scotland. These Japanese larches were established from seed brought from Japan in approximately 1883 or 1884 (Chittenden 1932), sown in 1884 and outplanted in 1887 (Brown 1899). Hybrid seed was first produced when European larch growing close to the Japanese larches frequently cross-pollinated them (Edwards 1956). The first artificial controlled crossings between these larches were undertaken by Leven in 1924 and 1925 (Syrach-Larsen 1956).

Improvement Programs

In both Canada and the United States, tree improvement work on several *Larix* species has recently been initiated, since it has become apparent that this genus has potential for genetic improvement and subsequent management under short rotations (Schreiner 1970).

In northeastern North America, European larch, Japanese larch, their hybrids and tamarack are being included in several breeding programs. In New York State, five clonal seed orchards of Japanese larch have been established since 1966, and the International Paper Company in Maine has planted a 2.5-ha orchard. Additional clonal seed orchards will probably be established in the northeast with trees selected from plantations and provenance trials (Carter and Simpson 1985). In New Brunswick, phenotypically desirable Japanese larch trees have been selected from a provenance trial, grafted, and planted in a seed orchard (Fowler 1975). These clones are undergoing progeny testing to identify superior clones.

Because European larch exhibits widespread geographic variation in growth rate, stem form, and disease resistance (Baldwin 1966), seed source plays an important role in tree-improvement programs for this species. Provenance tests in Canada and the United States have shown that the most promising sources are from southern Poland and northern Czechoslovakia. There is presently no breeding program for European larch in the northeast, but seed should be obtained from the previously mentioned provenances for reforestation (Carter and Simpson 1985).

At the Maritimes Forest Research Centre in New Brunswick, larch improvement work has been carried out to select superior hybrids. Hybrid Japanese x European larch have been produced and tested on a limited scale, although no steps have been taken for their mass production at this point (Fowler 1975). One of the most promising hybrids so far is the (*L. laricina* x *L. leptolepis*) x *L. decidua* cross.

Tamarack improvement programs that emphasize extensive plus-tree selection followed by grafting and seed-orchard establishment are also in place in Maine and eastern Canada. The New Brunswick Tree Improvement Council (NBTIC) has developed a breeding strategy for tamarack (Simpson 1983).

In Quebec, genetic-improvement programs have been undertaken on Japanese larch and European larch, and clonal seed orchards have been established from trees selected from the best provenances of these species (Stipanic 1975). Controlled crosses between both species are planned to develop more productive hybrids under local climatic conditions (Vallee and Stipanic 1983). Because of the lack of stability of cold hardiness in the Japanese larch provenances tested, genetic improvement of this species has been initiated by the creation of multi-provenance orchards established in three regions of southern Quebec.

In Ontario, early tree-improvement work began at PNFI, concentrating on European larch, with a minor interest in Japanese larch. Recent 20-year measurements indicate that only seed from proven sources should be used in establishing plantations of exotic larch in Ontario (Calvert and Rauter 1978). Japanese larch seed-production areas were established in 1979 with the objective of producing seed after selection for hardiness, freedom from pests, growth rate, and stem and crown form (Murray 1982). Scions from superior phenotypes of European larch selected in PNFI plantations were provided for inclusion in Japanese x European hybrid larch seed orchards that have been established in Quebec and by OMNR in southeastern Ontario. Scions from these and other selected trees have been grafted at PNFI for future use in breeding work.

In the north-central Lake States, experimental plantings comparing different larch species have been established throughout the region by the U.S. Forest Service (Jeffers and Isebrands 1974). Testing of the Japanese x European hybrid is one of the highest priorities to determine which seed sources should be used. Applied breeding programs to achieve even greater improvements have been recommended. Individual-tree selection, on the basis of outstanding height and diameter growth coupled with physiological and biological criteria from the most promising, best-adapted seed sources, has been suggested for the development of seed orchards. Physiological criteria could include photosynthetic efficiency, as determined by branch habit, leaf display, and leaf area, as well as by utilization of the growing season. Biological criteria could include extractive content, an important factor in larch utilization.

A program of genetic improvement of larch was recently established at the Institute of Paper Chemistry in Wisconsin (Einspahr et al. 1984). The objectives of this program are to provide a reliable source of high-quality larch and hybrid-larch seed through the use of a seed-orchard approach similar to that used for southern pines (Kellison and Sprague 1981). This program may result in first-generation gains of 10 to 15% in volume growth, with similar gains for second-generation seed orchards; 20-year-old plantations produced from second-generation seed sources may produce average growth of 180 to 220 ft^3/ac (126 - 134 m^3/ha) annually on good sites.

Growth and Yield of Exotic Larch

The larches and some of their hybrids have produced large quantities of fiber and timber in many parts of the world, including North America (Cook 1969, Schreiner 1970, Jeffers and Isebrands 1974). These species have tremendous juvenile growth, they can outcompete many other coniferous species, and the various larch species together cover a wide range of sites (Cook 1969). Because of their rapid growth and yields, it seems that many larches and larch hybrids could provide a good alternative source of coniferous fiber through management under short-rotation systems.

European larch was introduced to the United States in the mid-19th century, and from 1860 to 1880 it was one of the most popular plantation species in the northern Midwest States (Hunt 1932). Planting of this larch began in New York and Pennsylvania in the early 20th century. European larch was recommended for planting in

Ontario as early as 1880 (Phipps 1885). The enthusiasm for planting this species was initially based on good reports of its performance by Europe and the United States. Later, evidence of good hardiness and growth rates in Ontario was provided by several ornamental plantings, by the first recorded plantations at the Ontario Agricultural college in Guelph in 1880, and by plantations at the Central Experimental Farm in Ottawa in 1888 (Anon. 1880, Zavitz 1907). European larch was subsequently grown in provincial tree nurseries in Ontario and planted to a small extent thereafter, mainly on dry sites and in mixtures with pine or spruce as a means of managing the Larch sawfly (Richardson 1924, Hunt 1932).

Planting of Japanese larch in both Europe and North America is relatively recent (Stone 1957) and this species was not used for forestry much before 1900 (Cook 1969). The first introductions to Canada went to PNFI in 1926 (Holst 1974). Plantings of Japanese larch in New York and Pennsylvania began in the 1930s, where it soon became preferred to the European larch because of its good health, wider site ability and greater reliability (Cook 1969). It is now considered to be the fastest growing of the larches (Littlefield and Eliason 1956, Schober 1958, Eliason and Carlson 1963, Stairs 1965, McGillivray 1969), although significant differences in growth exist among provenances.

The earliest planting of Dunkeld hybrid larch was at PNFI, where it was planted along with imported Japanese larch in 1920 (Holst 1974). Dunkeld larch did not come to New York until 1933. All imported lots of hybrid-larch seed produced plantations of superior quality in New York (Cook 1969). It was observed that the hybrid tended to combine the best characteristics of each parent—straightness of stem and sometimes light branching from the European larch, and vigorous growth, abundant, early flowering, and relative freedom from pests from the Japanese larch.

The majority of the early exotic larch plantations in the U.S. were established in New York (Cook 1969), Pennsylvania (Grisez 1968), New Hampshire (Baldwin 1958), and several other northeastern states (Hunt 1932, Genys 1960). The survival of these early plantings was variable; however, those that did survive possessed good form and growth, and encountered few insect and disease problems. Diameters of 41 cm at breast height and heights of 30 m were common at 50 years (Einspahr et al. 1984). Instances of poor survival were attributed to poor stock-handling techniques and a lack of control of competing vegetation.

Provenance trials and demonstration plantations of European larch and Japanese larch were established in great numbers in the northeastern United States and throughout the Lake States. The results of these trials confirmed earlier observations of exceptional growth and form (McComb 1955, Genys 1960, Kepler and Gatherum 1964, Gatherum 1966, Farnsworth et al. 1972, Barnes 1977). Reports of height growth of more than 7 m in 11 years in Michigan were given by Barnes (1977) for one good source of European larch from Germany. In northern Wisconsin, 14 selected trees representing five provenances averaged 15 m in height and 20 cm DBH at 25 years from seed (Jeffers and Isebrands 1974). On a productive site in southwestern Wisconsin, a 19-year-old plantation of European larch outproduced both red and white pine in height, diameter and volume; it was 16.5 m in height, 7 cm DBH, and produced 189 m^3/ha by that age (Erdmann 1966). Similarly, European larch was taller than any other species planted in western Iowa plots by 12 years of age. In Maine, 27-year-old European larch grew an average of 62 cm per year, whereas white pine and white spruce grew only 43 cm per year over the same period (Young 1957).

Japanese larch at age 24 years in a Minnesota test had grown faster than native conifers of a similar age (Schantz-Hansen and Hall 1952). However, tamarack, red pine, jack pine, white pine and white spruce had all surpassed the larch by age 45 (Alm et al. 1972), another observation in favor of growing larch under short rotations.

In Vermont, a trial planting of Japanese larch developed so rapidly that most of the trees had reached the minimum merchantable size for pulpwood and sawlogs by 18 years (Adams and Hutchison 1961); the trees averaged 14 m in height and 19 cm DBH.

Growth of exotic larches, including European and Japanese larches, their hybrids, and Siberian and Dahurian larches, was studied by Genys (1968). He found that average heights ranged from 53.3 cm to 1.27 m by the fifth year from seed. All sources of Japanese larches grew somewhat faster than the European larches, but both exhibited provenance variation. The Japanese larches all grew late into the fall and formed terminal buds later than the other larches studied. The faster-growing sources of European larch also set bud later in the fall than the slower-growing sources. Hybrid larch grew rapidly, but not quite as quickly as the best source of Japanese larch. Hybrids were intermediate between parent species in the time that they set bud. Siberian and Dahurian larches grew slowly, and were only 69 to 84 cm in height at age 5 years. Both of these species set terminal buds earlier than other species.

In a more recent study of the growth of exotic larches, Carter and Canavera (1981) found that the average survival and growth of a number of sources of Japanese, European, hybrid and Siberian larch ranged from good to outstanding at three locations in Maine. The hybrids grew fastest in central Maine, averaging 1.09 m in 3 years. Siberian larch was shortest at this location, and European and Japanese larch were intermediate in height. In northern Maine, Siberian larch was the tallest species (73.5 cm average height) and Japanese larch was shortest (58.6 cm average height) after the same time. The Japanese and hybrid larches were more affected by frost than were the European or Siberian larches, which probably accounted for their lower survival and growth rates in the more northerly conditions.

A study of the performance of a number of sources of tamarack, Siberian larch, European larch, Japanese larch, and the hybrids of European larch and Japanese larch in north-central Wisconsin indicated that hybrids were the tallest after 8 years from seed (Riemenschneider and Nienstaedt 1983). The tallest sources reached 4.69 m by this age. These results substantiate other reports of superiority of the first-generation hybrid between the two larches. The hybrids exceeded the European larch mean height by 12% and tamarack by 23%, small increases in comparison with those in other reports. This result may indicate that better parent breeding stock might improve the performance of the hybrid in this area. The Japanese larch ranked lower in height than all other species by the end of the 8-year period, reaching only 3.7 m. Siberian larch had the lowest 5-year height, but by the eighth year, it ranked second only to the European x Japanese hybrid (at 4.31 m), which may indicate that a percentage of natural Siberian x European larch hybrid was in the seedlot.

In Canada, the 1926 plantings of Japanese larch and Dunkeld hybrid larch are presently the oldest demonstrations of the superiority of the hybrid to the mother species. At 43 years, the mean height of the hybrid was 19.9 m, whereas that of the Japanese larch was only 15 m. Diameters were 37 and 32 cm respectively, and all differences were significant (Holst 1974). Between 1950 and 1975, more than 20 trials were established by Mark Holst at PNFI, and many more were established with cooperators throughout eastern Canada and the United States (Calvert and Rauter 1978). Most species and varieties were incorporated in the tests, including European and Japanese larches and their hybrid, Siberian and western larches, several varieties of Dahurian larch, hybrids of Siberian and European larches, several varieties of Dahurian larch, hybrids of Siberian and European larches, and tamarack. Recent 20-year measurements indicated that height growth of seedlots varied from 72 to 113% of the plantation mean, indicating the importance of selecting the proper seed source for planting. OMNR has planted a number of exotic larch trials in various locations in Ontario over the years; however, these are not well documented and most seed origins are unknown (Calvert and Rauter 1978).

In the Maritimes, work on larches began with various introductions in the 1950s, with the intention that larches could play an important role in Canadian reforestation (MacGillivray 1969). Work continued up to the 1970s (Fowler et al. 1973). Early growth of all provenances of Japanese and European larches as well as of tamarack greatly exceeded that of Norway spruce (*Picea abies*), white spruce (*P. glauca*) and red spruce (*P. rubens*) (MacGillivray 1969). A study in New Brunswick comparing various provenances of Japanese and European larches as well as tamarack showed that Japanese larch was superior in height and diameter growth by age 12, and increased its superiority by age 19 (Park and Fowler 1983). Tamarack had an early height advantage over the other species, but this diminished after age 8. European larch was the slowest growing species in height, but exceeded tamarack in diameter after age 8. The average height and diameter achieved by Japanese larch provenances at age 19 were 12.17 m and 16.53 cm, respectively. For European larch and tamarack, heights were 8.65 and 10.18 m, and diameters at breast height were 14.32 and 12.91 cm, respectively.

Systematic testing of a number of larches began in Newfoundland in 1967 (Hall 1973). In most of the experiments, the exotic larches grew faster than native black spruce (Hall 1977). These encouraging results led to the establishment of a species trial of various exotic larches and tamarack (Hall 1982). Growth of hybrid larch on this productive trial site was significantly better than that of tamarack after 10 years, when the two tested hybrid larch seedlots had reached heights of 1.96 and 2.21 m, respectively. Growth of Japanese larch was greater than that of tamarack after 8 years, but the differences were not significant. The tamarack was slightly taller by the 10th year, and appeared to be gradually outgrowing the Japanese larch: the tamarack had reached a height of 1.7 m, whereas the Japanese larch was only 1.71 m tall. In contrast, on a lower elevation site, tamarack reached a height of 2.18 m at the same age, but was outproduced by the Japanese larch there (Hall 1973). Growth of Japanese larch and tamarack was also greater than that of all other species, including black, white, Norway, and Sitka (*Picea sitchensis*) spruces, and jack pine (*Pinus banksiana*) and Scots pine (*Pinus sylvestris*), on a less productive site (Hall 1983). These results indicate that there is considerable potential for the exotic larches as well as tamarack for reforestation in Newfoundland. However, the author recommended field testing be done on a variety of sites before ultimately drawing conclusions about the suitability of exotics for reforestation.

In Quebec, studies of larch species have shown that they have spectacular growth during their first 20 years, which suggests that they should be managed under rotations of less than 30 years (Vallee and Stipanic 1983). In southern Quebec, European and Japanese larches and their hybrid survive and grow best on sites of medium moisture. Popovich and Houle (1970) reported a total annual production of 12.4 m^3/ha and a height of 19 m for a sample 28-year-old larch plantation on a site with a medium moisture regime near Drummondville, Quebec. This rate of production was greater than that achieved by white spruce or red pine (*Pinus resinosa*) on the same site, which attained only 6.6 and 6.4 m^3/ha, respectively, at the same age. However, on a much wetter site, productivity of only 5.6 m^3/ha and a height of only 14 m were attained by the larch. A study by Bolghari and Bertrand (cited by Vallee and Stipanic 1983) indicated that European and Japanese larches in Quebec could produce from 10 to 14 m^3/ha annually on high-quality sites. Total production was 100 to 200 m^3/ha for 2.4- and 1.5-m spacings and the mean DBH of the trees at the 2.4-m spacing was above the sawlog limit of 20 cm after 30 years of age. Wilson (1968) found that a 10-year-old Japanese larch plantation at the Canadian International Paper forest farm near Harrington, Quebec produced five times more wood than white spruce of the same age; in this plantation, 36 m^3/ha of pulpwood was produced by the larch. Paille and Bitto (1979) reported that the same plantation at 22 years of age had a mean annual increment of 8.9 m^3/ha, and that the trees had a mean height of 18.3 m and a mean DBH of 18.5 cm.

From the results of these studies in Quebec, Vallee and Stipanic (1983) have concluded that *Larix* species are the most productive of the conifers in Quebec, perhaps in Canada, for rotations of less than 30 years.

Larch Utilization

The interest in larch developed in North America because of the rapid growth and genetic potential of the species that have been planted. However, the question of wood quality and potential utilization of the genus has arisen.

There has generally been little interest in the use of larch in North America, although many larch species have been used extensively in other parts of the world. Larch wood, particularly that of the European ·and Japanese species, is highly regarded in Europe and the species is often referred to as the "European Douglas fir", since good logs from properly managed stands command the highest prices (Pneumaticos and Lucas 1979). The wood is primarily used for construction lumber, posts, poles, furniture and panelling. In Finland, Siberian larch is used for many valuable products such as timber, props, poles, piles and log cabins, and in the Soviet Union it is even used for demanding applications in interior decoration and furniture manufacture (Hakkila et al. 1972). The excellent resistance of larch to decay has led to a particular recommendation of this genus for structures exposed to changes in humidity (Hakkila 1961). The greatest use for larch in North America has been for general construction purposes in the form of dimension lumber, small timbers, planks and boards, as well as for some finish products from the higher-grade materials (Balatinecz 1983). Tamarack has been used for some of these purposes, but western larch is more highly regarded for finish applications.

Larch wood has also been used for pulp in many countries, especially in northern Europe and Russia (Kubes and Swan 1974, Isebrands and Hunt 1975), although it has not been used for this purpose on a large scale in North America because of the belief that it gives lower pulp yields with poorer properties than do most other conifers (Jeffers and Isebrands 1974, Isebrands and Hunt 1975). The wood of larch has a moderately high specific gravity and moderately long tracheids (Balatinecz 1983). All species of larch have higher densities than any Canadian conifer (Panshin and de Zeeuw 1970) and thus, fiber production per unit volume is also greater for larch wood. The fiber lengths of mature Japanese and European larches have been reported to be similar to those of pine and spruce (Einspahr et al. 1984).

When lower pulp yields occur in larch, it is primarily because of the large quantities of resin and water-soluble extractives (arabinogalactans) present in larch heartwood. These substances interfere with cooking in the sulfite process and bleaching in the kraft process (Leatheart 1969, Nevalainen and Hosia 1969). In spite of their high solubles content, several larch species studied in North America, including Siberian larch, alpine larch, and tamarack, have given at least as good a pulp yield per unit volume as other softwoods because of the higher densities of the larch (Wells and Rue 1927). Although the high extractive levels create some difficulties with the pulping process, many reports of larch pulping in the literature have been made for either slow-grown or old-growth trees 50 to 80 years old (Hakkila and Winter 1973, Einspahr et al. 1984). Trees grown under either of these conditions have a greater heartwood content than that of younger trees, which accentuates the resin and extractive problems. In addition, in many of these studies, the wood has been pulped by the sulfite process, which has been shown to be inefficient for pulping larch (Nevalainen and Hosia 1969). Research has shown that the kraft pulping process is more suitable for larch, and that larch wood can be readily converted into an excellent kraft pulp (Perry and Cook 1965). Cook (1947) observed that the kraft pulp yield of European larch was only slightly less than that of spruce, and that the larch pulp was comparable to spruce pulp in strength properties. Cook believed that yields could be increased by adjusting the cooking schedules to fit the specific requirements of larch. Zaitseva et al. (1958) demonstrated that larch pulp yields could be increased by increasing the sulfidity in the kraft process without detracting from other pulping properties. It has been observed that larch kraft pulps often resemble southern pine kraft pulps and that larch pulps are suitable for paper and boards that require superior tear properties (Nevalainen and Hosia 1969, Hakkila et al. 1972). The tear factors of pulps made from Siberian and alpine larches as well as from tamarack have been compared with those of other conifers and the larch pulps have always shown superior tear strength; however, burst and tensile values were lower (Nevalainen and Hosia 1969, Hansmann and Sugden 1983).

In North America, studies of the wood of younger trees of several larch species and hybrids have indicated that juvenile wood may not have the utilization problems associated with older wood. Young larch wood consists mainly of sapwood, which is lower in both resin and extractive content than mature wood, thus making the juvenile wood easier to pulp (Uprichard 1963, Hakkila et al. 1972). Isebrands and Hunt (1975) found that 10-year-old rapid-grown juvenile Japanese larch had low extractive levels throughout the trees, which had been grown with thorough weed control as well as regular fertilization and irrigation. Hillis (1971) believes that such intensive silvicultural practices may prolong the juvenile period, thus delaying heartwood formation and decreasing the content of extractives. Klemm (1967) concluded that fertilization of several conifers decreased extractive content because it increased the amount of sapwood produced, and it also increased the uniformity of the wood produced. Isebrands and Hunt (1975) observed that fertilization of short-rotation Japanese larch over several growing seasons tended to decrease specific gravity within entire tree rings, since the latewood content of each ring is decreased. At the same time, uniformity within annual rings was increased, as was observed by Klemm (1967). Because uniform wood properties within tree rings improve the efficiency of processing raw material, the corresponding increase in wood uniformity, along with increased volume production, outweigh the decline in specific gravity that results from fertilization. In addition, some larch individuals maintain a high specific gravity during rapid growth by producing dense springwood (Pearson and Fielding 1961).

Although bark percentages are generally lower in mature plantations, Isebrands and Hunt (1975) found that SRIC Japanese larch had a low proportion of bark for its age, which they believed was attributable to intensive management practices including fertilization and irrigation. In this study, bark percentages ranged from 14 to 21.3% of total tree weight, depending upon position in the tree. Studies of bark content in mature wood of other larch species show average contents of 12 to 14%. Hakkila et al. (1972) reported 12.3% (by weight) bark content in 50-year-old Japanese larch. However, Nevalainen and Hosia (1969) found that the bark content ranged as high as 19% (volume basis) for 31-year-old Siberian larch. It appears that intensive management of short-rotation larch may decrease bark percentages in comparison with trees that are not managed intensively. Further research on bark components of larch is recommended (Isebrands and Hunt 1975).

Packman (1966) found that, although young Japanese larch wood has low specific gravity, shorter tracheid length, and a higher lignin content than mature larch wood, it contains less extractives and requires less bleaching to attain the desired brightness and also compares favorably in physical pulp properties with other species. Isebrands et al. (1982) showed that wood chips from whole-tree, SRIC juvenile (8-year-old) hybrid larch from plantations growing in Wisconsin can be successfully mixed with mill-run debarked jack pine chips at up to 25% of the total mix without significantly affecting pulp yield or strength. In a study of pulpwood-size 18- to 24-year-old European, Japanese and hybrid larch trees growing in the Lake States, the trees had less heartwood, lower specific gravity, shorter fibers, and about 50% less extractives than 50-year-old larch (Einspahr et al. 1983). When these trees were pulped and compared with pulped 50- to 60-year-old jack pine, the larch had greater amounts of heartwood, similar levels of lignin and alcohol-benzene extractives, higher amounts of hot-water extractives, and shorter fiber lengths. When pulped at similar rates, the larch pulp yields ranged from 1 to 4% greater than those of jack pine, and the pulp had similar strength in terms of burst factor, tear factor and breaking strength.

Tree Improvement

Tree improvement can play an important role in the pulping characteristics of larch. Variation has been observed in several important wood-quality characteristics of the larches. Many wood properties are under strong genetic control and possess moderate to high heritabilities (Smith 1967, van Buijtenen 1969, Zobel 1970, Shelbourne and Stonecypher 1971, Kellison 1976, Zobel et al. 1978). Sachsse et al. (1978) reported significant differences among 22 Japanese larch clones in the percentage of heartwood, percentage of latewood, resin content, ring width, tracheid length, toughness and modulus of rupture. Mikami et al. (1972) found significant differences among 80 clones of Japanese larch in the amount of spiral grain and made gross heritability estimates of 0.35 to 0.42 for grain inclination in each annual ring and of 0.49 for maximum grain inclination. Lee (1976) found significant differences in wood specific gravity among 22 seedlots of Japanese larch growing in southwestern lower Michigan, although no significant variation in tracheid length was evident among the same seedlots. Further research on other species and hybrids of larch is necessary to determine the potential for wood characteristics to be used as traits for selection and breeding to improve wood quality.

Vegetative Propagation

Vegetative propagation is particularly applicable to *Larix* species because of frequent limitations of their seed supply. The rooting of cuttings is presently the most common method of vegetative propagation for larch, and therefore this review will concentrate on this method.

Larix species have generally been considered more difficult than other species to root from cuttings (Wright 1976). For larch, the rooting of twigs and branches is not a normal reproductive process, as it is in *Populus*. Most species of *Larix* do not have preformed root primordia in their stems, so roots must instead be induced from tissues that would normally not root, and root initiation may be tissue-specific (Libby 1974). For example, root initiation may occur quite easily in root tissue, since that is where new roots are needed, but it does not occur readily in stem tissue, which would not normally form roots. The presence of root inhibitors, which override the rooting process in stems, has also been discovered; in stems, it would be wasteful to initiate roots.

Recorded attempts to root larch date back as far as 1908, when Kurdiani (1908) rooted European larch by placing softwood cuttings in sand in a cold frame. Frames were then covered with glass sashes and painted with lime for shading. The frames were shaded during the day and covered at night. Cuttings were watered daily, and after 2 to 3 months, 56 to 75% rooting was obtained. The author concluded that cuttings of European larch rooted more easily than pine cuttings. Since that time, the successful rooting of cuttings of several larch species has been achieved. However, rooting success has varied depending on a number of factors, including species, provenance or clone, age of the ortet, position of the cutting within the donor plant, time of cutting collection, application of rooting stimulants and various edaphic and environmental factors.

Species, Provenance and Clone

A comprehensive series of experiments was initiated at the Boyce Thompson Institute in 1948 in an attempt to find a suitable method for rooting softwood cuttings of *L. laricina, L. decidua, L. leptolepis, L. gmelini* and hybrid larch (*L. eurolepis*) (Chandler 1959). During the course of these experiments, a technique for successful rooting in a mist chamber was developed. In these studies, it was found that clonal variation existed in the rootability of *L. leptolepis* (1 to 20% rooting) and *L. eurolepis* (1 to 22% rooting). In a later set of experiments, Chandler (1967) found differences in rooting success among a number of larch species. For a consecutive 3-year period, the mean rooting success was 80% for Dahurian larch, 53% for hybrid larch, 48% for Japanese larch, 21% for European larch, 32% for tamarack, 6% for western larch, and 6% for Dahurian larch var. *olgensis*. Cook and Frommer (1969) found variation in survival percentages among four different hybrid larch clones rooted by means of Chandler's (1959) misting technique. Okada (1967) found large differences in the rooting ability of 10-year-old Japanese larch that were related to the clone used. Wunder (1974) observed that the rooting capacity and readiness of Japanese larch cuttings from seven geographical locations were related to provenance. Provenances that grew fastest in previous studies and that showed low susceptibility to both drought and excessive soil moisture (i.e., which therefore had a wide ecological spectrum) had the highest rooting success as cuttings. Several recent studies of the rooting of tamarack cuttings have shown significant differences in rooting success among clones (Carter 1984, Morgenstern et al. 1984, Farmer et al. 1986).

Age of Donor Plant

The age of the donor plant appears to be related to the ability of the cuttings to produce roots. Cuttings from juvenile plants generally have higher rooting percentages than those from mature plants. A number of studies with a variety of larch species have substantiated this conclusion. High rates of rooting of cuttings taken from 1-year-old juvenile seedlings of several larch species were reported by Fung (1978). Komissarov (1938) found that for untreated cuttings of Siberian larch, 20 to 30% rooting was obtained for 3-year-old cuttings, and only 10% rooting was achieved for 10-year-old trees. In Chandler's (1959) preliminary series of rooting experiments, cuttings from 2- to 4-year-old larch rooted best (32 to 38%) and cuttings from 27- to 30-year-old stock had the least rooting (7%). Chandler's (1967) later report confirmed these earlier findings. Cuttings from various species of larch that were 29 to 32 years old gave an average of 1% rooting, where as those from trees 9 to 12 years old gave 41% rooting. Thus, the author recommended that cuttings be taken before trees were 13 years old. Staubach (1983) achieved up to 42.5% rooting of western larch with 2-year-old donor plants, depending upon other treatments, but only 1.5 and 0.5% rooting of 10- and 20-year-old donors. No cuttings from 50-year-old donors rooted with any of several applied treatments. John (1977), for 1- to 17-year-old hybrid larch, Morgenstern et al. (1984), for 3- to 6-year-old tamarack, and Pottinger and Morgenstern (1986), for 3- to 10-year-old tamarack, all found that rooting decreased as the age of the donor plant increased. In contrast, Carter (1984) found that rooting success was not correlated with ortet age for tamarack ranging from 19 to 40 years old. In this study, rooting success ranged from 23 to 93%, with the youngest and oldest trees having relatively similar rooting percentages (81 and 89%, respectively). Carter suggested that perhaps age differences within this range of ages need not be a limiting factor in the selection of tamarack for propagation.

The advantage of rooting older material is that selected superior trees can be directly rooted and reproduced, since it is generally better to select trees for superior characteristics when they are beyond the juvenile phase. In addition, leafy cuttings taken from trees older than 10 years are larger, easier to handle, more robust, and produce more roots than cuttings from younger trees (John 1977). However, one of the major problems with rooting older material, if rooting can be achieved, is that plagiotropic growth ("side branching" of the rooted cuttings) tends to occur. Cook and Frommer (1969) found that 2 years after 12- to 13-year-old hybrid larch cuttings had been rooted, they showed some degree of topophysis, although by the fourth growing season, many of the trees were straightening up. John (1979) stated that rooted cuttings of hybrid larch are particularly prone to cyclophysis and topophysis, and cuttings from mature plants remain plagiotropic. Orthotropic growth can only be achieved readily if stock plants are under 4 years old.

Position of Cutting on Donor Plant

It has been observed that the closer a shoot apical meristem is to the base of a tree, the more juvenile it is (Olesen 1978, Bonga 1982). Consequently, cuttings taken from the lower branches in a tree's crown tend to root more easily than those from the upper crown. In contrast to this generalization, Chandler (1967) found no apparent effects as a result of crown position in a number of species of 7- to 9-year-old larch. However, the terminal portions of the current terminal shoots tended to root better than the basal portions. This same result was observed in Chandler's (1959) earlier experiments. In contrast, Wunder (1974) found no significant differences in the rooting percentages of basal and top cuttings of 5-year-old Japanese larch taken from 1-year-old twigs, although the top cuttings developed slightly higher root volumes. Komissarov (1964) found that well developed shoots of Siberian larch from the first order of branching rooted better than cuttings from weak shoots of the second-order branching. Komissarov stated that these differences among lignified cuttings of different orders of branching may depend on the speed with which their buds open. Fung (1978) found that terminal and lateral shoots of 1-year-old tamarack, Japanese larch, European larch and Siberian larch rooted easily and rapidly under a properly controlled rooting environment within a greenhouse. Although Staubach (1983) attempted to compare rooting success rates of western larch cuttings collected from the upper third and lower third of the crowns of 50-year-old trees, the number of cuttings that rooted were too small to draw any conclusions. Pottinger and Morgenstern (1986) compared the rooting of tamarack cuttings taken from the upper and lower crowns, and found no significant differences, although cuttings from the lower crown did have slightly higher rooting success (68%) than those from the upper crown (60%). In addition, these authors compared rooting survival, as well as height growth and degree of plagiotropism measured after 1 year in the nursery, between the cuttings taken from the two crown positions. Once again, there were no significant differences, although survival and height were slightly greater and plagiotropic growth was slightly lower in cuttings from the lower part of the crown.

Time of Cutting Collection

The time of cutting collection appears to influence rooting success in *Larix*. Generally, softwood cuttings taken during the growing season have been the most common type of cutting used for rooting larch (Chandler 1959, 1967; John 1977, 1979; Carter 1984; Morgenstern et al. 1984; Farmer et al. 1986; Pottinger and Morgenstern 1986). However, variation in rooting success has been observed when cuttings have been taken at different times during the growing season.

Chandler (1959, 1967) observed that, for all species of larch investigated, cuttings taken later in the growing season rooted better than those taken early in the season. In his earlier study, Chandler (1959) found that cuttings taken in August and September from hybrid larch, European larch, Japanese larch, and Dahurian larch rooted better than cuttings taken in May and June. Those taken in May, however, rooted better than those taken in June. The higher percentages of rooting obtained in August and September were, however, due in part to the material, some of which was from younger trees. In another of these experiments, cuttings taken in August rooted better than those taken in September. Chandler (1967) later reported that further experiments with Dahurian larch, European larch, Japanese larch, tamarack, western larch, Dahurian larch var. *olgensis*, and hybrid larch showed average rooting success of 44, 22 and 36% for cuttings taken in June, July and August, respectively, whereas those taken earlier than June or later than August either completely failed to root or only achieved 1 to 5% rooting.

Morgenstern et al. (1984) and Pottinger and Morgenstern (1986) investigated the effect of collection time on rooting of softwood tamarack cuttings. In both studies, cuttings were collected at various times between May and August. Morgenstern et al. (1984) found that the effects of rooting date were strong and significant. Cuttings rooted in mid-July had the highest rooting success, the largest percentage of cuttings with major roots, and the longest roots. All cuttings rooted between May and August required 3 months to root. This required rooting period creates problems with rooting of cuttings collected at the observed optimum time (in July), since they cannot be assessed until late October, at which time it is too late to transplant them outside. As a result, the cuttings must be overwintered in heated greenhouses, an expensive operation. Because of this, an earlier collection time (in May) was suggested, since cuttings taken at that time showed acceptable rooting percentages, formation of major roots, and root lengths. Pottinger and Morgenstern (1986) investigated the effect of collecting cuttings at different times in May. They found that differences in rooting success were not significant when cuttings were taken either at the beginning or the middle of May, possibly reflecting the similarity of the trees' physiological states at these times.

Komissarov (1964) stated that one should not be guided by calendar dates in the propagation of plants by cuttings, since the beginning of the growing season as well as the rate of shoot growth and development in the same plant may vary considerably in different years, depending upon the weather. Instead, Komissarov defined the best time for the rooting of softwood Siberian larch cuttings in terms of morphology and physiology: shoots can be considered ready for propagation when they are light green in their upper part and yellowish at the base, with lateral buds (light green in the upper part and brownish and larger in the lower part) developed along the entire shoot. As well, the shoot becomes straight along its entire length. The needles at the top begin to diverge from the shoot axis, and the apical bud is clearly visible. Wunder (1974) used the same approach for Japanese larch cuttings. He removed cuttings from the parent plant in such a way that the optimum time of removal could be determined. A series of cuttings was taken from 1-year-old twigs when the buds had fully opened. Several other series of cuttings were taken from 1-year-old twigs until the newly developing shoots had reached a length of 12 to 15 cm. Three sets of cuttings were also taken from these new shoots. The first set was taken when the new shoots showed no signs of lignification at the base, the second when the base began to lignify, and the third when the base had fully lignified. The results indicate that, for cuttings from 1-year-old twigs, the optimum time of removal is when the new shoots are about 5 cm long. The optimum time for removing current-year cuttings is when the base of the cuttings starts to show the first signs of lignification.

Several authors have investigated the possibility of rooting leafless winter hardwood cuttings of larch. Handling risks are substantially less when the shoots are dormant, and the entire rooting operation is less expensive with this approach, since cuttings initiate roots from late May to early June. As a result, there is a much longer period for development for the root system after root initiation than with cuttings that are rooted in mid-summer, so that rooted dormant cuttings do not have to be overwintered in a greenhouse at high expense (Mason 1984). John (1977) found that dormant cuttings from ortets of hybrid larch that were less than 1 year old did not root nearly as well as leafy softwood cuttings, although hormonal treatments with IBA caused a considerable increase in their ability to root. Experiments with cuttings taken from older ortets produced mixed results. Dormant cuttings from 3- to 8-year-old ortets produced < 20% rooting regardless of the treatments applied. Rooting of large and small dormant cuttings from 11-year-old ortets indicated that the larger cuttings rooted better than the smaller cuttings, but that the rooting was still poor when compared with that of leafy cuttings. John (1979) found that winter cuttings from young hybrid larch rooted at very high levels (>90%), which were similar to the rooting percentages achieved with summer softwood cuttings. Cold storage of dormant cuttings increased rooting, most probably because the cuttings were transformed from a dormant to a post-dormant state; *Larix* is a genus that requires a period of chilling for effective bud break and growth (Simak 1970). It may also be possible that a reduction in levels of inhibitory substances during cold storage (Wareing and Phillips 1970) with no reduction in nutrient reserves could have resulted in the cuttings being in the right physiological condition for rooting (Biran and Halevy 1973). It was also found in the latter study that warm storage of more than 3 weeks resulted in extensive callus development but a large reduction in subsequent rooting. Extended warm storage followed by cold storage drastically reduced rooting. John (1979) believes it is probable that after warm storage the hybrid larch cuttings were so depleted of reserves that they were unable to flush properly, carry out photosynthesis, and grow normally; as a result, the cuttings died soon after they were inserted into the propagation beds.

A recent study (Mason 1984) has confirmed the findings of John (1979) that hardwood cuttings of larch can be rooted successfully. In this study, young hardwood hybrid larch cuttings were collected from February to April and rooted after a period of 2 to 4 weeks of cold storage at 2°C. These cuttings achieved 80 to 90% rooting, although the form of many of the trees produced in this way showed a pronounced basal sweep. These observations, combined with the observation that softwood cuttings show poorer root development after root initiation as a result of limited length of the growing season after they are rooted, have resulted in greater research emphasis on the use of dormant larch cuttings. Experiments in progress are seeking to confirm the preliminary finding that dormant larch cuttings can be rooted with great success.

Rooting Stimulants

Various rooting stimulants have been used to initiate rooting in larch cuttings. The main types of stimulants used for many tree species are auxins, both natural and synthetic. These substances are growth regulators, and include the plant hormone indoleacetic acid (IAA) and the synthetic growth regulators indolebutyric acid (IBA), napthaleneacetic acid (NAA), and 2,4-cichlorophenoxyacetic acid (2,4-D). Auxins produce several characteristic responses in plants at high concentrations, such as stimulation of adventitious root development on stems and development of callus tissue on stem cuttings. These substances also inhibit root elongation (Salisbury and Ross 1978). Auxins have been applied in several ways to cuttings, including dipping the basal portions of the cuttings in powders containing the auxins and soaking the basal ends of cuttings in a dilute solution of the auxin in alcohol and/or water or a high concentration of auxin in alcohol.

Chandler (1959) used a powder form of auxin, "Hormodin 3" (0.8% IBA in talc), to root several larch species from softwood cuttings and achieved 11 to 38% rooting of the various species. Use of this same substance with western larch proved relatively unsuccessful, with only 0 to 10% rooting occurring with cuttings from trees at least 50 years old (Andrews 1980, Corse 1980). Morgenstern et al.

(1984) and Carter (1984) used rooting powders (Seradix 3; 0.008% 3-IBA and Rootone; napthaleneacetamide, 2-methyl-1-NAA, 2-methyl-1-napthaleneacetimide, and indole-3-butyric acid) to successfully root tamarack up to 40 years old. Komissarov (1964) achieved 40 to 80% rooting with Siberian larch cuttings that had been soaked for 18 to 24 hours in dilute solutions of IAA and NAA. Tests of several levels of auxin and the soaking method on Dahurian larch cuttings achieved only 6 to 16% rooting (Hyun 1956). John (1977) attempted to root softwood cuttings of 17-year-old hybrid larch with various auxin treatments. The best results (56% rooting) were achieved with an aqueous solution of 500 ppm IBA plus 500 ppm NAA with a 1-second dip. In a subsequent study, John (1979) used two levels of IBA in an aqueous solution with a 2-hour soaking of softwood cuttings from young hybrid larch, and achieved rooting in the range of 73-99%. In a recent study, Farmer et al. (1986) tried a number of rooting powders and solutions for rooting of tamarack from populations in Ontario. The study indicated that rooting successes were high (85 to 95%) but that there were no significant differences among the extents of rooting of cuttings treated with the various stimulants.

In addition to growth regulators, other stimulants such as vitamins, sugars, and other carbohydrates translocated through the cuttings from the leaves or applied with auxins may contribute to root formation in cuttings. Hartman and Kester (1975) have indicated the importance of a carbon source for the development of adventitious roots. Hyun (1956) found that 16% rooting of Dahurian larch cuttings was achieved with 10 ppm vitamin B_1, 10 ppm nicotinic acid, 10 ppm glucose, 2.5% sucrose, 40 ppm IBA and 40 ppm IAA. Other treatments were not as successful. Vitamin B_1 alone or mixed with IAA in water and with sugar and vitamin C did not appear to increase rooting of Siberian larch (Komissarov 1964). Andrews (1980) added powdered sugar to other possible rooting stimulants, including 1% IBA in talc, in an attempt to root western larch, but only 3.3% rooting was achieved.

Moisture

Moisture is a critical element for rooting cuttings. High humidity in the rooting environment is essential, so that the temperature is kept low and evapotranspiration in the cuttings is minimized. There is evidence that the moisture status of the cutting is most important during the few hours or days between severing the cutting from the donor plant and rooting it (Libby 1974). Chandler (1959) described a technique for rooting larch cuttings with a Watco mist-control unit installed in a greenhouse bench. The mist unit was set to provide 6 seconds of mist every 6 minutes. Attempts to root cuttings of various larch species before the use of this mist system were largely unsuccessful. Mist systems have been used subsequently by various researchers for the rooting of larch (Okada 1967; Cook and Frommer 1969; Wunder 1974; John 1977, 1979; Andrews 1980).

In his work with Japanese larch, Wunder (1974) found that a "relative moisture optimum" in the propagation chamber appeared to be the dominant factor stimulating cuttings to root. He observed that if moisture conditions above the optimum level were created, the stimulating effect on the cuttings was lost. Wunder stated that only under a certain moisture stress and in combination with optimum conditions of other factors is full rooting of cuttings obtained. Cuttings rooted with 100% success under these optimum conditions in a special propagation chamber with a semi-automatic overhead atomizer for irrigation. Wunder also noted that under 'absolute optimum moisture' conditions, cuttings stayed alive throughout the propagation period without forming any roots, presumably because of a lack of moisture stress.

Temperature

Libby (1974) stated that too low a temperature retards rooting, whereas too high a temperature stresses the cutting, since high temperatures combined with abundant moisture create pathogen problems. Thus, there is an optimum temperature range. Within that range, it is recommended that the top of the cutting be kept cooler that the bottom. Several studies of hybrid larch (John 1977, 1979) and Siberian larch (Komissarov 1964) have shown that the air temperature should be maintained at approximately 20°C, especially with misting. However, the temperature of the growing medium of larch is debated, and perhaps depends on the species. In his work with Siberian larch, Komissarov (1964) found that about twice as many cuttings (80%) rooted in substrate with a temperature up to 5°C higher than air as rooted in a substrate with temperatures 2 to 6°C lower than the air. In contrast, John (1977) found that the best rooting of hybrid larch cuttings (81 to 89%) occurred with rooting-media temperatures at or below air temperature (15-20°C); with media temperatures above air temperatures (24 to 27°C) rooting success was lower (68 to 74%).

Light Intensity

Light intensity may also affect rooting in larch. Komissarov(1964) found that poor rooting of Siberian larch occurred with low light intensities (600 to 900 lux) during midday hours, but acceptable rooting occurred at higher intensities (5000 to 6000 lux). He also recommended that the light be diffuse. No rooting was achieved when cuttings were rooted in complete darkness. In studies of hybrid larch rooting, John (1977, 1979) used 18-hour day lengths on a regular basis when rooting cuttings.

Rooting Medium

The rooting medium is very important since it provides moisture, allows air to reach the cuttings, and holds them in place. Different textures and compositions of rooting media appear important to the rooting process and to the subsequent form of the root system (Libby 1974). A mixture of sand and wetted peat has often been used as the substrate for larch rooting (Chandler 1959, John 1977). Fung (1978) used a 1:1 mixture of peat and vermiculite to root several species of larch successfully in a series of rooting trials. Many investigators who have studied the rooting of larch species have found that coarse sand or gravel is a much more effective medium, since mixtures containing peat can retain too much moisture and cause the basal ends of the cuttings to rot (Chandler 1967, Cook and Frommer 1969, Wunder 1974, John 1979).

Nutrient Status

An adequate level of nutrients is essential to the successful rooting of most species. Nitrogen, especially, is a very important element for rooting success (Hartman and Kester 1975). It has been observed that addition of nutrient solutions in low concentrations usually has a beneficial effect on rooting (Hartman and Kester 1975, Dormling et al. 1976). Fung (1978) used various fertilizer treatments containing nitrogen, phosphorus, potassium, calcium and magnesium in rooting trials with tamarack, Japanese larch, European larch and Siberian larch, and found that the growth of fertilized cuttings was significantly greater than that of untreated cuttings in terms of both top and root growth.

Larch Establishment

To achieve maximum survival and fiber production in larch plantations requires proper site selection and preparation, suitable spacing, good weed control, and possibly additional management practices such as fertilization and irrigation.

Site

A proper soil is a very important site requirement for larch. It has been observed that the growth of European larch and Japanese larch in New York was most closely associated with drainage class and soil depth above a layer that restricted root development (Aird and Stone 1955). Cook (1969) stated that this depth should be at least 16 inches (6.3 cm). The exotic larches have greatly different drainage tolerances than native tamarack, which grows well on wet to moist sites. Japanese larch will tolerate moister sites than European larch, which has a drainage tolerance ranging from fresh to dry sites. Cook (1966) stated that hybrid larch will grow on a wide variety of sites provided there is adequate moisture, good aeration and drainage, and freedom from late frosts. Although the best growth is on deep, fertile, well watered soils, this larch will do better than many other species on drier soils. Grisez (1968) pointed out that European larch grew well on two moderately well drained soils and on two well drained soils. Japanese larch grew best on well drained soil, although its growth was good even on more poorly drained soil. It has therefore been recommended that the exotic larches be planted on deep, moist, well drained sandy-loam to silt-loam soils (Hunt 1932, Aird and Stone 1955, Grisez 1968).

The larches, especially Japanese larch, are very susceptible to late-spring frost damage and should therefore be planted where there is good air drainage and no frost pockets (Cook 1969, Heit 1972). In addition, since larches are also shade-intolerant, they should be planted in full sunlight (Cook 1969).

Site Preparation

Little published literature is available concerning the specific site-preparation requirements of the various larch species. However, it is known that good site preparation, including the application of pre-emergent herbicides, is essential for the establishment of larch plantations (Netzer 1984).

In Pennsylvania, several studies were done to find practical methods for converting scrub oak (*Quercus* spp.) areas to productive Japanese larch plantations (McNamara and Reigner 1955, 1960). These studies indicated that site preparation before planting was necessary, and that seedlings planted on prepared areas grew significantly faster than those on unprepared areas. Site-preparation methods included rototilling (several intensities), root raking and bulldozing. Although height and survival of the seedlings increased with increasing intensity of rototilling, this treatment alone was not as effective as the other two methods, which actually remove vegetation. Rototilling merely inhibits vegetation, and competing species reinvade the site quickly. Because Japanese larch is noted for its inability to withstand competition, the author recommended that site preparation be used to remove all vegetation in the vicinity of each seedling. Cook (1969) recommended removing shrubs or other competing vegetation with herbicide applications the summer before planting of larch. For sites that are not well drained because of hardpans in the soil, Cook suggested that additional soil depth and improved drainage might be achieved by plowing two furrows together to form ridges that could be spaced about 10 or 12 feet (3 to 3.7 m) apart. This has been attempted in preparing sites with hardpan soil for planting of Japanese larch and other conifers in Britain (Wilson and Pryatt 1984). Growth increased initially, but there was no significant increase in growth after 30 years when compared with larch on sites subjected to complete cultivation.

Site-preparation methods used in the establishment of several exotic and hybrid larch plantations on old-field sites in the Lake States have involved plowing, disking and herbicide applications during the season before planting. In a study of various establishment practices for hybrid larch in Wisconsin, Phipps and Noste (1976) used intensive site preparation to remove sod and some scattered aspen. A crawler tractor with a straight blade levelled and cleared the site, which was subsequently disked with a light farm tractor to remove weeds.

In a study of herbicide use with European larch, glyphosate was applied at a rate of 2.2 kg/ha in August of the year before planting (Netzer 1984). Moldboard plowing and disking followed in October, and the site was re-disked late in May before planting. In another experimental larch plantation, the site was plowed, disked, and treated with herbicide in strips the summer before spring planting (Riemenschneider and Nienstaedt 1983).

Because of the lack of information on the preparation of sites for larch planting, further research is necessary to provide recommendations for specific sties in a particular area. Phipps and Noste (1976) stated that there is a need to evaluate and develop better site-preparation methods that will concentrate moisture and nutrients in the root zone of planted seedlings to attain truly superior growth.

Post-planting Weed Control

Several studies have been carried out to investigate the effects of post-planting chemical weed control on the growth and survival of planted larch. Careful use of herbicides for weed control in larch plantations is required because of the extreme sensitivity of larch to herbicide damage (Netzer 1984). Herbicide use with larch is also complicated by the tree's long growing season, which prevents overspraying in late summer to control competition.

In Wisconsin, Knighton (1970) studied the effects of a fall (October) application of simazine at a rate of 5 lb/acre (4.6 kg/ha) to European larch planted the previous spring. The study indicated that growth of the sprayed seedlings was significantly less than that of unsprayed trees, and mortality was also 2% greater on sprayed trees. From these results, the author suggested that simazine should not be used in young European larch plantations. McCavish (1980) observed that Japanese larch planted in Britain was particularly susceptible to hexazinone (Velpar) sprayed at a medium volume and applied during the active growing period. In France, glyphosate applied at a rate of 2 kg/ha to actively growing European larch caused unacceptable rates of injury; however, when the herbicide was applied in October, the larch was only slightly injured by rates of 0.7 and 1.4 kg/ha (Frochot et al. 1981). In OMNR's Eastern Region, six trials have indicated that simazine and glyphosate can be applied at normal rates for Japanese larch, whereas lighter rates of simazine are still necessary with European larch (Lucas 1981).

Containerized hybrid larch seedlings were outplanted in Wisconsin in a study to evaluate the effects of various container systems and competition control treatments (Phipps and Noste 1976). The herbicides evaluated were Casoran G4 and Roundup, at several combinations and with various container types. The results indicated that survival was considerably lower on plots treated with the pre-emergent herbicide Casoran after one growing season. Casoran was applied in bands after fall planting, whereas Roundup was applied as a direct spray during the summer (early July) after planting. The authors suggested that the lower survival in the plots treated with Casoran may indicate a toxic effect, or that shading by the herbaceous vegetation in the control plots provided a more favorable environment for the trees by reducing transpiration and soil moisture evaporation. The control and Roundup treatments were similar with respect to survival because the herbicide effect was only present during the latter part of the growing season.

A recent study on newly planted European larch was carried out in Wisconsin, where 17 herbicides were oversprayed at various rates (Netzer 1984). The herbicides were applied in various formulations in the summer, 1 day after planting, and they were incorporated into the soil immediately after application by using a hand rake. The best treatment in terms of weed control was simazine, applied as a wettable powder at 1.1 kg/ha, which controlled weeds significantly better than all other treatments and resulted in 100% survival of the trees. Other top-ranking treatments were bifenox, oxyfluorfen, pronamide and oxyzalin, which also provided adequate weed control (42 to 53%) and no damage to the larch. Herbicides such as dichlobenil, linuron, diuron and hexazinone gave adequate (in the case of hexazinone, excellent) weed control, but the resultant height growth and survival of the larch were poor. Linuron and diuron have post-emergent activity, which may have caused damage to the larch. If these herbicides had been applied before planting, they might have been more acceptable treatments. In contrast, EPTC treatments and the control had excellent survival, but poor weed control reduced growth of the larch. Height growth at the end of the first growing season was 1.5 times greater in the six best treatments than in the unsprayed control. The results of this study indicate that both herbicide type and application are important factors in determining the success of treatment. Excellent results were achieved with simazine at 1.1 kg/ha, but this herbicide gave poor results at 2.2 kg/ha. Herbicide formulation may also be important since the granular herbicides gave poor results. The study provides guidelines for the use of alternative herbicides on larch, but the specific weed species and soil texture of a particular site must also be carefully considered in making weed-control prescriptions.

Spacing

The initial spacing of a plantation can be varied to accommodate its objectives, particulary with respect to desired products, species characteristics and site productivity. In a 25-year study of European larch planted at spacings ranging from 1.8 x 1.8 m to 4.3 x 4.3 m, it was evident that, within limits, the effects of initial spacing on radial growth and stem form are transitory (Morrow 1984). Wide spacing merely delayed the need for the first thinnings by several years. Morrow recommended an initial spacing of 3 x 3 m, or rectangular spacing of either 3.4 x 2.7 m or 3.7 x 2.4 m, where 1000 trees/ha are established, since many financial objectives can be achieved at this spacing. Morrow stated that closer spacings are seldom justified to reduce loss of either wood quality or volume, and pre-commercial thinnings would be more expensive. Planting less than 740 trees/ha risks a loss of wood quality and, for pole production, volume. At such extremely wide spacings, the trees may become poorly distributed and, as a result, growth losses may occur.

In contrast, for the SRIC system, it is recommended that larch be planted at closer spacings than are generally recommended for conifer management (Jeffers and Isebrands 1974). Several spacing studies for larch in Europe have substantiated this idea. Bonnemann et al. (1971) investigated the growth of European larch at 1- x 1-m, 2- x 2-m and 3- x 3-m spacings after 17 and 22 years. For the 1- x 1-m spacing, approximately one-third of the trees had died after 17 years, and mortality increased to 50% by 22 years. In the 2- x 2-m plots, natural mortality was just becoming noticeable at 22 years. Height growth was not affected by spacing at 17 years, but it had increased with increasing spacing by 22 years. As spacing increased, basal area and volume production, as well as the number of straight stems, decreased. Natural beech (*Fagus* spp.) reproduction present at the time of planting died under the dense stands, but survived in the more widely spaced stands. From these results, the 3- x 3-m and 1- x 1-m spacings were rejected, and 1.5- x 1.5-m to 2- x 2-m spacings were considered appropriate.

The same study was evaluated again when the trees were 30 years old (Fromsdorf and Magnussen 1980). By this time, the densely stocked (1 x 1 m) plots had 1200 stems/ha after two thinnings, and the widely spaced plots had 700 stems/ha. There was a larger number of dominant, well formed stems at the dense spacings. Continued development of the natural beech understory occurred in the 2- x 2-m and 3- x 3-m spacings, but the beech did not thrive in the 1- x 1-m spacings. As a result of thinnings in the 1- x 1-m plots, a great number of small-volume stems had been cut at high cost and with a low revenue. On the other had, for a maximum-value-turnover production goal, the number of larches with long, straight and clean boles was too low in the widely spaced 3- x 3-m plots. Therefore, as in the previous evaluation, these authors recommended the 2- x 2-m spacing in order to attain the necessary 250 to 300 stems/ha at the age of 30 years if the right provenance is used and pruning is carried out.

Another study in Germany investigated the effects on growth of Japanese larch planted at 1- x 1-m, 2- x 2-m, 3- x 3-m and 4- x 4-m spacings after 51 years (Hinners and Stratmann 1984). At this age, all spacings showed similar heights, and diameters at the wider spacings were clearly superior to those at closer spacings. Heavy low thinnings at the closer spacings did not result in the desired improvement in diameter growth, perhaps because of severe growth depression that must have already existed in the plots with denser stockings when the thinnings began. Increased branchiness and poorer stem form occurred as spacing widened. For total volume production, the 1- x 1-m spacing was clearly superior to the others, but the 2- x 2-m spacing was apparently overtaking the closer spacing at this age. From the results, the authors recommend establishing Japanese larch at 4000 to 2500 stems/ha (1.6 x 1.6 to 2.0 x 2.0 m spacing) and subsequently reducing stem numbers early by precommercial thinnings followed by low thinning in the young stands afterwards. This prescription should guarantee satisfactory diameters and acceptable quality without any noteworthy losses in volume production.

In agreement with these studies, Jeffers and Isebrands (1974) believe that SRIC larch can be planted successfully at 1.8- x 1.8-m spacings, or possibly less, with improved material. From this recommendation, a pulpwood rotation age of 20 to 25 years would be feasible. The exact rotation age would depend on the species and growth rate, as well as on the cultural treatments that are carried out. Schreiner (1970) recommended that fiber production of larch could be carried out under rotations of 6 to 16 years.

Fertilization and Irrigation

Jeffers and Isebrands (1974) recommended that intensive management practices such as fertilization and irrigation should be utilized in SRIC plantations. The larches, especially Japanese larch, are very sensitive to long mid-summer droughts (Heit 1972). Therefore, irrigation may be particularly important. Young Japanese larch are known to respond well to fertilizer applied in conjunction with irrigation (Jeffers and Isebrands 1974). The principles of fertilization and irrigation for larch are similar to those for hybrid poplar.

The effect of nutrient deficiencies on wood properties of 2-year-old western larch seedlings grown in solutions deficient in minerals has been investigated (Murphey et al. 1969). When available mineral elements, including nitrogen, phosphorus, potassium, calcium, magnesium and other macro- and micronutrients were reduced, significant differences were noticed in all physical and mechanical wood properties measured when compared with a control. These properties included the number of tracheids, diameter of resin canals, number of epithelial cells, width of rings, number of rays, diameter of tracheid walls, length of tracheids and specific gravity.

Studies of the performance of various larches have used fertilization and irrigation to promote maximum production. Isebrands and Hunt (1975) irrigated newly planted Japanese larch regularly throughout the growing season when rainfall fell below 2.5 cm. In the third and fourth growing seasons, between 50 and 60 g of 10-10-10 fertilizer was applied to each tree in the spring, in mid-June and mid-August, and in late September. A single fertilizer application was made in July of the fifth growing season, and a final application was made in June of the eighth year. Fertilization increased volume production and wood uniformity, although specific gravity decreased as a result of decreased latewood production, as discussed previously in the section on larch utilization. Zavitkovski et al. (1982) kept soil moisture near field capacity, by irrigating as required, in a study of biomass production in 4- to 9-year-old intensively cultured hybrid larch. A high level of soil nutrients was maintained by annual fertilization with nitrogen, phosphorus and potassium at rates of 150, 40, and 40 kg/ha, respectively.

LITERATURE CITED[1]

Adams, W.R. and Hutchison, G.O. Jr. 1961. Total and merchantable volume growth of Japanese Larch. Agric. Exp. Stn. Univ. VT and State Agric. Coll., Bull. 620. 8 p.

Ahuja, M.R. 1983. Somatic cell differentiation and rapid clonal propagation of aspen. Silv. Genet. 32:131-135.

Aird, P.L. 1962. Fertilization, weed control, and the growth of poplar. For. Sci. 8(4):413-428.

Aird, P.L. and Stone, E.L. 1955. Soil characteristics and the growth of European and Japanese larch in New York. J. For. 53:425-429.

Akinyemiju, O.A. and Dickman, D.I. 1982a. Variation among 21 *Populus* clones in tolerance to simazine and diuron. Can. J. For. Res. 12(3):708-712

Akinyemiju, O.A. and Dickman, D.I. 1982b. Contrasting effects of simazine on the photosynthetic physiology and leaf morphology of two *Populus* clones. Physiol. Plant. 55:402-406.

Akinyemiju, O.A., Isebrands, J.G., Nelson, N.D. and Dickmann, D.I. 1982. Use of glyphosate in the establishment of *Populus* in short rotation intensive culture. p. 94-102 *in* J. Zavitkovski and E.A. Hansen, *Ed.* North American Poplar Council Meeting, Rhinelander, WI. 20-22 July 1982.

Al'benski, A. 1940. [Specific characters in F_1 of interspecific *Larix* hybrids.] Proc. Leningrad Acad. Agric. Sci. USSR 23/24:20-23.

Albenskiy, A.V. and Delcina, A.V. 1934. Opyt gibrid izaciy topoly v laboraatoiy. Opty Issledowan 8:107-119.

Allen, R.M. and McComb, A.L. 1955. Uber faktoren die bewurzelung der steckling e von der *Populus deltoides* Bartr. beeinflussen. Zbl. ges. Forstw. 74:199-220.

Allen, R.M. and McComb, A.L. 1956. Rooting of cottonwood cuttings. USDA For. Serv., Southeastern For. Exp. Stn., Occas. Pap. 151. 10 p.

Alm, A.A., Jensen, R.A. and Brown, B.A. 1972. Growth and survival of exotic and native species at Cloquet, Minnesota. Minn. For. Res. Notes 237. 4 p.

Anderson, H.W. and Zsuffa, L. 1975. Yield and wood quality of hybrid cottonwood grown in two-year rotation. Ont. Min. Nat. Resour., Div. For., Maple, Ont. For. Res. Rep. No. 101.

Andrews, D. 1980. Rooting western larch. p. 54-55 *in* Progress report of the Inland Empire Cooperative Forest Tree Improvement Program. Aug. 1980.

Anon. 1880. Annual report. Ont. Fruit Growers Assoc.

Anon. 1939. A fast-growing and winter-hardy poplar hybrid still to be found for the Lake States. USDA For. Serv., Lake States For. Exp. Stn. Tech. Note 153. 1 p.

Anon. 1958. Poplars in forestry and land use. Food and Agriculture Organization of the United Nations. Rome, Italy. 511 p.

Anon. 1968. Forest fertilization theory and practice. Papers presented at the symposium on forest fertilization, April 1967. Gainesville, FL, Tennessee Valley Authority. 306 p.

---

[1] The references in this list have not been confirmed by Forestry Canada, Ontario Region, and may contain inaccuracies.

Anon. 1973. Forest fertilization symposium proceedings. Dep. Environ., Can. For. Serv. and USDA For. Serv., State Univ. of NY Coll. of Environ. Sci. and For., USDA For. Serv., Northeastern For. Exp. Stn., Gen. Tech. Rep. NE-3. 246 p.

Anon. 1979a. FAO secretariat statistics on *Populus* planting. Proc. Tech. Consult. on Fast-growing plantation broad-leaved trees for Mediterranean and temperate zones, Lisbon. FAO FGB-79 Vol. 1:1-16.

Anon. 1979b. Poplars and willows. United Nations, FAO For. Series No. 10. 320 p.

Anon. 1983. New forests in eastern Ontario. Hybrid Poplar. Ont. Min. Nat. Resour., Toronto, Ont. Sci. and Tech. Series. Vol. 1. 336 p.

Armson, K.A., Robinson, F.C. and Osborn, J.E. 1980. Forest management manual for the province of Ontario. Ont. Min. Nat. Resour., For. Resour. Gr., Toronto, Ont. 132 p.

Bagley, W.T. 1972. A comparison of poplar clone performance in Nebraska. p. 76-79 *in* Proc. 8th Central States For. Tree Improv. Conf., 11-13 Oct.

Balatinecz, J.J. 1983. Properties and utilization of larch grown in Canada - an overview. p. 65-80 *in* Larch Symp.: potential for the future. Ont. Min. Nat. Resour., Toronto, Ont. and Univ. Toronto.

Baldwin, H.I. 1958. European larch in New Hampshire. Forest Notes. Proc. New Hampshire For. Soc. Concord, NH. 59:15-21.

Baldwin, H.I. 1966. Geographic variation in European larch. p. 24-29 *in* Proc. 13th Northeastern For. Tree Improv. Conf., Univ. NY, Albany, NY.

Barker, R.G. 1974. Papermaking properties of young hardwoods. Tappi 57(8):107-111.

Barkley, B. 1983. A silvicultural guide for hybrid poplar in Ontario. Ont. Min. Nat. Resour., Fast-Growing Hardwoods Program. 35 p.

Barnes, B.V. 1977. The international larch provenance test in southeastern Michigan, USA. Silv. Genet. 26:145-148.

Barocka, K.H., Baus, M. and Lontke, E. 1984. Tissue culture as a tool for mass *in vitro* propagation of aspen. Silv. Genet. Cited by Frohlich and Weisgerber. 1984.

Barry, W.J. and Sachs, R.M. 1968. Vegetative propagation of quaking aspen. California Agric. 22(1):14-6.

Benson, M.K. 1972. Breeding and establishment - and promising hybrids. p. 88-96 *in* Aspen: Symp. Proc. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-1.

Benson, M.K. and Schwalbach, D.E. 1970. Techniques for rooting aspen sprouts. Tree Planters' Notes 21(3):12-14.

Benson, M.R. and Einspahr, D.W. 1967. Early growth of diploid, triploid and triploid hybrid aspen. For. Sci. 13(2):150-155.

Berlyn, G.P. 1961. Factors affecting the incidence of reaction tissue in *Populus deltoides* Batr. Iowa State J. Sci. 35(3):367-424.

Bey, C.F., Krajicek, J.E., Williams, R.D. and Phares, R.E. 1975. Weed control in hardwood plantations. p. 69-84 *in* John S. Wright, *Ed.* Proc. Herbicides in Forestry. For. Conf. 1975. Purdue Univ., West Lafayette, IN.

Bier, J.E. 1939. Septoria canker of introduced and native hybrid poplars. Can. J. Res. (C)17:195-204.

Biran, I. and Halevy, A.H. 1973. Endogenous levels of growth regulators and their relationship to the rooting of dahlia cuttings. Physiol. Plant. 28:436-442.

Blackmon, B.G., Baker, J.B. and Cooper, D.T. 1979. Nutrient use by three geographic sources of eastern cottonwood. Can. J. For. Res. 9:532-534.

Blankenhorn, P.R., Bowersox, T.W., Kuklewski, K.M. and Stimely, G.L. 1985. Effects of rotation, site and clone on the chemical composition of *Populus* hybrids. Wood and Fiber Sci. 17(3):351-360.

Bloomberg, W.J. 1959. Root formation of black cottonwood cuttings in relation to region of the parent shoot. For. Chron. 35:13-17.

Bloomberg, W.J. 1962a. Cytospora canker of poplars: factors influencing the development of the disease. Can. J. Bot. 40:1271-1280.

Bloomberg, W.J. 1962b. Cytospora canker of poplars: the moisture relations and anatomy of the host. Can. J. Bot. 40:1281-1292.

Bloomberg, W.J. 1963. The significance of initial adventitious roots in poplar cuttings and the effect of certain factors on their development. For. Chron. 39:279-289.

Bobrovy, 1982. Brief remarks on the distinctive biological features and nature of Siberian larch tree stocks. (translation). New Zealand Dep. Internal Affairs, Wellington, N.Z. 4 p.

Bonga, J.M. 1982. Vegetative propagation in relation to juvenility, maturity and rejuvenation. p. 387-412 *in* Tissue culture in forestry. Martinus Nyhoff Publishers NV, The Hague.

Bonnemann, A., Huss, J. and Warth, H. 1971. Initial spacing of European Larch. Forstarchiv 42(6):116-122.

Bonner, F.T. and Broadfoot, W.M. 1967. Growth response of eastern cottonwood to nutrients in sand culture. USDA For. Serv. Southern For. Exp. Stn., Res. Note SO-65. 4 p.

Borset, O. and Haugberg, M. 1960. "Opsa" 176 p. Det Norske Skogselskab.

Bouvarel, P. and Lemoine, M. 1957. Selection et amélioration des peupliers de la section *Leuce* en France. p. 325-341 *in* Proc. 6th Congr. int'l Peupliers. Paris 1957.

Bowersox, T.W. 1970. Influence of cutting size on juvenile growth and survival of hybrid poplar clone NE-388. Tree Planters' Notes 2(4):1-3.

Bowersox, T.W. and Ward, W.W. 1970. Black polyethylene mulch - an alternative to mechanical cultivation for establishing hybrid poplars. Tree Planters' Notes 21(1):21-24.

Braun, H.J. 1963. Wurzelkeime in jungen und alteren Sprossachsen von *Populus*. Z. Bot. 51:441-451.

Brayshaw, J.C. 1965. Native poplars of southern Alberta and their hybrids. Dep. For. Can., Publ. 1109. 40 p.

Brown, J.R. 1899. Notes on *Larix leptolepis*. Trans. Roy. Eng. Arboric. Soc. iv: 271-276.

Cain, N. and Ormrod, D. 1984. Hybrid vigor as indicated by early growth characteristics of *Populus deltoides*, *P. nigra* and *P. euramericana*. Can. J. Bot. 62:1-8.

Calvert, R.F. and Rauter, R.M. 1978. Status of larch improvement. p. 145-152 *in* J.B. Scarratt, *Comp.* Tree Improvement Symposium. Dep. Environ, Can. For. Serv., Sault. Ste. Marie, Ont. COJFRC Symp. Proc. 0-P-7.

Carlson, C.E. and Blake, G.M. 1966. Hybridization of *Larix occidentalis* and *Larix lyalii*. p. 45-49 *in* Proc. 13th Northeastern Tree Improv. Conf., 1965. Albany, NY.

Carter, K.K. 1984. Rooting of tamarack cuttings. For. Sci. 30(2):392-394.

Carter, K.K. and Canavera, D. 1981. Early growth of exotic larches at three locations in Maine. Cooperative For. Res. Unit, Res. Note 8. 7 p.

Carter, M.C. and White, E.H. 1971. Dry weight and nutrient accumulation in young stands of cottonwood (*Populus deltoides* Bartr.). Auburn Univ. Agric. Exp. Stn., Circ. 190. 14 p.

Ceulemans, R., Impens, I., Hebrant, F. and Moermans, R. 1980. Evaluation of field productivity of several poplar clones based on their gas exchange variables determined under laboratory conditions. Photosynthetica 14:355-362.

Chalupa, V. 1981. Clonal propagation of broad-leaved forest trees *in vitro*. Comm. Inst. For. Czechosloveniae 12:255-271.

Chandler, C. 1959. The propagation of *Larix* from softwood cuttings. Contrib. Boyce Thompson Inst. 20(3):231-238.

Chandler, C. 1967. A progress report on the larch improvement program at Boyce Thompson Institute. Contrib. Boyce Thompson Inst. 23:319-326.

Cheng, W.W. and Bensend, D.W. 1979. Anatomical properties of selected *Populus* clones grown under intensive culture. Wood Sci. 11:182-187.

Chittenden, F.J. 1932. Conifers in cultivation: the report of the conifer conference held by the Royal Horticultural Society, 10-12 Nov. 1931. Roy. Hort. Soc., London, Eng. 634 p.

Christie, C.B. 1978. Rapid propagation of aspens and silver poplars using tissue culture techniques. Proc. Internat'l Plant Propagation Soc. 28:255-260.

Cook, D.B. 1947. European larch as a pulpwood. J. For. 45:763-764.

Cook, D.B. 1966. Growth and silviculture of larch hybrids. p. 21-23 *in* Proc. 13th Northeastern For. Tree Improv. Conf.

Cook, D.B. 1969. Planted larch in New York. Albany, NY. 115 p.

Cook, D.B. and Frommer, C.H. 1969. Rooting softwood cuttings of larch. p. 6-8 *in* Proc. 16th Northeastern For. Tree Improv. Conf.

Correns, E. 1961. On abnormal wood fibres. Paperi ja Puu 43(2):47-62.

Corse, T. 1980. An effort to root larch cuttings. Unpublished report from the Flathead Indian Reservation, 1980. 2 p. Cited *in* M. Staubach, 1983. Vegetative propagation of western larch (*Larix occidentalis* Nutt.). M.S. Thesis, Univ. of ID. 67 p.

Cram, W.H. 1960. Performance of seventeen poplar clones in South Central Saskatchewan. For. Chron. 36:204-209.

Cram, W.H. and Lindquist, C.H. 1981. Refrigerated storage for hardwood cuttings of willow and poplar. Tree Planters' Notes 33(4):3-5.

Crist, J.B. 1980. Anatomical characteristics of nine *Populus* clones grown under short rotation intensive culture. p. 6-7 *in* Proc. 34th Annual Meeting, For. Prod. Res. Soc., 7-10 July 1980. Boston, MA.

Crist, J.B. 1983. Synopsis of utilization research of SRIC raw materials. p. 154 *in* Intensive Plantation Culture: 12 Years Research. USDA For. Serv., North Central For. Exp. Stn. Gen. Tech. Rep. NC-91.

Crist, J.B., Mattson, J.A. and Winsauer, S. 1983. Effect of severing method and stump height on coppice growth. *In* Intensive plantation culture: 12 years research. USDA For. Serv., North Central For. Exp. Stn. Gen. Tech. Rep. NC-91.

Crosson, P. 1981. Conservation tillage and conventional tillage: a cooperative assessment. Soil Conserv. Soc. Amer., Ankeny, IA. 35 p.

Cunningham, F.E. 1953. Rooting ability of native cottonwood depends on the clone used. USDA For. Serv., Northeastern For. Exp. Stn. Res. Note 26. 2 p.

Cunningham, F.E. and Sowers, D.W. 1965. Simazine no substitute for cultivation in hybrid poplar plantations. Tree Planters' Notes 28:10-13.

Cutter, B.E. and Murphey, W.K. 1978. Effects of potassium on growth and wood anatomy of a *Populus* hybrid. Wood and Fiber 9(4):282-288.

Dadswell, H.E. and Wardrop, A.B. 1959. Desirable trees for paper. Pulp and Paper. April: 117-121.

Dadswell, H.E., Watson, A.J. and Nicholls, J.W.P. 1959. What are the wood properties required by the paper industry in the trees of the future? Tappi 42(7):521-526.

Dallimore, W. and Jackson, A.B. 1948. Handbook of *Coniferae* including *Ginkgoaceae*. 3rd. ed. Edward Arnold Ltd., London. 686 p.

Dallimore, W. and Jackson, A.B. 1954. A handbook of *Coniferae* including *Ginkgoaceae*. Edward Arnold Ltd., London. 686 p.

Danfield, W., Martishus, J. and Hansen, E. 1983. Application date affects herbicide tolerance of hybrid poplars. USDA For. Serv., North Central For. Exp. Stn., Res. Note NC-3301. 3 p.

Davidson, W.H. 1979. Hybrid poplar pulpwood and lumber from a reclaimed strip-mine. USDA For. Serv., Northeastern For. Exp. Stn. Res. Note NE-282. 2 p.

Dawson, D.H. 1976. History and organization of the maximum wood yield program. p. 115 *in* Intensive plantation culture: five years research. USDA For. Serv., North Central For. Exp. Stn. Gen. Tech. Rep. NC-21.

Dawson, D.H., Isebrands, J.G. and Gordon, J.C. 1976. Growth, dry weight yields, and specific gravity of 3-year-old *Populus* grown under intensive culture. USDA For. Serv., North Central For. Exp. Stn., Res. Pap. NC-122.

Debell, D.S. and Alford, L.T. 1972. Sprouting characteristics and practices evaluated for cottonwood. Tree Planters' Notes 23:1-3.

Debell, D.S., Brunette, A.P. and Schweitzer, D.L. 1977. Expectations from intensive culture on industrial forest lands. J. For. 75(1):10-13.

Demeritt, M.E. Jr. 1979. Poplar culture in the Northeast. p. 31-34 *in* Annual Meeting of the North American Poplar Council. Proc. 197.

Demeritt, M.E. Jr. 1981. Growth of hybrid poplars in Pennsylvania and Maryland clonal tests. USDA For. Serv., Northeastern For. Exp. Stn., Res. Note NE-3302.

Dickman, D. 1979. Physiological determinants of poplar growth under intensive culture. p. 12-1 to 12-12 *in* Proc. North Amer. Poplar Council Ann. Mtg., 6-9 Sept. 1977. Ont. Min. Nat. Resour., Brockville, Ont. For. Res. Inf. Pap. No. 102.

Dickman, D., Phipps, H. and Netzer, D. 1980. Cutting diameter influences early survival and growth of several *Populus* clones. USDA For. Serv., North Central For. Exp. Stn., Res. Note NC-261. 4 p.

Dimpflmuir, R. 1959. Die Bastardierung in der Gattung *Larix*. Forstwiss. Forsch. 12. 75 p.

Dormling, I., Ehrenberg, C. and Lindgren, D. 1976. Vegetative propagation and tissue culture. Roy. Coll. For. Stockholm, Sweden. Dep. For. Genet., Res. Note. Paper presented at the XVI IUFRO Congress. Oslo, Norway. 18 p.

Edwards, M.V. 1956. The hybrid larch *Larix* x *eurolepis* Henry. Forestry 29:29-43.

Edwards, W.R.N. and Kissock, W.J. 1975. Effect of soaking and deep planting on vegetative propagation of *Populus* and *Salix*. International Poplar Commission, 15th Session, United Nations, FAO, Rome. Dec. 1975.

Einspahr, D.W. 1968. Growth and nutrient requirements of hybrids between *Populus canescens* and *Populus tremuloides*. Inst. Pap. Chem. Genet. and Physiol., Note 4. 17 p.

Einspahr, D.W. 1969. Growth and nutrient requirements for hybrids between *Populus canescens* and *Populus grandidentata*. Inst. Pap. Chem. Genet. and Physiol., Note 7. 21 p.

Einspahr, D.W. 1971. Growth and nutrient uptake of aspen hybrids using sand culture techniques. Silv. Genet. 20(4):132-137.

Einspahr, D.W. and Benson, M.K. 1964. Production and evaluation of aspen hybrids. J. For. 62:806-809.

Einspahr, D.W., Benson M.R. and Peckham, J.R. 1968. Wood and pulp properties of five-year old diploid and triploid hybrid aspen. Tappi 51(2):72-75.

Einspahr, D.W., McDonough, T.J. and Joachimides, T. 1983. Kraft pulping characteristics of European, Japanese and European x Japanese larch hybrids. Tappi 66(8):72-76.

Einspahr, D.W. and Winton, L.L. 1976. Genetics of quaking aspen. USDA For. Serv., Res. Pap. WO-25.

Einspahr, D.W., Wyckoff, G.W. and Fiscus, M. 1984. Larch - a fast-growing fiber source for the Lake States and Northeast. J. For. 82:104-106.

Ek, A.R. and Dawson, D.H. 1976. Yields of intensively grown *Populus*: actual and projected. p. 117 *in* Intensive plantation culture: five years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-21.

Eliason, E.J. and Carlson, D.E. 1963. Comparative volume production of some species of larch. New York Conserv. Dep., Notes on Forest Investigation No. 46. 2 p.

Erdesi, J. 1965. *Populus tremula* et *Populus canescens* en plaine de la Voivodina. Topola, Beograd 9, Nos. 52-54, 8-28. Cited *in* D.H. Dawson, 1976. History and organization of the maximum wood yield program. p. 117 *in* Intensive plantation culture: five years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-21.

Erdmann, G.G. 1966. Promising conifers for western Iowa. USDA For. Serv., North Central For. Exp. Stn., Res. Pap. NC-8. 8 p.

Fairbairn, W.A. 1959. Early controlled cross-fertilization of European and Japanese larches. Scottish For. 13(3):167-169.

Farmer, R.E. Jr. 1963. Vegetative propagation of aspen by greenwood cuttings. J. For. 61:385-386.

Farmer, R.E. Jr. 1966. Rooting dormant cuttings of mature cottonwood. J. For. 64:196-197.

Farmer, R.E. Jr. 1973. Vegetative propagation and the genetic improvement of North American hardwoods. New Zealand J. For. Sci. 4(2):211-220.

Farmer, R.E. Jr. 1976. Relationships between genetic differences in yield of deciduous tree species and variation in canopy size, structure and duration. p. 119-137 *in* M.G.R. Cannel and F.T. Last, *Ed*. Tree physiology and yield improvement. Academic Press, New York, NY.

Farmer, R.E. Jr., Foster, H.A., Bakowsky, O., MacDonald, B., O'Reilly, G. and Reinholt, R. 1986. A vegetative propagation system for tamarack. Northern J. Appl. For. 3:91-93.

Farnsworth, D.H., Gatherum, G.E., Jokela, J.J., Kriebel, H.B., Lester, D.T., Merritt, C., Pauley, S.S., Read, R.A., Sajdak, R.L. and Wright, J.W. 1972. Geographic variation in Japanese larch in north central United States plantations. Silv. Genet. 21:139-147.

Fasehun, F.E. 1978. Effect of irradiance on growth and photosynthesis of *Populus* x *euramericana* clones. Can. J. For. Res. 8:94-99.

Fast, G. 1980. Orchideenkultur. Stuttgart.

Fege, A.S. 1983. The practice and physiological basis of collecting, storing and planting *Populus* hardwood cuttings. *In* Intensive plantation culture: 12 years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-91.

Fege, A.S. and Phipps, H. 1983. Effect of collection date and storage conditions on field performance of *Populus* hardwood cuttings. Can. J. For. Res. 114(1):119-123.

Ferguson, K., Rose, D., Lothner, D.C. and Zavitkovski, J. 1981. Hybrid poplar plantations in the Lake States - a financial analysis. J. For. 79(1):664-667.

Ford, H.F. and Williamson, M.J. 1952. Cover crops no substitute for cultivation in hybrid poplar plantings. USDA For. Serv., Northeastern For. Exp. Stn. Res. Note No. 14.

Foulger, A.N. and Hacskaylo, J. 1968. Stem anatomy variations in cottonwood growing under nutrient-deficient conditions. USDA For. Serv., North Central For. Exp. Stn., Res. Pap. NC-23. p. 41-47.

Foulger, A.N., Shire, E.A. and Freese, R. 1971. Effect of nutrient concentration on the stem anatomy of eastern cottonwood seedlings. Wood Fiber 2:340-346.

Fowler, D.P. 1975. Exotic softwood trees in the Maritimes: which ones should we plant? Dep. Envir., Can. For. Serv., Fredericton, New Brunswick. For. Res. Tech. Note No. 84. 7 p.

Fowler, D.P., MacGillivray, H.G., Manley, S.A.M. and Bonga, J.S. 1973. Tree breeding at the Maritime Forest Research Centre. Proc. 14th Can. Tree Improv. Assoc. Part 1:21-28.

Frochot, H., Pitsch, M., and Wehrlen, L. 1981. Selectivity of glyphosate in terms of the rate used and the growth stage of young forest seedlings of both conifers and deciduous species. *In* Compte Rendu de la 11^{e} Conf. du Columba, 1981. Tome 2:545-553.

Frohlich, H.J. 1965. Aussichten fur den Anbau von Balsampappeln und Balsamkreuzungen. Holzzucht, Reinbek 19:1-14.

Frohlich, H.J. 1982. Fortschritte bei der vegetativen Vermehrung. Forstarchiv 53:3-9.

Frohlich, H.J. and Weisgerber, H. 1984. Research on *in-vitro* techniques within the framework of poplar breeding - results and future trends. Paper presented at the 17th Session of the International Poplar Commission, Ottawa, 1-4 Oct. 1984. 14 p.

Fromsdorf, U. and Magnussen, S. 1980. The European larch spacing experiment in the Karlshafen Forest Administration, Hesse. Forstarchiv 51(6):113-118.

Fung, M.Y.P. 1978. Vegetative propagation of larch seedlings. M.Sc.F. Thesis, Univ. of Toronto, Fac. For., 113 p.

Gatherum, G.E. 1966. European larch provenance trial in northeastern Iowa. Iowa State Sci. J. 40:287-291.

Geimer, R.L. and Crist, J.B. 1980. Structural flakeboard from short rotation intensively cultured hybrid poplar clones. For. Prod. J. 30:42-48.

Genys, J.B. 1960. Geographic variation in European larch. Fox For. Res. and Demonstration Forest. Bull. No. 13. 100 p.

Genys, J.B. 1968. Performance of different larches in central Maryland. Chesapeake Sci. 9:139-141.

Genys, J.G. 1972. Diversity in Japanese larch from different provenances studied in Maryland. p. 2-4 *in* Proc. 19th Northeastern For. Tree Improv. Conf. 2-4 Aug. 1971. Univ. Maine, Orono, ME.

George, E.J. 1936. Growth and survival of deciduous trees in shelter-belt experiments at Mansen, North Dakota. 1915-34. USDA For. Serv., Tech. Bull. No. 496.

Giertych, M. 1979. Summary of results on European larch (*Larix decidua* Mill) height growth in the IUFRO 1944 provenance experiment. Silv. Genet. 28(5/6):244-256.

Grisez, T.J. 1968. Growth and development of older plantations in northwestern Pennsylvania. USDA For. Serv., Res. Pap. NER-104, 40 p.

Gruschow, G.F. 1939. Performance of hybrid poplar cuttings in the Forest Service Nursery, Vallonia, Indiana. USDA For. Serv., Central States For. Exp. Stn. Note 39. 8 p.

Haines, S.G. and DeBell, D.S. 1979. Use of nitrogen-fixing plants to improve and maintain productivity of forest soils. p. 279-303 *in* Proc. Impact of intensive harvesting on forest nutrient cycling. State Univ. of New York, Coll. Environ. Sci. and For., Syracuse, NY.

Haissig, B.E. 1974. Origins of adventitious roots. New Zealand J. For. Sci. 4: 299-310.

Hakkila, P. 1961. Lehtikuusipuun kayttomahdollisuukista. Suomen Puutalous 43(2):61-62.

Hakkila, P., Nikki, M. and Palenius, I. 1972. Suitability of larch as pulpwood for Finland. Paperi ja puu 4(2):41-58.

Hakkila, P. and Winter, A. 1973. On the properties of larch wood in Finland. Comm. Inst. For. Fenn. 79(7). 45 p.

Hall, J.P. 1973. Survival and growth of exotic trees in Newfoundland. Dep. Environ., Can. For. Serv., St. John's, Nfld. Inf. Rep. N-X-85. 23 p.

Hall, J.P. 1977. Comparison of the early growth of *Larix* and *Picea* in plantations in Newfoundland. Dep. Fish. Environ., Can. For. Serv. Bi-Monthly Res. Notes 33:2, 13-14.

Hall, J.P. 1982. Growth and development of exotic tree species in Newfoundland. Dep. Environ., Can. For. Serv., St. John's, Nfld. Inf. Rep. N-X-212. 36 p.

Hall, J.P. 1983. Comparison of the growth of larch with other conifers on reforested and afforested sites in Newfoundland. For. Chron. 59(1):14-16.

Hamaya, T. and Inokuma, T. 1957. Native species of *Populus* in Japan. For. Agency, Min. Agric., Tokyo. 17 p.

Hansen, E.A. 1978. Forest irrigation: a review. p. 126-137 *in* Proc. Soil moisture-site productivity symposium, 1-3 Nov. 1977. Myrtle Beach, SC.

Hansen, E.A. 1981. Root length in young hybrid *Populus* plantations: its implication for border width of research plots. For. Sci. 27(4):808-814.

Hansen, E.A. 1983. Irrigating forest plantations. p. 46-53 *in* Intensive plantation culture: 12 years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-91.

Hansen, E.A. 1986a. Planting date affects survival and height growth of hybrid poplar. For. Chron. 62(3):164-169.

Hansen, E.A. 1986b. Nutrient sources for fast growing forests: principles, practices, and future directions. Paper submitted at IEA Task Force II Workshop, 21-23 May 1986. Kingston, Ont. 6 p.

Hansen, E.A. and Baker, J.B. 1979. Biomass and nutrient removal in short rotation intensively cultured plantations. p. 130-151 *in* Proc. 1979 Symp. on Impact of intensive harvesting on forest nutrient cycling, 13-16 August 1979. State Univ. of New York, Syracuse, NY.

Hansen, E.A., Dawson, D.H. and Tolsted, D.N. 1980. Irrigation of intensively cultured plantations with paper mill effluent. Tappi 63(11):139-143.

Hansen, E.A., Moore, L., Netzer, D., Ostry, M., Phipps, H. and Zavitkovski, J. 1983. Establishing intensively cultured hybrid poplar plantations for fuel and fiber. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-78. 24 p.

Hansen, E., Netzer, D. and Rietveld, W.J. 1984. Site preparation for intensively cultured hybrid poplar plantations. USDA For. Serv., North Central For. Exp. Stn., Res. Note NC-320. 4 p.

Hansen, E.H., Netzer, D. and Rietveld, W.J. 1984. Weed control for establishing intensively cultured hybrid poplar plantations. USDA For. Serv., North Central For. Exp. Stn., Res. Note NC-317. 6 p.

Hansen, E.A. and Phipps, H.M. 1983. Effect of soil moisture tension and preplant treatments on early growth of hybrid *Populus* hardwood cuttings. Can. J. For. Res. 13(3):458-464.

Hansen, E.A. and Tolsted, D.N. 1981. Effect of cutting diameter and stem or branch position on establishment of a difficult-to-root clone of a *Populus alba* hybrid. Can. J. For. Res. 11:723-

Hansen, E.A. and Tolsted, D.N. 1985. Nitrogen sources and fertilizer rates affect growth of hybrid poplar. *In* J.O. Dawson and K.A. Majerus, *Ed.* Proc. Fifth Central Hardwood Forest Conf., Dep. For., Univ. of Illinois, Urbana-Champaign, IL.

Hansmann, A. and Sugden, E.A.N. 1983. The chemistry and kraft pulping of larch. p. 115-135 *in* Proc. Larch Symposium: Potential for the Future. March 1983. Ont. Min. Nat. Resour., Toronto, Ont. and Univ. Toronto.

Hartman, H.T. and Kester, D.E. 1975. Plant propagation: principles and practices. Prentice-Hall, Inc., New York. 662 p.

Hattemer, H.H. and Seitz, F.W. 1967. Einige ergebnisse von testanbauten mit aspenhybriden. 2. Kreuzungen der jahre 1953 und 1958. Silv. Genet. 6:6-13.

Haywood, W.F. and McNabb, H.S. Jr. 1979. Moisture stress and incidence of stem cankers in intensively grown poplars. p. 123-132 *in* Proc. First North Central Tree Improv. Conf., 21-23 August 1979. Madison, WI.

Heilman, P. and Stettler, R.F. 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4 year plantation. Can. J. For. Res. 15:384-388.

Heimberger, C. 1936. Report on poplar hybridization. 1936. For. Chron. 12:285-290.

Heimberger, C. 1958. Poplar breeding in eastern Canada. Cellulosa e Carta 9(3):7-11.

Heit, C.E. 1972. Propagation from seed. Part 23: growing larches. Amer. Nurseryman 135:14-15, 99-110.

Hellinga, G. 1957. Selectie en veredeling van *Leuce* - populieren op het Bobouwproefstation T.N.O. Ned. Bos (ch)b. - Tijdschr. 29:70-81.

Henry, A. 1914. The artificial production of vigorous trees. J. Dep. Agric. Tech. Inst. 15:34-52.

Henry, A. and Flood, M.G. 1919. The history of the Dunkeld larch, *Larix eurolepis*, with notes on other hybrids. Proc. Roy. Irish Acad. 35:55-56.

Hesmer, H. 1951. Das pappelbuch. Verlag des deutschen pappelvereins, Bonn.

Hicks, R.J., Jr. 1971. Rooting of quaking aspen cuttings: anatomical and biochemical studies. Ph.D. Thesis, Univ. New York, State Coll. For., Syracuse, NY.

Hillis, W. 1971. Distribution, properties, and formation of some wood extractives. Wood Sci. Technol. 5:272-289.

Hinners, K. and Stratmann, J. 1984. Spacing experiment with Japanese larch in the Neumiinster Forest District. Allegmeine Forst-und Jadzeitung 155(12):257-266.

Holder, D.A., Read, E.W. and Manchester, D.F. 1977. The pulping behaviour of four particular hybrid poplars compared to trembling aspen. *In* Proc. North Amer. Poplar Counc. Meet. 1977.

Holst, J. 1974. Performance of Japanese larch and the Dunkeld hybrid larch at the Petawawa Forest Experiment Station. For. Chron. 50(3):1-2.

Holt, D.H. and Murphey, W.K. 1978. Properties of hybrid poplar juvenile wood affected by silvicultural treatments. Wood Sci. 10(4):198-203.

Houtzagers, G. 1937. Het geslacht *Populus* in verband met zijn beteekensis voor de houlteelt. H. Veenman & Zonen, Wageningen, The Netherlands.

Hunt, S.S. 1932. European larch in northeastern United States. Harvard For. Bull. 16. 45 p.

Hutchinson, J.G. 1981. Fast-growing young poplars make good panels, study says. For. Ind. 108(4):58-59.

Hyun, S.K. 1956. Forest tree breeding work in Korea. Inst. For. Genet., Central For. Exp. Stn., Suwon, Korea. Inst. Paper No. 1:1-16.

Hyun, S.K. and Son, D.S. 1976. Neue pappel-hybriden fur das Hachland von Korea. Holzzucht 30:40-43.

Ingestad, T. 1970. A definition of optimum nutrient requirements in birch seedlings. I. Physiol. Plant. 23:1127-1138.

Isebrands, J.G. 1982. Toward a physiological basis of intensive culture of poplar. p. 81-90 *in* Proc. TAPPI Res. and Devel. Division Conf. 29 Aug.- 1 Sept. Asheville, NC.

Isebrands, J.G. and Bensend, D.W. 1972. Incidence and structure of gelatinous fibers within rapid-growing eastern cottonwood. Wood Fiber 4(2):61-71.

Isebrands, J.G., Einspahr, D.W., Phelps, J.E. and Crist, J.B. 1982. Wood and kraft pulping properties of juvenile hybrid larch grown under intensive culture. Tappi 65(19):122-126.

Isebrands, J.G. and Hunt, C.M. 1975. Growth and wood properties of rapid-grown Japanese larch. Wood and Fiber. 7(2):119-128.

Isebrands, J.G. and Michael, D.A. 1985. Effects of leaf morphology and orientation on solar radiation interception and photosynthesis in *Populus*. Proc. IUFRO Workshop. Oct. 1985. Tsukuba, Japan.

Isebrands, J.G. and Nelson, N.D. 1979. Distribution of number of leaves and leaf area in short rotation intensive cultured Populus "Tristis". p. 426 *in* Proc. 5th North Amer. For. Biol. Workshop, Univ. of Florida, Gainesville, FL. (Abstract).

Isebrands, J.G. and Nelson, N.D. 1980. Photosynthate distribution within short rotation intensively cultured *Populus* clones during the establishment year. p. 150 *in* Proc. North Amer. For. Biology Workshop. 11-12 Aug. 1980. Edmonton, Alta. (Abstract).

Isebrands, J.G. and Nelson, N.D. 1982. Crown architecture of short-rotation, intensively cultured *Populus*. II. Branch morphology and distribution of leaves within the crown of *Populus* "Tristis" as related to biomass production. Can. J. For. Res. 12:853-864.

Isebrands, J.G., Nelson, N.D., Dickman D.I. and Michael, D.A. 1983. Yield physiology of short rotation intensively cultured poplars. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-91.

Isebrands, J.G. and Parnham, R.A. 1974. Tension wood anatomy of short-rotation *Populus* sp. before and after kraft pulping. Wood Sci. 6(3):256-265.

Jeffers, R.M. and Isebrands, J.G. 1974. Larch potential in the north central States. p. 80-85 *in* Proc. 8th Central States For. Tree Improv. Conf., Columbia, MO. 1972.

Jensen, I.J. and Harrington, F.M. 1930. Dry-land shelter-belt tests at the Judith Basin Branch Station. Univ. Montana Agric. Exp. Stn., Bull. No. 233.

John, A. 1977. Vegetative propagation of hybrid larch (*Larix* x *eurolepis* Henry) in Scotland. I: Vegetative propagation of forest trees - physiology and practice. p. 129-136 *in* Lectures from a symposium in Uppsala, Sweden.

John, A. 1979. Propagation of hybrid larch by summer and winter cuttings. Silv. Genet. 28(5/6):220-225.

Johnsson, H. 1956. Genetique et amélioration des peupliers. p. 369-410 *in* Les peupliers dans la production du bois et l'utilisation des terres. United Nations, FAO Publ. No. 12.

Johnsson, H. 1976. Das produktions potential der hybridaspe (*Populus tremula* x *tremuloides*) in sudschweden. Holzzucht. 30:19-22.

Keiding, H. 1967. Preliminary investigations of inbreeding and outcrossing in Larch. Silv. Genet. 17(5/6):159-164.

Kellison, R.C. 1976. Genetic improvement of forest trees. *In* Chemical Engineer in Pulp and Paper Technology. AIChE Symposium Series Vol. 72, No. 157.

Kellison, R.C. and Sprague, J. 1981. Genetics program increases pine disease resistance, growth rate. Pulp and Paper 55:187-191.

Kepler, J.E. and Gatherum, G.E. 1964. Japanese larch provenance trial in northeast Iowa. Iowa State J. Sci. 38:393-403.

Khalil, M.A.K. 1984a. The potential of poplars in the boreal regions. I. Survival and growth. Silv. Genet. 33(1):1-8.

Khalil, M.A.K. 1984b. The potential of poplars in the boreal regions. II. Genotypic stability and productive quality of clones. Silv. Genet. 33(1):8-11.

Khosla, P.K. and Khurana, K.D. 1982. Evolution of genus *Populus* Linn. and systematic placement of *P. ciliata* Wall. ex Royle. J. Tree Sci. 1:81-87.

Klemm, G.S. 1967. Some aspects of the qualities of wood from fertilized forests. p. 120-130 *in* Proc. 4th Tappi For. Biol. Conf., Pointe Claire, Que.

Knighton, D. 1970. Simazine may stunt young European larch. Tree Planters' Notes 21(2):17.

Knox, R.B., Willing, R.R. and Ashford, A.E. 1972. Role of pollen wall proteins as recognition substances in interspecific incompatability in poplars. Nature 237:381-383.

Komissarov, D.A. 1938. Applying of growth substances to increase in rooting capacity of cuttings of woody species and shrubs. Comptes Rendu Acad. Sci. URSS 18:63-68.

Komissarov, D.A. 1964. Biological basis for the propagation of woody plants by cuttings. [Translated from Russian to English by Z. Shapiro.] Jerusalem: IPST Press. 250 p. (cited in Staubach 1983).

Kopecky, F. 1956. The problems of black-poplar breeding in Hungary. Erdes zeti Kut. No. 1:17-32.

Kopecky, F. 1962. Anvarak nemesitese. p. 83-118 *in* B. Keresztesi, *Ed.* A magyar nyarfatermesztes, mezogazdasagi Kiado, Budapest.

Koster, R.W. 1968. Outdoor propagation from leaf cuttings of *Populus deltoides* balsam poplars and hybrids. Internat'l Poplar Commission. 13 Sept. 9 p.

Krinard, R.M. and Johnson, R.L. 1975. Ten year results in a cottonwood spacing study. USDA For. Serv., Southern For. Exp. Stn., Res. Pap. SO-106.

Krinard, R.M. and Randall, W.K. 1979. Soaking aids survival of long unrooted cottonwood cuttings. USDA For. Serv., Tree Planters' Notes 30(3):16-18.

Kubes, G. and Swan, H.S.D. 1974. The availability and suitability of larch as pulpwood. Its extractives and their uses. Pulp and Paper Res. Inst. Can., Lab. Rep. 287:1-24.

Kurdiani, S. 1908. Of comparative ability of our forest trees to be vegetatively propagated by cuttings. Lesnoi Zhurrnal 38(3):306-315.

Lane, R.D. and McComb, A.L. 1953. Effects of grass competition upon the establishment of hardwood plantations in Iowa. Iowa State College, Agric. Exp. Stn., Ames, IA. Res. Bull. 399.

Langner, W. 1962. Ergebnisse zuchterbscher Arbeiten mit Schwarzpappeln. Holz-zbl. 88:2509-2512.

Larsen, C.M. 1957. L'enracinement individuel des boutures de peuplier. Zuchter Spec. No. 4.

Larson, P.R. 1969. Wood formation and the concept of wood quality. Yale Univ. School For., Bull. 74. 54 p.

Larson, P.R. 1972. Putting basic research into practice. Tech. Pap. Amer. Pulpwood Assoc. Jan. 1972.

Larson, P.R., Dickson, R.E. and Isebrands, J.G. 1976. Some physiological application for intensive culture. p. 117 *in* Intensive plantation culture: five years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-21.

Larson, P.R. and Gordon, J.C. 1969. Photosynthesis and wood yield. Agric. Sci. Rev. 7:7-14.

Larson, P.R. and Isebrands, J.G. 1972. The relation between leaf production and wood weight in first year root sprouts of two *Populus* clones. Can. J. For. Res. 2:98-104.

Laundrie, J.F. and Berbee, J.G. 1972. High yields of kraft pulp from rapid growth hybrid poplar trees. USDA For. Serv., For. Prod. Lab. Res. Pap. FPL 186. 25 p.

Leatheart, P. 1969. Home grown timbers - larch. Quart. J. For. 63:122-128.

Lee, C.H. 1976. Geographic variation of growth and wood properties in Japanese larch in southwestern lower Michigan. USDA For. Serv., Gen. Tech. Rep. 26.

Lee, D.K. and McNabb, H.S. 1979. Biomass production in coppiced hybrid poplar plantations as influenced by stump height, season of cutting, and number of seasons of growth at Ames and Rhinelander plantations. Unpubl. Rep. (on file at the For. Sci. Lab., Rhinelander, WI.) 10 p.

Lester, D.T. 1964. A provenance test of Japanese larch. Univ. Wisconsin For. Res. Notes 112. 6 p.

Libby, W.J. 1974. A summary statement on the 1973 vegetative propagation meeting in Rotorua, New Zealand. New Zealand J. For. Sci. 4(2):454-458.

Littlefield, E.W. and Eliason, E.J. 1956. Report on an experimental plantation of several species of larch in New York. Silv. Genet. 5:166-169.

Lothner, D.C. 1986. Dollars and sense: fertilization of intensively cultured plantations. Paper submitted at IEA Task Force II Workshop, 21-23 May 1986. Kingston, Ont. 12 p.

Lothner, D.C., Rose, D., Zavitkovski, J. and Ferguson, K. 1981. A financial analysis of poplar intensive cultures in the Lake States. p. 145-163 *in* Energy from Biomass and Waste. V: Symposium Papers. Inst. Gas Technology, Lake Buena Vista, FL.

Lucas, J.S. 1981. Larch program - five year summary. 1976-1981. Eastern Region, Ont. Min. Nat. Resour. 15 p. + appendices.

Lust, N. and Mohammady, N. 1973. Regeneration of coppice. Sylva Gandavensis 39, Research Centre of Silviculture, Management and Forest Policy of the State Univ., Ghent, Belgium. 28 p.

MacGillivray, H.G. 1967. Hybrid between tamarack and Japanese larch appears promising in south-central New Brunswick. Can. Dep. For. Rural Develop., Bi-monthly Res. Notes 23:2-3.

MacGillivray, H.G. 1969. Larches for reforestation and tree improvement in eastern Canada. For. Chron. 45:440-444.

Mahon, J.E. 1966. Empirical yields from stands of black cottonwood in the Lower Fraser River Valley. Univ. B.C., Fac. For., B.S.F. Thesis. 59 p.

Maini, J.S. and Horton, R.W. 1966. Vegetative propagation of *Populus* sp. I. Influence of temperature on formation and initial growth of aspen suckers. Can. J. Bot. 44:1183-1189.

Marton, R., Stairs, G.K. and Schreiner, E.J. 1968. Influence of growth rate and clonal effects on wood anatomy and pulping properties of hybrid poplars. Tappi 51(5):230-235.

Mason, W.L. 1984. Vegetative propagation of conifers using stem cuttings. II. Hybrid larch. For. Commission, UK, Res. Inf. Note No. 91. 3 p.

Mayer-Krapoll, H. 1956. The use of commercial fertilizers - particularly nitrogen - in forestry. Published originally by Ruhr-Stickstoff, Aktiengesellschaft, Bochum, Germany. 111 p.

McCavish, W.J. 1980. Hexazinone - a new forest herbicide. *In* Proc. Weed Control, For. Conf., 1-2 April 1980. Univ. Nottingham, England.

McComb, A.L. 1955. The European larch: its races, site requirements and characteristics. For. Sci. 1:298-318.

McKee, R.H. 1931. New hybrid poplars for pulpwood. Mech. Eng. 53:345-349.

McKittrick, R., White, E.H. and Abrahamson, L.P. 1986. No-till trials with Canadian hybrid poplar clones in Southern New York. Submitted abstract, I.E.A. Task Force II Workshop, 20-23 May 1986. Kingston, Ont.

McKnight, J.S. 1970. Planting cottonwood cuttings for timber products in the South. USDA For. Serv., Southern For. Exp. Stn., Res. Pap. SO-60. 17 p.

McNamara, E.F. and Reigner, I.C. 1955. Root competition slows growth of plantings on unprepared sites in scrub oak. USDA For. Serv., Northeastern For. Exp. Stn. For. Res. Note No. 54. 3 p.

McNamara, E.F. and Reigner, I.C. 1960. Effect of competition on height growth and survival of planted Japanese larch. USDA For. Serv. Northeastern For. Exp. Stn., For. Res. Note No. 103, 4 p.

Melchior, G.H. and Seitz, F.W. 1966. Einige ergebnisse bei testanbauten mit Aspenhybriden. 1. Kreuzungen des Jahres 1951. Silv. Genet. 15:127-133.

Menetrier, J. 1979. Research and development work on poplars. XV. Effect of fertilizer type and the method, rate, and timing of its application on plantations of cuttings. Serv. de la Recherche For., Que. Memoire No. 50. 57 p.

Menetrier, J. and Vallee, G. 1980. Research and development work on poplars. XVI. Results of a trial of forty fertilization treatments on a plantation of cuttings. Serv. de la Recherche For., Que. Memoire No. 57. 82 p.

Merritt, C. and Bramble, W.C. 1966. Poplar plantation research in Indiana - a five-year report. Purdue Univ., Agric. Exp. Stn., Res. Bull. No. 818. 15 p.

Michael, D., Dickmann, D.I. and Nelson, N. 1980. Seasonal and diurnal patterns of photosynthesis and leaf conductance in the first year stands of two *Populus* clones grown under intensive culture. Proc. North Amer. For. Biol. Workshop, 11-13 Aug. Edmonton, Alta. 149 p. (Abstract).

Mikami, S., Watanabe, M. and Ohta, N. 1972. Clonal variation in spiral grain of *Larix leptolepis* Ford. J. Japanese For. Soc. 54:213-217.

Mohrdiek, O. 1983. Discussion: future possibilities for poplar breeding. Can. J. For. Res. 13(3):465-471.

Morel, G. 1960. Producing virus-free Cymbidiums. Amer. Orchid. Soc. Bull. 29:495-497.

Morgenstern, E.K., Nicholson, J.M. and Park, Y.S. 1984. Clonal selection in *Larix laricina*. I. Effects of age, clone, and season on rooting of cuttings. Silv. Genet. 33(4/5):155-160.

Morrison, I.K. 1974. Mineral nutrition of conifers with special reference to nurient status interpretation: a review of literature. Dep. Environ., Can. For. Serv. Publ. 1343.

Morrow, R.R. 1984. Growth of European larch at five spacings. New York's Food and Life Sci. Bull., Cornell Univ. Agric. Exp. Stn., Rep. No. 75. 11 p.

Muhle Larson, C. 1943. Stiklinger of urgeagtige skud paa rodder of baevreasp og graapoppel. Dansk Skorforen Tidsskr. 28:96-113.

Muhle Larson, C. 1963. Considerations sur l'amélioration du genre *Populus* et specialement sur la section Aigeiros. United Nations, FAO/FORGEN 2b19. 8 p.

Muhle Larson, C. 1964. Notes complementaires de l'Institut de Populiculture de Grammont sur les problemes développés à la station 1,2 et 7 du voyuage d'études du 24/6-64. FAO/CIP Congr. Central Europe, 1966 No. 13 and 19. 4 p.

Muhle Larson, C. 1967. Remarques concernant les test précoces dans le travail d'amélioriation du genre *Populus*. Forstpfflanzen-Forstaman 2:33-36.

Muhle Larson, C. 1970. Recent advances in poplar breeding. Internat'l Rev. For. Res. 3:1-67.

Muntzing, A. 1936. The chromosomes of a giant *Populus tremula*. Hereditas 21:383-393.

Murphey, W.K., Bowersox, T.W. and Blankenhorn, P. 1979. Selected wood properties of young *Populus* hybrids. Wood Sci. 11:263-267.

Murphey, W.K., Brady, S.L. and Behan, M.J. 1969. Anatomy and physical properties of two-year Western Larch seedlings grown in mineral deficient solutions. For. Prod. J. 19(12):28-37.

Murray, G. 1982. Genetics of larches and deciduous hardwoods, Petawawa, 1978-1981. p. 144-146 *in* Proc. 18th meeting Can. Tree Improv. Assoc. Part 1. 17-20 Aug. 1981. Duncan, B.C.

Myers, G.C. and Crist, J.B. 1986. Feasibility of manufacturing hardboard from short-rotation intensively cultured *Populus*. For. Prod. J. 36(1):37-34.

Nelson, J.D., Burk, T. and Isebrands, J.G. 1981. Crown architecture of short-rotation intensively cultured *Populus*. I. Effects of clone and spacing on first-order branch characteristics. Can. J. For. Res. 11(1):73-81.

Nelson, N.D. and Ehlers, P. 1981. Comparative photosynthesis within two poplar clones grown in growth room, greenhouse, and field. Plant Physiol. Suppl. 67:93 (Abstract)

Nelson, N.D. and Michael, D. 1982. Photosynthesis, leaf conductance, and specific leaf weight in long and short shoots of *Populus* "Tristis # 1" grown under intensive culture. For. Sci. 28:737-744.

Netzer, D.A. 1984. Herbicide trials on European larch in northern Wisconsin. USDA For. Serv., North Central For. Exp. Stn., Res. Note NC-318. 2 p.

Netzer, D.A. and Noste, N.V. 1978. Herbicide trials in intensively cultured *Populus* plantations in northern Wisconsin. USDA For. Serv., North Central For. Exp. Stn., Res. Note NC-235. 4 p.

Nevalainen, K. and Hosia, M. 1969. The suitability of larch as a fiber raw material. II. Larch as a fiber raw material. Paperi ja Puu 51:503-510.

Nilsson - Ehle, H. 1936. Uber eine in der Natur gefundene Giasform von *Populus tremula*. Hereditas 21:379-382.

Okada, S. 1967. A study on the cuttings of Karamatsu, *Larix leptolepis*. J. Japanese For. Soc. 49(8):316-320.

Olesen, P.O. 1978. On cyclophysis and topophysis. Silv. Genet. 27:173-178.

Ostry, M.E. and McNabb, H.S. Jr. 1982. Preventing blackstem damage to *Populus* hardwood cuttings. p. 36-43 *in* Proc. North Amer. Poplar Council Meeting, 29-22 July 1982. Rhinelander, WI.

Packman, D.F. 1966. Pulping of British softwoods. Part II. Preliminary studies on Japanese larch. Holzforschung 20:110-113.

Paille, G. and Bitto, H. 1979. Le mélèze japonais de Harrington: un exemple de haute productivite et de cooperation en foresterie. Foret-conservation 45(4).

Panshin, A.J. and de Zeeuw, C. 1949. Growth related defects in wood. p. 306 *in* A.J. Panshin and C. de Zeeuw. Textbook of Wood Technology. Vol. 1. McGraw-Hill Book Co., New York, NY.

Panshin, A.J. and de Zeeuw, C. 1970. Textbook of wood technology. 3rd ed. McGraw-Hill, Toronto, Ont. 705 p.

Papaioannou, J. 1963. The geographical distribution of *Populus nigra L.* var *pubescens* Parlat. and of *Populus thevestina* Dode and their hybrids. United Nations, FAO/FORGEN 4/11. 1-15.

Park, Y.S. and Fowler, D.P. 1983. Provenance test of Japanese larch in eastern Canada, including comparative data on European larch and tamarack. Silv. Genet. 32(3/4):96-101.

Parnham, R.A., Robinson, K.W. and Isebrands, J.G. 1977. Effects of tension wood on kraft paper from a short-rotation hardwood (*Populus* "Tristis No. 1"). Wood Sci. Tech. 11:291-303.

Patschke, W. 1912. Uber die extra tropischen und ostaasiatischen coniferen und ihre Bedeutung fur die pflanzen geographische Glieederung Ostasiens - cited in Engler, A. "Botanik Jahr, buch". 443:626-776.

Pauley, S.S., Mohn, C.A. and Cromell, W.H. 1965. NC-51 Japanese larch seed source tests in Minnesota. Minn. For. Notes 157. 2 p.

Pearson, F. and Fielding, H. 1961. Some properties of individual growth rings in European larch and Japanese larch and their influence upon specific gravity. Holzforschung 15:82-89.

Perry, H.J. and Cook, D.B. 1965. Pulpwood for 1995. Pulp and Paper 39:33-34, 44.

Petersen, L. and Phipps, H. 1976. Water soaking pretreatment improves rooting and early survival of hardwood cuttings of some *Populus* clones. Tree Planters' Notes 27(1):12-22.

Phelps, J.E., Isebrands, J.G., Einspahr, D.W., Crist, J.B. and Sturas, J.A. 1985. Wood and paper properties of vacuum airlift segregated juvenile poplar whole tree chips. Wood Fiber Sci. 17(4):529-539.

Phelps, J.E., Isebrands, J.G. and Jowett D. 1982. Raw material quality of short-rotation intensively cultured *Populus* clones. I. A comparison of stem and branch properties at three spacings. IAWA Bull. 3(3-4):193-200.

Phipps, H.M. 1976. Propagation research in the establishment of maximum yield plantations. p. 117 *in* Intensive plantation culture: five years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-21.

Phipps, H.M. 1978. Rooting *Populus* cuttings in various media bound with a liquid plymer. Plant Propag. 24(2):11-13.

Phipps, H.M., Belton, D. and Netzer, D. 1977. Propagating cuttings of some *Populus* clones for tree plantations. Plant Propag. 23(4):8-11.

Phipps, H.M., Hansen, E.A. and Fege, A.S. 1983. Preplant soaking of dormant *Populus* hardwood cuttings. USDA For. Serv., North Central For. Exp. Stn., Res. Rep. NC- 241. 8 p.

Phipps, H.M. and Netzer, D.A. 1981. The influence of collection time and storage temperature on *Populus* hardwood cutting development. Tree Planters' Notes 32(4):33-36.

Phipps, H.M. and Noste, N.V. 1976. Some problems of establishing and managing intensively cultured planted stands. p. 117 *in* Intensive plantation culture: five years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. No. NC-21.

Phipps, R.W. 1885. Annual report. Ont. Dep. Agric.

Piccarolo, G. 1948. Experiences faites dans la culture du peuplier en Italie. p. 97-140 *in* Proc. 10th Congr., Zurich.

Plonski, W.L. 1960. Normal yield tables. Ont. Dep. Lands and For., Silvicult. Serv., Toronto, Ont. Bull. 2.

Pneumaticos, S.M. and Lucas, J.S. 1979. Larch utilization: a feasibility proposal. Ont. Min. Nat. Resour., Eastern Region.

Popovich, S. 1982. Performance of hybrid poplars in Quebec ten years after planting. Dep. Environ., Can. For. Serv., Ste-Foy, Que. Inf. Rep. LAU-X-44. 23 p.

Popovich, S. and Houle, H. 1970. Étude prélimenaire de trois plantations du Quebec (croissance, rendement et productivité). Dep. Environ., Can. For. Serv., Ste-Foy, Que. Inf. Rep. Q-F-X-3.

Pottinger, A.J. and Morgenstern, E.K. 1986. Factors influencing successful propagation of young tamarack stem cuttings. Fac. For., Univ. New Brunswick, Fredericton, N.B. 8 p.

Pourtet, J. 1979. Poplars and willows of the world. p. 12-52 *in* M. Viart, *Ed.* Poplars and willows. United Nations, FAO, Rome. 328 p.

Raitanen, W.E. 1978. Energy, fibre and food: agriforestry in eastern Ontario. Special paper presented at 8th World For. Congr., 16-28 Oct. 1978, Jakarta, Indonesia. 13 p.

Randall, W.K. and Miller, J.E. 1971. Mist propagation recommended for expanding cottonwood rapidly. Tree Planters' Notes 22(4):9-13.

Randall, W.K. and Mohn, C.A. 1969. Clone-site interaction of eastern cottonwood. p. 89-91 *in* Proc. 1969 10th Southern Conf. on For. Tree Improv., 17-19 June 1969. College Station, Texas A&M Univ., Houston, TX.

Rauter, R.M. and Graham, B.J. 1983. The genetics and tree improvement potential of larches in Ontario. p. 11-26 *in* Larch Symposium: Potential for the Future. March 1983. Ont. Min. Nat. Resour. and Univ. of Toronto, Toronto, Ont.

Read, R.A. 1967. Hybrid poplar performance at 10 years in the Nebraska Sandhills. USDA For. Serv., Rocky Mountain For. Exp. Stn., Res. Note RM-91, 8 p.

Rehder, A. 1947. Manual of cultivated trees and shrubs. 996 p.

Rehder, A. 1954. Manual of cultivated trees and shrubs hardy in North America (2nd ed.). MacMillan Co., NY. 996 p.

Rehfeldt, 1970. Genecology of *Larix laricina* (Du Roi) K. Koch in Wisconsin. I. Patterns of natural variation. Silv. Genet. 18:9-16.

Ribe, J.H. 1974. A review of short-rotation forestry. Univ. of Maine, Life Sci. and Agric. Exp. Stn., Misc. Rep. 160. 52 p.

Richardson, A.H. 1924. Forest tree planting. Ont. Dep. Lands and For., Toronto, Ont. Bull. 1:1-67.

Ridge, C.R., Hinckley, T.M., Stettler, R.F. and van Volkenburgh, R. 1986. Leaf growth characteristics of fast-growing poplar hybrids. Tree Physiol. 1(2):209-216.

Riemenschneider, D.E. and Nienstaedt, H. 1983. Height growth to age 8 of larch species and hybrids in Wisconsin. USDA For. Serv., North Central For. Exp. Stn., Res. Pap. NC-239. 6 p.

Rogers, D. 1986. Growth stability of hybrid poplar. Submitted abstract, IEA Task Force II Workshop, 20-23 May 1986. Kingston, Ont.

Rose, D., Ferguson, K., Lothner, D.C. and Zavitkovski, J. 1981. An economic and energy analysis of poplar intensive cultures in the Lake States. USDA For. Serv., North Central For. Exp. Stn., Res. Pap. NC-196. 44 p.

Rudolf, P.O. 1948. Planting of hybrid poplar in the Lake States. USDA For. Serv., Lake States For. Exp. Stn., Pap. No. 14. 17 p.

Sachsse, A., Wulf, A. and Miller-Schonau, R. 1978. Vergleichende Untersuchungen liniger Holzeigenschaften verschiedener Klone der Japanischen Larche (*Larix leptolepis* Gord.). Holz als Roh-und Werkstoff 36:61-67.

Salisbury, F.B. and Ross, C.W. 1978. Plant physiology. 2nd ed. Wadsworth Publishing Co. Inc., Belmont, CA. 436 p.

Schantz-Hansen, T. and Hall, O.F. 1952. Results of testing exotic trees and shrubs for hardiness in northern Minnesota. Univ. Minn., Sch. For., St. Paul, MN. Minn. For. Note 5. 2 p.

Schier, G.A. 1978. Vegetative propagation of Rocky Mountain aspen. USDA For. Serv., Intermountain For. and Range Exp. Stn., Res. Pap. INT-44. 13 p.

Schier, G.A. 1980. Rooting stem cuttings from aspen seedlings. USDA For. Serv. Intermountain For. and Range Exp. Stn. Res. Note INT-282. 4 p.

Schmid, A. 1981. Pour la promotion du peuplier tremble. Mitt. Schweiz. Pappel-Arbeitsgemeinschaft No. 32.

Schmidt, F.L. and Debell, D.S. 1973. Wood production and kraft pulping of short-rotation hardwoods in the Pacific Northwest. p. 507-516 *in* H.E. Young, *Ed.* IUFRO Biomass Studies. Univ. Maine Press, Orono.

Schober, R. 1958. Ergebrisse von Larch - Art - und provenieenzversuchen. Silv. Genet. 7:137-154.

Schreiner, E.J. 1959. Production of poplar timber in Europe and its significance and application in the United States. USDA For. Serv., Agric. Handbook No. 150. 124 p.

Schreiner, E.J. 1970. Mini-rotation forestry. USDA For. Serv., Northeastern For. Exp. Stn. Res. Pap. NE-174. 32 p.

Schreiner, E.J. 1972. Procedure for selection of hybrid poplar clones for commercial trials in the northeastern region. p. 108-116 *in* Proc. 1972 19th Northeast. For. Tree Improv. Conf., 2-4 Aug. 1972. Univ. of Maine, Orono, ME.

Segaran, S. and Rathwell, R.K. 1978. Growth performances of hybrid *Populus* Walker (Syn. Hybrid *Populus* 44-52) in Manitoba. Man. Dep. Renewable Resour. and Transp. Serv., Manuscript Rep. 78-16. 39 p.

Seitz, F.W. 1954. Die bewertung lines Norm-Abweichers aus der Graupappel-Mannigfaltigheit als Zuchtungmittel. Pap. 8th Internat'l Bot. Congr., Paris, 1954 Sect. 13.

Seitz, F.W. 1963. Untersuchungen zur Zuchtung von *Leuce* - Pappeln. Holz-Zbll. 89:623-624.

Sekawin, M.N. 1962. Quelques observations sur la section des peupliers de la section *Leuce* en Italie. p. 806-807 *in* Proc. 5th World For. Congr., Seattle, 1960.

Shapiro, S. 1958. The role of light in the growth of root primordia in the stem of the Lombardy poplar. p. 445-465 *in* K.Y. Thimann, *Ed*. The physiology of forest trees. Ronald Press, NY.

Sheedy, G. 1982. Poplar research and development. XIX. Effects of fifteen fertilizer treatments on cuttings of two hybrid poplar clones. Serv. de la Recherche For., Que. Memoire No. 75. 36 p.

Shelbourne, C.J.A. and Stonecypher, R.W. 1971. The inheritance of bole straightness in young loblolly pine. Silv. Genet. 20:151-156.

Simak, M. 1970. Photo- and thermoperiodic responses of different larch provenances (*Larix decidua* Mill.). Stud. For. Suec. Skogshagsk 86. 33 p.

Simpson, J.D. 1983. The New Brunswick Tree Improvement Council's breeding strategy for tamarack. p. 219-224 *in* Proc. 28th Northeastern For. Tree Improv. Conf., Univ. New Hampshire, Durham.

Smith, B.J. 1967. The heritability of fiber characteristics and its application to wood quality improvement in forest trees. Silv. Genet. 16:41-50.

Smith, J.H.G. 1980. Growth and yield of poplar in British Columbia. p. 51-60 *in* Proc. 2nd Ann. Meeting of the Poplar Counc. of Can., 19-22 Aug. 1980. Richmond, B.C.

Smith, J.H.G. and Blom, G. 1966. Decade of intensive cultivation of poplars in British Columbia shows need for long term research to reduce risks. For. Chron. 42(4):359-376.

Smith, J.H.G. and Blom, G. 1970. Poplar spacing trials show way to gains in wood yield. Can. For. Ind. 90(7):40-41.

Smith, J.H.G. and Debell, D.S. 1973. Opportunities for short rotation culture and complete utilization of seven northwestern tree species. For. Chron. 49:31-34.

Smith, N.G. and Wareing, P.F. 1972a. The distribution of latent root primordia in stems of *Populus robusta*, and factors affecting the emergence of preformed roots from cuttings. Forestry 45:197-209.

Smith, N.G. and Wareing, P.F. 1972b. Rooting of hardwood cuttings in relation to bud dormancy and the auxin content of the excised stems. New Phytol. 71:63-80.

Smith, N.G. and Wareing, P.F. 1974. The distribution of latent root primordia in stems of *Populus* x *robusta*, and factors affecting the emergence of preformed roots from cuttings. Forestry 45:197-209.

Stairs, G.R. 1966. Geographic variation in Japanese larch. p. 30-36 *in* 13th Northeast For. Tree Improv. Conf. Proc., 12-13 Aug. 1965. Albany, NY.

Stairs, R.S. 1965. Geographic variation in Japanese larch. State Univ. New York, Coll. For., Syracuse. 7 p. (Mimeo).

Stanhill, G. 1957. The effect of differences in soil-moisture status on plant growth: a review and analysis of soil moisture regime experiments. Soil Sci. 84(3):205-214.

Stark, R.W. 1965. Recent trends in forest entomology. Ann. Rev. Entomol. 10:303-324.

Starr, G.H. 1971. Propagation of aspen trees from lateral roots. J. For. 69:866-867.

Staubach, M.C. 1983. Vegetative propagation of western larch (*Larix occidentalis* Nutt.). M.S. Thesis, Univ. of Idaho. 67 p.

Steinbeck, K., McAlpine, R.G. and May, J.T. 1972. Short rotation culture of sycamore: a status report. J. For. 70:210-213.

Steneker, G.A. 1976. Early performance of poplar clones in Manitoba. Dep. Environ., Can. For. Serv., Edmonton, Alta. Inf. Rep. NOR-X-156. 25 p.

Stettler, R.F. 1968. Irradiated mentur pollen: its use in remote hybridization of black cottonwood. Nature 219:746-747.

Stipanic, A. 975. L'amélioration du genre melèze (*Larix* sp.) au Service de la recherche du ministere des Terres et Forêts du Quebec. Serv. de la Rech., Dir. Gen. des Forets, Min. des Terres et For. du Que., Memoire No. 20. 37 p.

Stone, E.L., Jr. 1957. British yield tables for European and Japanese larches in New York. Cornell Univ., Agron. Paper 397.

Stout, A.B. and Schreiner, E.J. 1933. Results of a project in hybridizing poplars. J. Hered. 24:216-229.

Strong, T.F. and Zavitkovski, J. 1983. Effect of harvesting season on hybrid poplar coppicing. *In* Intensive plantation culture: 12 years research. USDA For. Serv., North Central For. Exp. Stn., Gen. Tech. Rep. NC-91.

Syrach-Larsen, C. 1934. Forest tree breeding. p. 93-113 *in* Royal Veterinary and Agric. Coll. Yearbook, Copenhagen.

Syrach-Larsen, C. 1937. The employment of species types and individuals in forestry. Roy. Veterinary Agric. Coll. Yearbook, 1937. Raitzel, Copenhagen. 154 p.

Syrach-Larsen, C. 1956. Genetics in silviculture. (Transl. by M.C. Anderson.) Oliver and Boyd, Edinburgh. 224 p.

Syrach-Larsen, C. and Westergaard, M. 1938. Contributions to the cytogenetics of forest trees. I. A triploid hybrid between *Larix decidua* Mill. and *Larix occidentalis* Mull. J. Genet. 36:523-530.

Tew, R.K. 1970. Root carbohydrate reserves in vegetative reproduction of aspen. For. Sci. 16:318-320.

Toda, K. and Mikami, S. 1976. The provenance trials of Japanese larch established in Japan and the tentative achievements. Silv. Genet. 25(5/6):209-216.

Uprichard, J.M. 1963. The extractives content of New Zealand grown larch species. Holzforschung 17:129-134.

Urie, D.H. 1975. Nutrient and water control in intensive silviculture on sewage renovation areas. Iowa State J. Res. 49(3):313-317.

Vallee, G. 1977. Poplar research and management at the Quebec Ministry of Lands and Forests. *In* Proc. North American Poplar Council Annual Meeting, 6-9 Sept. 1977. Brockville, Ont.

Vallee, G. and Stipanic, A. 1983. Growth and performance of larch plantations. p. 47-63 *in* Proc. Larch Symposium: Potential for the Future. Mar. 1983. Ont. Min. Nat. Resour. and Univ. of Toronto, Toronto, Ont.

van Buijtenen, J.P. 1969. Controlling wood properties by forest management. Tappi 52:257-259.

van Vloten, H. 1955. Veredeling van populieren. Korte Meded. Boshouwproefsta. T.N.O. Wageningen No. 21.

Vaughan, D.H., Smith, E.S. and Brann, D.E. 1978. Energy requirements for corn production using various practices and under-row ripping. p. 8 *in* 1978 winter meeting Amer. Soc. Agric. Engineers, Chicago, IL. Pap. No. 78-15190.

Viart, M. 1979. Mini-monographie sur les peupliers. FAO Tech. Consult. on Fast-growing Plantation Broad-leaved Trees for Mediterranean and Temperate Zones, Lisbon, United Nations, FAO/FGB-79, Vol. 1:1-16.

von Althen, F.W. 1979. Preliminary guide to site preparation and weed control in hardwood plantations in southern Ontario. Dep. Environ., Can. For. Serv., Sault Ste. Marie, Ont., Inf. Rep. 0-X-288. 22 p.

von Althen, F.W. 1981a. Site preparation and post-planting weed control in hardwood afforestation: white ash, black walnut, basswood, silver maple, hybrid poplar. Dep. Environ., Can. For. Serv., Sault Ste. Marie, Ont., Inf. Rep. 0-X-325. 22 p.

von Althen, F.W. 1981b. Planting studies with hybrid poplars and cottonwoods in southwestern Ontario. Dep. Environ., Can. For. Serv., Sault Ste. Marie, Ont., Inf. Rep. 0-X-332. 17 p.

Walters, J. 1963. Growth of U.B.C. Research Forest experimental plantations. *In* Annual Report for 1962-63. UBC Research Forest, Haney, B.C.

Wang, C.W. 1971. The early growth of *Larix occidentalis* x *L. leptolepis* hybrid. Univ. Idaho, For. Wildl. and Range Exp. Stn. Note No. 17. 4 p.

Wareing, P.F. and Phillips, I.D.J. 1970. The control of growth and differentiation in plants. Pergammon Press.

Weber, J.C., Stettler, R.F. and Heilman, P.E. 1985. Genetic variation and productivity of *Populus trichocarpa* T. and G. and its hybrids. I. Morphology and phenology of 50 native clones. Can. J. For. Res. 15(2):376-383.

Wells and Rue. 1927. USDA Dep. Bull. 1485, cited by K. Hunt, 1979. Kraft pulping of *Larix* species. Dep. Environ., Can. For. Serv. Bi-monthly Res. Notes 35:16-17.

Wendel, G.W. 1972. Results of a 20-year test of hybrid poplars in West Virginia. USDA For. Serv., Northeastern For. Exp. Stn., Res. Paper NE-237.

Wettstein, W.V. 1930. Die Zuchtung von Pappeln (*Populus*). Zuchter 2:219-220.

White, D.J.B. and Robards, A.W. 1965. Gelatinous fibres in ash (*Fraxinus excelsior* L.). Nature 205:818.

Wilcox, J.R. and Farmer, R.E. Jr. 1968. Heritability and C effects in early root growth of eastern cottonwood cuttings. Heredity 23:239-245.

Wilkinson, R.C. 1974. Realized and estimated efficiency of early selection in hybrid poplar clonal tests. p. 26-32 *in* Proc. 21st Northeastern For. Tree Improv. Conf., 27-30 Aug. 1973. Univ. of New Brunswick, Fredericton, N.B.

Wilson, K. and Pryatt, D.P. 1984. An experiment in intensive cultivation of upland heath. Forestry 57(2):117-141.

Wilson, M.R. 1968. Japanese larch provides first commercial pulpwood crop from Harringtonn plantation. Forêt-conservation. March 20-21.

Winton, L.L. 1968. Plantlets from aspen tissue culture. Science 160:1234.

Winton, L.L. 1971. Tissue culture method of European aspen. For. Sci. 17:348-350.

Wright, J.W. 1962. Genetics of forest tree improvement. United Nations, FAO For. Prod. Stud. 16. 399 p.

Wright, J.W. 1976. Introduction to forest genetics. Academic Press, New York.

Wunder, W.G. 1974. Vegetative propagation of Japanese larch. New Zealand J. For. Sci. 4(2):161-166.

Ying, C.C. and Bagley, W.T. 1977. Variation in rooting capability of *Populus deltoides*. Silv. Genet. 25(5/6):204-207.

Young, H.E. 1957. Coniferous plantation growth in central and southern Maine - a preliminary report. Univ. of Maine, For. Dep., Tech. Note 45. 4 p.

Zahner, R. 1968. Water deficits and growth of trees. *In* T.T. Kozlowski, *Ed.* Water deficits and plant growth. II. Academic Press, NY.

Zaitseva, A., Fedorishcheva, I., Antonovskii, S. and Nikitin, N. 1958. Kraft pulp from *Larix dahurica* wood. Trudy Inst. Lesa. Akad. Nauk SSSR 45:70-78.

Zarges, R.V., Neuman, R.D. and Christ, J.B. 1980. Kraft pulp and paper properties of *Populus* clones grown under short-rotation intensive culture. Tappi 63(7):91-94.

Zavitkovski, J. and Isebrands, J.G. 1983. Biomass production and energy accumulation in the world's forest. *In* Proc. For. Prod. Res. Soc., Wood Energy Forum. 1983. Nashville, TN.

Zavitkovski, J.J., Isebrands, J.G. and Crow, T.R. 1974. Application of growth analysis in forest biomass studies. p. 196-226 *in* Proc. 3rd North Amer. For. Biol. Workshop, Colorado State Univ., Fort Collins, CO.

Zavitkovski, J., Lundgren, A. and Strong, T.F. 1982. Biomass production of 4- to 9-year-old intensively cultured *Larix eurolepis* grown in "Scotch Plaid" plots in Wisconsin. USDA For. Serv., North Central For. Exp. Stn., Res. Pap. NC-231. 10 p.

Zavitz, E.J. 1907. Farm forestry. Ont. Dep. Agric., Bull. 155:1-50.

Zobel, B.J. 1970. Developing trees in the Southwestern United States with wood qualities most desirable for paper. Tappi 53:320-325.

Zobel, B.J., Jett, J.B. and Hutto, R. 1978. Improving wood density of short-rotation southern pine. Tappi 61:41-44.

Zobel, B.J. and Kellison, R.C. 1972. Short rotation forestry in the southeast. Tappi 55:1205-1208.

Zsuffa, L. 1973a. A summary of interspecific breeding in the genus *Populus*. *In* D.P. Fowler and C.W. Yeatman, *Ed.* Proc. Symp. on interspecific and interprovenance hybridization in forest trees. 28-30 Aug. Fredericton, N.B.

Zsuffa, L. 1973b. Hybrid poplar pulpwood production trials in Southeastern Ontario. For. Chron. 49(3):125.

Zsuffa, L. 1976. Grundlagen und Aussichten der Pappel-zuchtung in Ontario, Kanada. Holzzucht. 30:37-40.

Zsuffa, L. 1979. The features and prospects of poplar breeding in Ontario. p. 1-1 to 1-5 *in* Proc. North Amer. Poplar Counc. Annual Meeting, 6-9 Sept. 1977. Brockville, Ont. Ont. Min. Nat. Resour., For. Res. Inf. Pap. No. 102.

Zsuffa, L., Anderson, H.W. and Jaciw, P. 1977. Trends and prospects in Ontario's Poplar management program. For. Chron. 53:195-200.

Zufa, L. 1968. The present work on poplar breeding in Ontario. p. 1-16 *in* 13th session, Internat'l Poplar Commission.

Zufa, L. 1971. A rapid method for vegetative propagation of aspens and their hybrids. For. Chron. 47(1):1-4.