PROCEEDINGS

SYMPOSIUM '89

Peat and Peatlands
Diversification and Innovation

Volume I – Peatland Forestry

Edited by J.K. Jeglum and R.P. Overend

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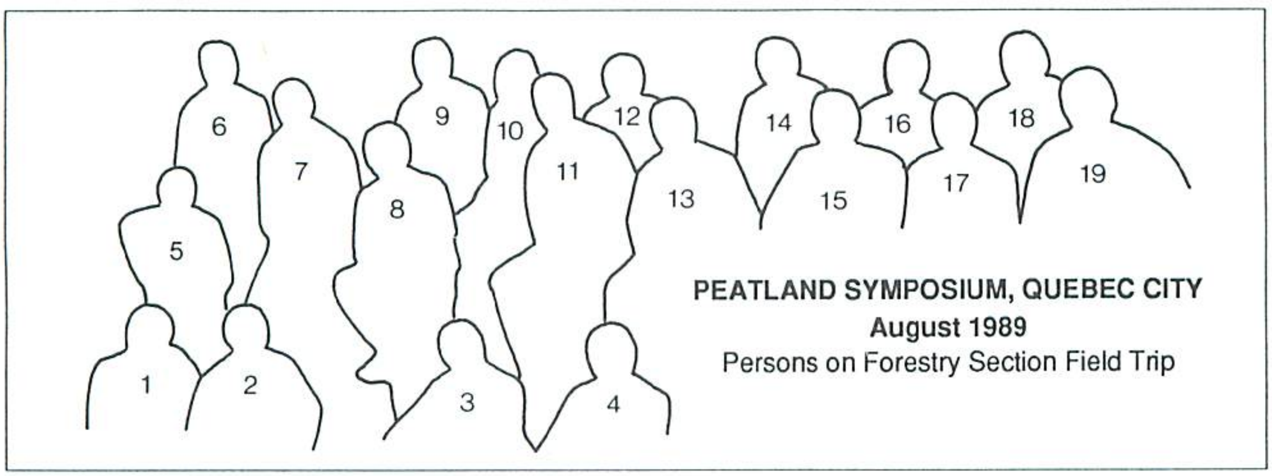
THE ROLE OF METHANE GAS IN PEATLAND HYDROLOGY: A NEW CONCEPT

S.P. Mathur[1], A. Brown[2], H. Dinel[1], A. Buttler[3] and M. Levesque[1]

[1] Land Resource Research Centre
Agriculture Canada
Ottawa, Ontario

[2] National Research Council of Canada
Ottawa, Ontario

[3] University of Neuchatel,
Neuchatel, Switzerland



Participants in the post-symposium field tour in Quebec

1 John Berry, British Columbia, Canada
2 Juhani Päivänen, Finland
3 Francois Trottier, Quebec, Canada
4 Jean-Louis Bélair, Quebec, Canada
5 Larry Turchenek, Alberta, Canada
6 Graham Hillman, Alberta, Canada
7 Hannu Mannerkoski, Finland
8 Harri Vasander, Finland
9 Antti Mäkitalo, Finland
10 Deborah Rogers, Ontario Canada
11 Markku Saarinen, Finland
12 Timo Penttilä, Finland
13 Sam Takyi, Alberta, Canada
14 Richard Rothwell, Alberta, Canada
15 Erik Sundström, Sweden
16 John Jeglum, Ontario, Canada
17 Léopold Roy, Property Owner, Quebec, Canada
18 Elon (Sandy) Verry, Minnesota, USA
19 Björn Hånell, Sweden

also on the tour were: Finn Braekke, Norway; Peter Neily, Nova Scotia, Canada; Fred Haavisto, Ontario, Canada

Photo by Fred Haavisto

FOREWORD

The proceedings of Symposium '89 — Peat and Peatlands: Diversification and Innovation — have been prepared by the Canadian Society of Peat and Peatlands (CSPP) and Forestry Canada on behalf of the organizers of the symposium: the Centre Québecois de Valorisation de la Biomasse (CQVB) and the Canadian National Committee of the International Peat Society (CNCIPS).

Proceedings serve a purpose very different from that of the physical meeting; they are primarily a matter of record, encapsulating a small fragment of progress in one field of specialization into a hard copy that will reach a far wider audience than the 320 participants in the meeting.

In collecting and editing the papers we have tried to ensure that the proceedings meet the needs of researchers, technologists and industrialists who are attempting to adapt the use of the peat resource to the new challenges of the last decade of the 20th century. Society's perception of peat and peatland use is changing. In part, this is because the rapid growth of their use for energy has enabled the resource to be quantified and has given us detailed knowledge of the substance we call peat and of its potential. Peat is neither a fossil material like coal nor a renewable material like the biomass in trees. It can be considered a very transformed biomass and, as we understand the properties that microbial transformation has created, new opportunities emerge through the application of biotechnology. The extensive nature of peatlands, a dominant feature of boreal landscapes, makes them a land resource that can be used effectively for the production of biomass in the form of forests. Recent developments in peatland forestry have opened new possibilities, and these proceedings record the results of a very successful international meeting held under the overall umbrella of Symposium '89.

The theme 'Diversification and Innovation' was followed very closely by the papers presented in Québec City. The possibility of high-value applications of peat is exciting, and the presentations cover the use of peat in substrates designed for horticulture, applications in composting and nitrogen retention, and others in which the unique absorbency characteristics of peat are exploited. The issues of peat characterization and mining were not neglected. In fact, standardization and correlations of in-situ peat characteristics with potential applications are becoming *more* rather than *less* important as new uses are being made of peat.

The peatland forestry theme was timely for this symposium, as it was held in the province in which the most progress has been made in research and in the practice of forest drainage, including programs of government-assisted operational drainage. The symposium began with overviews and updates of research programs by countries and provinces. The growth response of trees and seedlings and various aspects of their nutrition are key elements in the successful application of drainage and fertilization. More in-depth sessions dealt with peat environments and hydrologic characteristics in relation to drainage. Of particular interest were the final sessions on environmental impact and management considerations, such as cost-effectiveness and prescriptions.

Neither a symposium nor its proceedings appear fully formed out of the void. We thank the Board of Directors and our conference Cochairmen Marcel Risi and Bernard Bélanger for their direction and strong support of this conference. Members of the Scientific Program Committee — Ralph Overend (Chair), Esteban Chornet, Bernard Coupal, Charles Tarnocai, Clay Rubec, John Jeglum, Alain Bélanger, Michel Caron, Léon E. Parent, and Louis Canuel — were strongly supported by the staff of the CQVB. It is impossible to mention all the individuals who worked with dedication in what was such an overwhelming team effort, but we must single out Denis Morrissette, Coordinator of the organizational staff, who was always there when we needed assistance of any kind.

The conference organizers thank the following sponsors for their generous financial support in making the conference and publication of the proceedings possible:

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du Sud de Montréal

The post-symposium peatland forestry field trip was arranged jointly by the Québec participants and generously funded by Ministère de l'Énergie et des Ressources du Québec.

R.P. Overend and J.K. Jeglum

AVANT-PROPOS

Le procès-verbal du Symposium de 1989 – La tourbe et les tourbières: diversification et innovation — a été préparé conjointement par la Société canadienne de la tourbe et des tourbières et Forêts Canada au nom des organisateurs, le Centre québécois de valorisation de la biomasse (CQVB) et le comité national canadien de la Société internationale de la tourbe.

Le procès-verbal a un but très différent de celui de la réunion; c'est avant tout la relation officielle écrite d'une faible partie du progrès accompli dans un domaine de spécialisation, et cet imprimé permet de rejoindre un public beaucoup plus nombreux que, par exemple, les 350 personnes qui ont assisté à la réunion.

En rassemblant et préparant les communications pour la publication, nous nous sommes efforcés de voir à ce que le procès-verbal satisfasse aux besoins des chercheurs, technologues et industriels qui tentent d'adapter l'utilisation de la tourbe aux nouveaux défis de la dernière décennie du vingtième siècle. La société voit d'un oeil différent la tourbe et les tourbières, en partie parce que l'accroissement rapide de leur utilisation pour des fins énergétiques a permis de quantifier la ressource et nous a apporté une connaissance détaillée de la matière que nous appellons tourbe et de son potentiel. La tourbe n'est ni une matière fossile, comme le charbon, ni une matière renouvelable, comme la biomasse des arbres. Elle peut être considérée comme une biomasse très transformée, et, à mesure que nous connaissons les propriétés auxquelles a donné lieu la transformation microbienne, de nouvelles possibilités voient le jour grâce à l'application de la biotechnologie. En raison de leur étendue, les tourbières, une caractéristique dominante du paysage boréal, constituent une ressource qui peut servir efficacement à la production de biomasse souls la forme de forêts. Les progrès récents dans le domaine de l'exploitation de la tourbe pour des fins forestières ont fait naître de nouvelles possibilités, et le procès-verbal enregistre les résultats d'une réunion internationale très fructueuse tenue dans le cadre du Symposium de 1989.

Les communications présentés à Québec se sont fortement inspirées du thème <<Diversification et innovation>>. La possibilité d'applications extrêmement utiles pour la tourbe est très interessante et les communications portaient sur l'utilisation de la tourbe dans le substratum destiné à l'horticulture, pour le compostage et la rétention de l'azote ainsi que pour d'autres applications où la propriéte d'absorption particulière à la tourbe est mise à profit. Les questions de la caractérisation et de l'extraction de la tourbe ont aussi éte traitées. En fait, l'uniformisation des caractéristiques de la tourbe sur place et leur corrélation ainsi que les applications potentielles qui s'y rattachent deviennent plus importantes que moins a mesure que cette matière donne lieu à de nouvelles utilisations.

Le thème de l'exploitation forestière était tout indiqué pour un symposium tenu dans la province où le plus de progrès ont été réalisés dans le domaine de la recherche et de la mise en pratique du drainage des forêts, y compris les programmes de drainage opérationnel subventionnés par le gouvernement. Le symposium a débuté par des aperçus et des bilans des programmes de recherche de divers pays et provinces. La réaction de croissance des arbres et des semis et les divers aspects de leur nutrition sont des éléments essentiels du succès du drainage et de la fertilisation. Des séances ont traité plus en profondeur de certains sujets comme l'environnement des tourbières et leurs caractéristiques hydrologiques envisagés par rapport au drainage. Les séances finales portant sur les incidences environnementales et les questions de gestion, comme le rapport coût/rendement et les prescriptions, ont été très intéressantes.

Un symposium et un procès-verbal ne se préparent pas tout seuls. Nous remercions le comité de direction ainsi que les deux coprésidents, Marcel Risi et Bernard Bélanger, pour la façon dont ils ont dirigé la conférence et l'énorme appui qu'ils lui ont accordé. Les membres du comité du programme scientifique, Ralph Overend (président), Esteban Chornet, Bernard Coupal, Charles Tarnocai, Clay Rubec, John Jeglum, Alain Bélanger, Michel Caron, Léon E. Parent et Louis Canuel, ont éte considérablement aidés dans leur travail par le personnel du CQVB. Il est impossible d'énumérer toutes les personnes dont le dévouement a permis de réaliser un effort

d'équipe aussi extraordinaire, mais il nous faut mentionner en particulier Denis Morissette, le coordonnateur du personnel de l'organisation, qui a toujours été là pour tout ce dont nous avions besoin.

Les organisateurs de la conférence remercient de leur généreuse aide financière les commanditaires suivants:

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La tournée d'observation sur le terrain de l'exploitation de la tourbe pour des fins forestières, qui a eu lieu après le symposium, avait éte organisée avec la collaboration des participants de Québec et financée par le ministère de l'Énergie et des Ressources du Québec.

R.P. Overend et J.K. Jeglum

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Section I
Forest Management on Peatlands: Country Overviews

PEATLAND FORESTRY IN FINLAND: PRESENT STATUS AND PROSPECTS

J. Päivänen
Department of Peatland Forestry
Helsinki, Finland

ABSTRACT

In this paper, the term **peatland** or **mire** is used to refer in general to a site supporting a peat-forming vegetation. Peatlands are most extensive in cool, humid climates and occur mainly in temperate, boreal and subarctic zones in the northern hemisphere.

Finland is situated between 60° and 70° N latitude. In the southern part of the country the altitude is usually less than 150 m above sea level. In terms of peatland area, Finland is one of the foremost countries in the world. The total peatland area was originally about 10.4 million ha, or one third of the country's entire land area. Over time, some 0.7 million ha have been cleared for agriculture and 0.1 million ha reserved for peat harvesting. A nationwide conservation plan for peatlands applies to about 0.8 million ha.

Some peatlands support tree growth even in their natural state, but forest drainage has made wood production the most extensive method of using peatland resources economically. The total land area drained for forestry already exceeds 5.7 million ha although part of this area is classified as paludified mineral soil forests. The drained area corresponds to one fourth of the forest land area in the country.

Forest drainage guidelines use information derived from basic and applied research, including studies of peatland ecosystems, site type classification, hydrology, growth and yield, and silviculture. According to the National Forest Inventory (NFI), forest drainage, fertilization and other silvicultural measures have increased the annual growth of peatland forests by at least 7 million m^3. Trees grown in forest drainage areas account for almost one fourth of the country's forests.

RÉSUMÉ

Dans la présente communication le terme <<tourbière>> (**peatland** ou **mire**) désigne de façon générale une station où la végétation se transforme en tourbe. Les tourbières sont le plus étendues sous les climats frais et humides et s'observent surtout dans les zones tempérées, boréales et subarctiques de l'hémisphère nord.

La Finlande est située entre le 60^e et le 70^e degré de latitude nord. Dans le Sud, le terrain se trouve à habituellement moins de 150 m d'altitude. La Finlande est l'un des pays qui possèdent les plus grandes étendues de tourbières. À l'origine, la superficie de celles-ci totalisait environ 10.4 millions d'hectares, soit le tiers de toute la superficie du pays. Quelque 0,7 million d'hectares ont été défrichées pour l'agriculture, tandis que 0,1 million ont été réservés à l'extraction de la tourbe. Environ 0,8 million d'hectares sont protégés par un plan national de conservation des tourbières.

Dans certaines tourbières, même dans leur état naturel, croissent des arbres, mais le drainage à des fins d'exploitation forestière a fait de la production de bois la méthode la plus extensive d'exploitation économique des ressources des tourbières. La superficie totale drainée à cette fin dépasse déjà 5,7 millions d'hectares, mais une partie de cette superficie est classée dans la catégorie des forêts à sol minéral paludéen. La superficie drainée correspond au quart de la superficie forestière du pays.

Les lignes directrices sur le drainage forestier s'inspirent de l'acquis de la recherche fondamentale et appliquée, y compris des études sur les écosystèmes des tourbières, l'accroissement, le rendement et la sylviculture, de la classification des types de stations ainsi que de l'hydrologie. Selon l'inventaire forestier national, le drainage forestier, la fertilisation et d'autres mesures sylvicoles ont permis d'augmenter l'accroissement annuel dans les forêts de tourbière d'au moins 7 x 10^6 m^3. Les arbres cultivés dans les tourbières drainées en vue de l'exploitation forestière constituent près du quart des forêts du pays.

INTRODUCTION

The term **peatland** or **mire** is used to refer in general to a site type supporting peat-forming vegetation. Hence, a mire site is a wetland ecosystem maintained by humid climate and high groundwater level, in which part of the organic material produced accumulates as a result of incomplete decomposition. In the mire ecosystem the biocoenoses and environment are strongly interconnected; in fact, the vegetation forms its own growing substrate. This means that the soil characteristics may change more readily than in mineral soils.

Owing to the different definitions of peat and peatlands, the official figure of about 422 million ha is a very rough estimate of the total peatland area of the world (Kivinen and Pakarinen 1981). It is probably a conservative estimate because knowledge of tropical peatlands, in particular, is scanty. This enormous peatland area has great potential for forestry (Fig.1) However, as recently as 1980, only 9.3 million ha had been drained for forestry, more than half of them in Finland (ibid.).

Figure 1. Sparsely forested composite site type (herb-rich sedge birch-pine fen, RhSR) 50 years after drainage.

CONCEPT OF PEATLAND FORESTRY

Research on peatlands is based heavily on general sciences like physics, hydrology, climatology, geology, botany and chemistry. Peatland forestry is an applied science encompassing the following fields:

1) Mire characteristics
(origin, development, nutrient status, water regime, temperature conditions, mire site types and mire complex types).

2) Peatland amelioration
(development of equipment and techniques for amelioration, changes in peat soil properties as a result of drainage, effect of developing tree stands on site properties, environmental effects)

3) Silviculture, growth and yield of tree stands, harvesting of timber
(revival, regeneration, afforestation, thinning, fertilization, maintenance of ditches)

4) Economics of mire utilization
(cost:benefit studies and investment decision models for wood production, other fields of mire utilization)

In practice, the term **peatland forestry** implies that the main purpose of peatland utilization is wood production. In Finland it is the forested and sparsely forested mire site types that are of primary use in forestry. Some of these sites support tree growth even in their natural state, but growth can be increased considerably by forest drainage.

BACKGROUND

Finland is situated between 60° and 70° N. Usually less than 150 m above sea level in the south, the land rises to over 600 m in the north. The average annual temperature on the southern coast is +5°C and at the polar circle +1°C. The annual cumulative temperature (degree-days over +5°C) on the southern coast is 1350, and in northern Lapland it is 500. Mean annual precipitation varies from 700 (south) to 500 mm (north), and evapotranspiration from 350 (south) to 300 mm (north).

The total area of Finland is 338,000 km^2; of this, 305,000 km^2 is land, the rest is water. According to the NFI , 66% is forest land, 21% wasteland (including poorly productive land), 10% agricultural land and 3% built-up areas, roads, etc.

Ownership of forest land, on an area basis (not including wasteland), is as follows:

	(%)
Private	63
State	24
Companies	9
Municipalities, parishes, etc.	4
	100

There are over 300,000 private forest owners, much of whose land is located on better-than-average sites representing about 80% of the existing logging potential.

Some general information about the forests of Finland follows:

Productive forest land, million ha	20.5
Growing stock, including bark, million m^3	1723
Tree species distribution by volume, %	
Scots pine (*Pinus sylvestris*)	45
Norway spruce (*Picea abies*)	37
Birch (*Betula* sp.)	15
Alder (*Alnus* sp.) and poplar (*Populus tremula*)	3
Mean growing stock, including bark, m^3/ha	84
Mean annual increment on productive forest land, solid volume including bark, m^3/ha	3.5

In the 1960s, the total land drained exceeded the allowable amount considerably, because of overcutting. Therefore, several proposals were put forth for primary improvement and silvicultural programs.

Finland's economy is based heavily on the forest industry. About 80% of forest products are exported, and these account for approximately 40% of Finnish export earnings.

NATURE OF FINNISH PEATLANDS

Finland has one of the highest percentages of peatland area in the world. Peatland accounts for one third of the country's land area — some 9.7 million ha. To this figure can be added another 700,000 ha of peat soils used in agriculture, for a total of 10.4 million ha.

The Finnish peatland classification is based on the composition of the ground vegetation, which reflects the nutrient status of the site and is an indicator of other physico-chemical site factors (Cajander 1913).

The mire site types used in practical forestry (33 types in all) have been plotted against two environmental gradients: nutrient status (oligotrophic→ mesotrophic→ eutrophic) and degree of wetness (Fig. 2). The boundary between ombrotrophic and minerotrophic types is indicated as well. Abbreviations of the site type names have been derived from the Finnish names (see Laine et al. 1986). The site types have been grouped in three main categories:

- genuine, forested site types, with a natural tree stand and relatively uniform hummock or intermediate-level surface vegetation
- sparsely forested, composite site types (treed fens and bogs) characterized by a mosaic of hummock and hollow vegetation (These can be considered mixtures of forested and treeless site types.)
- treeless site types without a natural tree stand.

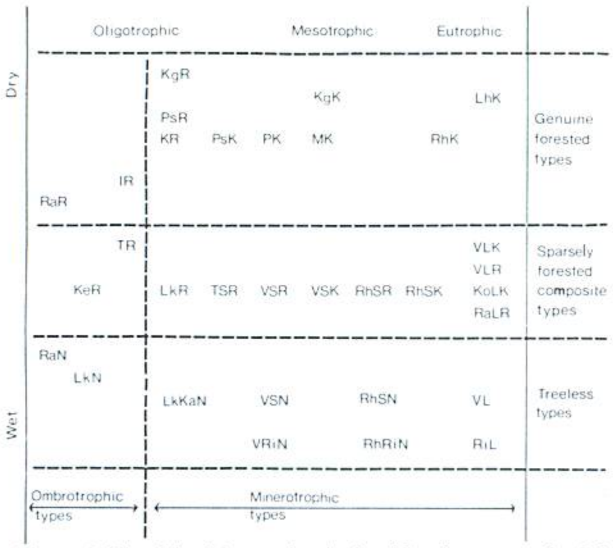

Figure 2. The Finnish peatland classification, organized by environmental gradients (Laine et al. 1986).

Genuine, minerotrophic, forested sites are called **swamps**, whereas ombrotrophic sites are called **bogs**. Sites with a shallow peat layer (< 30 cm) are also classified as **mires**. (In English these are called **paludified forests.**) In the treeless and composite site type groups the term **fen** is applied to minerotrophic sites and **bog** to ombrotrophic sites.

In the NFI, another approach to classifying mire sites has been used since 1960. The sites are divided into six site type groups (e.g., Paavilainen 1989). The use of two different systems presents problems when one trys to compare the results of different studies.

Norway spruce, a minerotrophic species, usually characterizes the richer swamps and treed fens, whereas the less demanding Scots pine is usually the dominant tree species of the poorer mires, including treed bog and poor treed fen and swamp. Birch (*Betula pubescens*) is a common species in minerotrophic swamps and treed fens. Approximately 25% of the original peatlands were hardwood-spruce swamps and treed fens, 45% were pine-dominated mires and 30% were treeless (open) mires.

At the regional level, mainly because of the macroclimate and topographical factors, two main peatland complexes are recognized in Finland: ombrotrophic mires (raised bogs) and minerotrophic mires (aapa and palsa mires) (see Ruuhijärvi 1982). The raised bogs receive their nutrients mainly from rainfall, whereas the aapa mires are dependent upon the surrounding mineral soil for nutrients.

PURPOSE OF FOREST DRAINAGE

In the case of undrained peatlands excessive water in the substrate checks root growth and microbial activity, and may cause unfavorable biochemical reactions. One of the most important purposes of drainage is, therefore, to adjust the water content of the soil to a level that ensures sufficient aeration (Päivänen 1973). This means that the groundwater level has to be lowered 30-40 cm from the peat surface. Increased aeration in the rooting zone improves microbal activity and results in organic matter decomposition and nutrient release.

Several Finnish studies have shown the response of trees to drainage (e.g., Heikurainen 1959, Heikurainen and Kuusela 1962, Laine and Starr 1979). Also, the continuity of post-drainage growth has been studied on naturally tree-covered peatlands (Seppälä 1969, Heikurainen and Seppälä 1973). Tree growth after drainage seems to increase gradually, even after the initial response period.

A special method for calculating the suitability of peatlands for forest drainage has also been developed (Heikurainen 1973). The increase in forest growth as a result of drainage depends on the fertility index (the edaphic wood-producing capacity of the site type) and the locality index (the effect of climatic conditions on post-drainage growth). By calculating the gross profit and the investment costs one can determine the profitability coefficient for the site to be drained.

DEVELOPMENT OF FOREST DRAINAGE ACTIVITY

History

The oldest areas drained for forestry are more than 100 years old. The purpose of the first ditching operations was to prevent paludification of mineral soils. Ditches were also dug during famine years (e.g., in the 1860s) to decrease unemployment. More systematic drainage to increase the growth of tree stands on wetlands was undertaken on state-owned lands in 1908 and on privately owned lands in 1928.

It was not until the 1960s, however, that forest drainage was employed in a nationwide campaign to increase forest growth. The area drained annually increased steadily until 1969, when a maximum of 295,000 ha was drained. The total forest drainage area (about 5.7 million ha), according to the most recent statistics, is greater than that found in the NFI (about 5.0 million ha). This is explained in part by the fact that in the NFI there may be overlap of classes; additional ditching in an area that had been poorly drained earlier may have been considered new ditching. On the other hand, some of the drained sites that originally supported a shallow peat layer may have been placed later in the mineral-soil category.

Most of the drainage has taken place on private land (Fig. 3). Forest amelioration on private land is entrusted to the District Forestry Boards, organizations promoting private forestry. Drainage operations on private land are performed cooperatively. The government subsidizes forest drainage on private forests by paying about 60% of the total drainage costs, partly as grants and partly as low-interest loans. Drainage planning and work supervision are paid for entirely by the government.

Drainage Equipment and Costs

Until the early 1950s, forest ditches were dug by hand. Mechanized forest drainage began in 1953 with the introduction of forest ditch plows. Optimal conditions for plowing were found in the large homogeneous peatland areas of northern and eastern Finland.

A forest ditch plow weighs 5,000-6,000 kg and requires a heavy tractor (14-18 tonnes) with a surface pressure not exceeding 30 kPa. The plow is pulled by a winch. A standard ditch may be plowed in firm peat soil at a rate of 500-600 m/hr.

The length of ditches made by plowing has decreased during the last two decades (Fig. 4). The most common machine now in use is the tractor digger, a unit consisting of a prime mover and hydraulically operated backhoe. The prime mover is usually a light-track tractor with a 45- to 75-kW engine. Forest ditches are dug longitudinally with a bucket scoop, and the cross-section measurements conform to the standard forest ditch dimensions. The output of a tractor digger is 70-90 m of forest ditch/hr. At present, most forest drainage is done with tractor diggers or somewhat larger excavators.

Both ditch digging and ditch cleaning are done by private contractors. Prices, which are based on work studies and cost analysis, are agreed upon annually by the associations of contractors and employers.

The cost of digging a standard-sized forest ditch (0.76 m^3/m) varies from 1.90 to 2.70 FIM/m and the total cost amounts to about 700 FIM/ha[1]. When the cost of main ditches, culverts and transportation of digging equipment is taken into consideration the total cost of drainage is about 900 FIM/ha.

Prospects

Recently, a national program was developed for forestry and the forest industry — "Metsä 2000" ("Forest 2000", Anon. 1986). It provided targets for wood production for all of Finland for the period 1986-2005. According to this program, the area drained annually for forestry purposes will decrease during the first 10-year period to 40,000 ha and during the second 10-year period to 15,000 ha (Fig. 5). The annual need for forest drainage renovation (cleaning of old ditches and additional ditching) was estimated to be 120,000 ha. This target has not been reached, however, during the first two years of the 20-year planning period.

[1] 1 FIM = ca CAD 0.27, 4 Aug. 1989

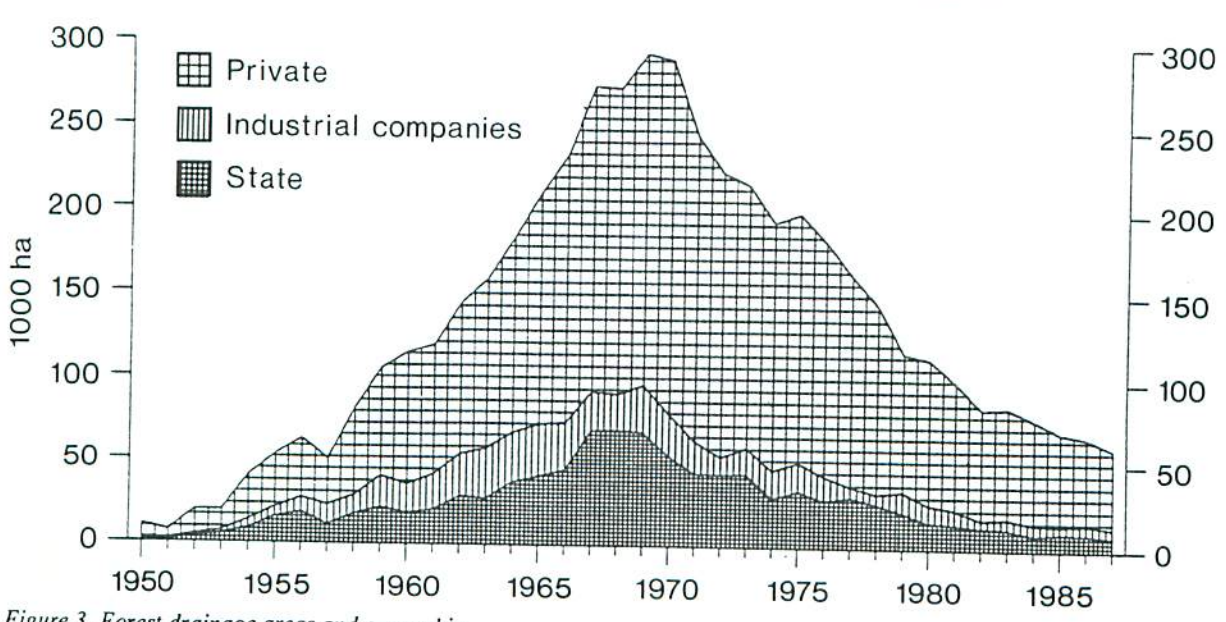

Figure 3. Forest drainage areas and ownership.

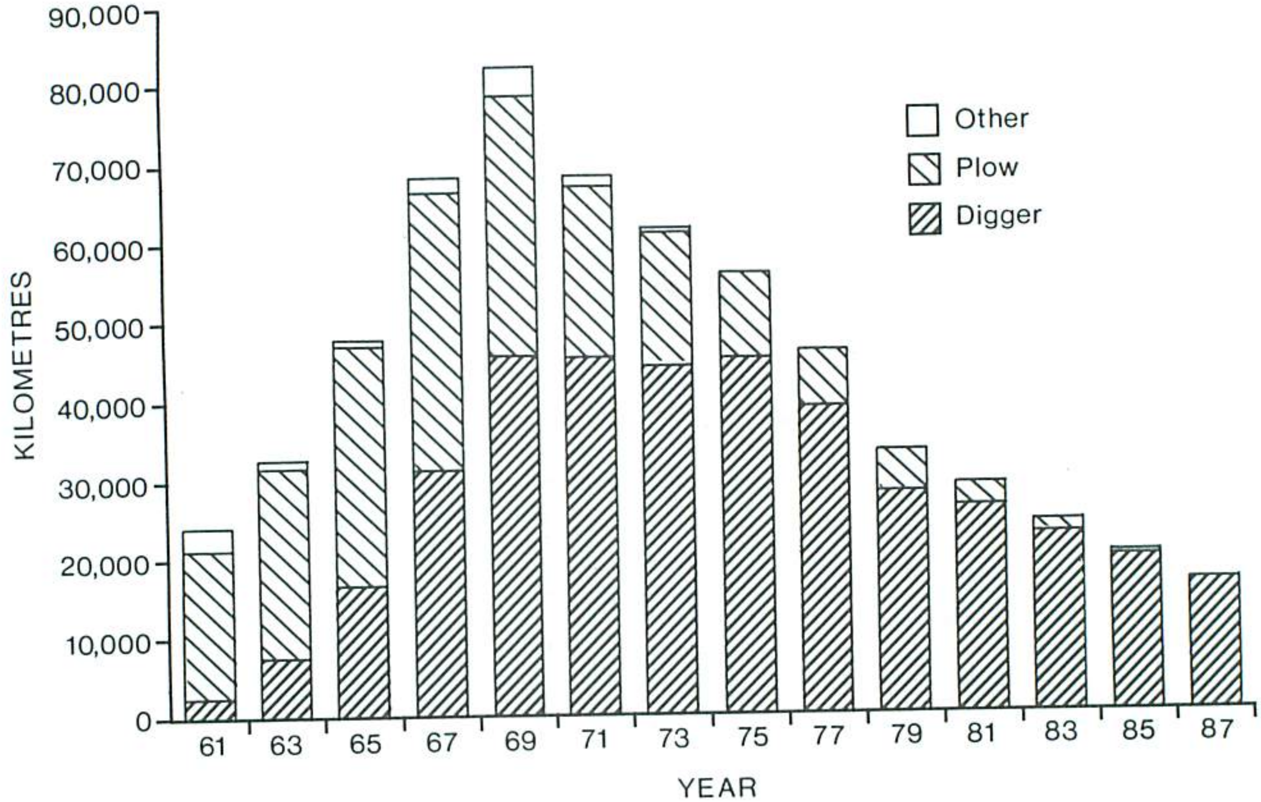

Figure 4. Forest ditching by year and method.

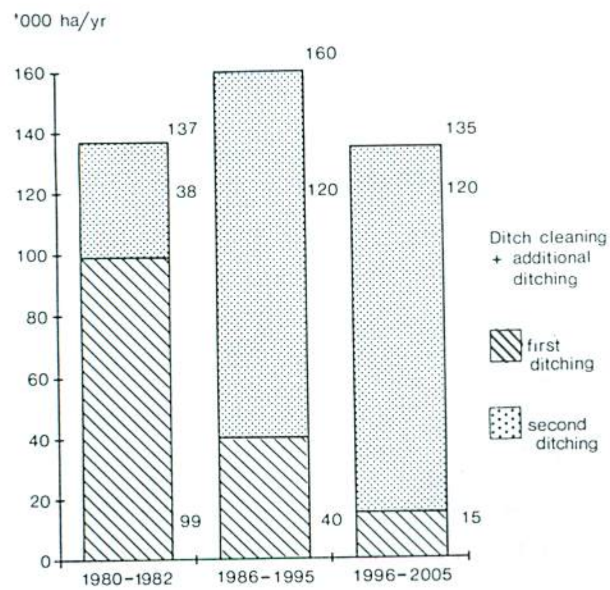

Figure 5. Projected areas of forest drainage by first ditching and second ditching (ditch cleaning and additional ditching).

DRAINAGE DESIGN AND DRAINAGE REQUIREMENTS

Aerial photographs and contour maps (e.g., 1:10,000) are essential for planning drainage. A few levelling lines should be run to obtain a general picture of gradient conditions. The first step in designing a ditch system is to locate the main ditch. This ditch is usually placed in the center of the peatland area where the peat is deepest and subsequent peat subsidence is greatest.

The dimensions of a main ditch depend mainly on its capacity to lead water away from the site. The water in the main ditch should not rise above a level that would prevent the drainage ditches from discharging. In bigger drainage areas the dimensions of the main ditch are calculated on the basis of the average peak flow (MHq), which takes into consideration spring snowmelt and other factors.

The drainage-ditch network proper consists of lateral ditches placed at a very low angle to the contour lines to ensure that there is a gradient toward the ditches. If the land slopes in different directions, the lateral ditch system is constructed in several different directions. Trap ditches are placed so as to collect surface water entering the drainage area, and are located on the border between the peatland and the surrounding mineral soil. For further details concerning the design of drainage systems see Päivänen and Wells (1977).

The effect of drainage is described by the term **drainage depth** or **drainage norm,** which is the mean distance between the soil surface and the water table during the growing season. A drainage norm between 30 and 40 cm is usually sought, but it is dependent on such factors as climate, topography, hydraulic conductivity and vegetation, and can be affected or altered by using various ditch depths and spacings (Meshechok 1969, Braekke 1983). The combination of ditch depth and spacing used is highly dependent on local conditions.

Ditch spacing may be considered biologically optimal if it yields the best tree growth, or economically optimal if it gives the highest rate of interest on the drainage investment. The latter spacing is always wider than the former. It is affected by digging costs and the discounted return as a result of drainage (Keltikangas 1971). On naturally tree-covered peatlands the volume of the tree stand is reduced because ditch lines are cleared. The volume of tree stand lost as a result of line clearing increases as the ditch spacing decreases (Seppälä 1972).

Operational recommendations for ditch spacing in Finnish conditions are as follows:

- shallow peat soils — 50 m
- forested peatlands — 40 m
- sparsely treed peatlands with a low gradient — 30 m

The following are recommended ditch depths for tree-covered peatlands:

- shallow peat (< 30 cm) soil — 70 cm
- deep peat (> 30 cm) soils — 80 cm
- wet, deep peat soils — 90 cm

For a more theoretical basis on which to specify ditch spacing according to hydraulic conductivity, precipitation and drainage norm see Toth and Gillard (1988).

GROWTH, YIELD AND BENEFITS

The profitability of draining peatlands depends on the fertility of the site, the state of existing growing stock, and the geographical location of the site. The more fertile the site, the more timber it contains and the further south it is, the more profitable drainage will be.

Even now, when most of the drainage areas are still at an early stage of development, the volume and growth of peatland forests have increased considerably. The effects of forest drainage, fertilization and silvicultural measures are obvious from statistics obtained from the NFI (3rd NFI 1951-53 and 7th NFI 1977-84) (e.g., Paavilainen and Tiihonen 1988, Paavilainen 1989):

- The total volume of peatland forests has increased by 12% over about 30 years.
- The increase in total volume growth over the same period has been 50%.
- As a result of drainage and fertilization, the growth of peatland forests has increased by at least 7 million m^3 annually, or by more than 10% of the total annual volume growth of all the forests.

The annual increase in growth may reach 13-18 million m^3 by the end of this century (Heikurainen 1982).

It has been estimated, by calculating the inputs (all cost factors) and outputs (the increase in allowable cut evaluated with stumpage prices), that the net profitability of Finnish forest drainage activity is more than 5% (Heikurainen 1980). The indirect effects (employment, balance of foreign payments, etc.) are not included in this estimate.

FORESTS ON DRAINED AREAS

Silvicultural Conditions

A recent nationwide field survey (Keltikangas et al. 1986) provides new information about the condition of tree stands growing on peatlands drained for forestry.

Most of the tree stands have, until now, reached only the stages of "seedling" and "advanced seedling" stand (46%) or "young thinning" stand (29%), and the portion consisting of "mature" and "shelterwood" stands is less than 4% (Table 1). It was estimated that 35% of the drained area needs silvicultural treatment in the first 10 years after inventory; the main measures required are seedling stand treatment and the first commercial thinning.

Table 1. Tree stand development classes on drained peatlands (Keltikangas et al. 1986)

	% of area	Mean volume m^3/ha
Open area or "seed-tree" stand	7	1
"Small seedling" and "advanced seedling" stand	46	11
"Young thinning" stand	29	59
"Advanced thinning" stand	10	122
"Mature" stand	3	149
"Shelterwood" stand	1	52
Low-yielding	4	15
Total and average	100	42

In virgin peatlands the DBH size-class distribution has a hyperbolic form: small stems are numerous, whereas large stems are very few. This means that the stands are uneven-aged. During the first decades after drainage, the unevenness in the age and size of the stands tends to become even more common (Hökkä and Laine 1988). It is especially evident on treed fens and treed bogs, which are only sparsely forested in the virgin stage.

On the nutrient-rich sites, birch is a pioneer tree species. This means that treatment of young stands is especially urgent on the better-than-average sites. Some of the birch stands may naturally develop a spruce understory. Very often spruce can be grown in the shade of birch: the first harvest will be partly birch pulpwood and partly veneer, whereas the second cutting will be among the advance seedlings of spruce.

Thinning on drained peatlands is a high priority if the aim is to grow lumber-sized trees. Usually cutting is done in fall and the wood is transported in winter when the ground is frozen, although year-round harvesting systems are being developed.

Mature tree stands typically regenerate easily on virgin peatland sites as well as on newly drained peatlands. At the final stage of succession, after drainage, the better sites are still highly receptive to regeneration. However, the poorer sites (with *Hylocomium* and *Pleurozium* cover) may need mechanical site preparation and even artificial regeneration (Kaunisto and Päivänen 1985).

According to the field survey cited earlier (Keltikangas et al. 1986) there are drained sites that should not have been drained because they are unsuitable for drainage. (Either the sites are poor or the climate is unfavorable.) This area constitutes about 14% of the total on average; in the south it is only 3% but in Lapland it accounts for as much as 28%.

Maintenance of Drainage

Several factors have an effect on the groundwater level (drainage norm) reached after drainage. Immediately after drainage, ditch depth and spacing, and peat-soil properties, are the most important factors. Drainage increases the growth of the stand, and this results in an increase in the standing volume. Later interception and evapotranspiration of the tree stand have an important role in controlling the drainage norm. The same conclusion has been reached in another way: thinning and clear-cutting cause the groundwater level to rise (Päivänen 1982).

With time, the ditch network gradually loses its drainage efficiency. The ditches become shallower because of peat subsidence, erosion and silting up, vegetation growing in the ditches, and litter and logging residues. There is also some potential for damage to the ditches during logging and wood extraction.

There are more than 1.4 million km of forest ditches in Finland, and only 12% of them have been cleaned. According to Keltikangas et al. (1986) there are 230,000 km of forest ditches that should be cleaned during the first 10-year period.

Tractor diggers have proven to be the best equipment for ditch cleaning. If the original ditch spacing is > 50 m, additional ditching (a new ditch midway between the original ditches) may be a good alternative. Very often, however, both ditch cleaning and additional ditching are needed in the same area. Studies dealing with these problems are in progress (Päivänen and Ahti 1988).

RESEARCH AND HIGHER EDUCATION IN PEATLAND FORESTRY

The Finnish Forest Research Institute, under the direction of the Ministry of Agriculture and Forestry, began its activities in 1918. The Institute employs a permanent staff of more than 800, of whom a quarter are researchers. Over half of the staff are employed in regional units. Since 1928 the Institute has had a Peatland Forestry Department, whose staff members study the characteristics, classification and hydrology of peatlands, drainage and improvement of peat soil fertility, and management of peatland forests. At five of the eight research stations work is being done on peatland forestry problems.

In the Faculty of Agriculture and Forestry at the University of Helsinki, 10 departments are involved in forestry education. One of them is the Department of Peatland Forestry, established in 1939, which provides both general and special courses on peatlands. During this 50-year period about 135 students majored in peatland forestry. During the same period 10 doctoral theses were published on peatland forestry problems.

CONCLUSION

This paper presents a general discussion of peatland forestry as it is practised in Finland. Forest drainage has proved to be a good method of increasing the growth of tree stands on peatlands with excess water in their substrate. However, many factors such as site type, climate, planning, silvicultural measures and environmental issues have to be considered.

In the near future the main emphasis in peatland forestry will be on ditch maintenance and silvicultural management of tree stands on drained peatlands.

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CURRENT STATUS OF FOREST DRAINAGE IN THE USSR AND PROBLEMS IN RESEARCH

S.E. Vompersky
Forest Research Laboratory of the USSR
USSR Academy of Science
Uspenskoe, Moscow Region, USSR

ABSTRACT

The USSR contains the greatest area of peatlands and excessively moist forested lands of any country in the world. There are about 5.5 million ha of drained forested land with effectively operating ditch networks, and another 1 million ha of older, drained forested lands that are ineffectively drained as a result of secondary waterlogging. The best drainage results have been achieved in the Baltic republics and in the Ukraine. Even though the efficiency of forest drainage in the Russian Soviet Federated Socialist Republic is, in the majority of cases, 30 to 40% below what was expected, drainage is still considered to be an important treatment for improving forest production. The reasons for ineffective drainage are: 1) insufficient intensity of drainage; 2) low quality of ditch construction; 2) sparse road networks; 3) peatlands that respond poorly as a result of low nutrient status, lack of trees, or unfavorable age or composition of tree species; and 4) lack of maintenance of the drainage systems.

Annual rates of new forest drainage have been declining because lands close to the reclamation stations have already been drained and because money needs to be spent on reconstruction of old drainage systems. As well, reconstruction of old drainage systems is hindered by the lack of machinery suitable for ditches not accompanied by roads.

Several problems remain to be addressed, namely: 1) development of rational methods for rehabilitating previously drained areas that have become waterlogged; 2) elaboration of optimal parameters of drainage systems and revision of existing recommendations for their construction; 3) monitoring of drained areas by means of remote sensing; 4) evaluation of the environmental effects of forest drainage; and 5) provision of information to promote more objective public attitudes toward the rational utilization of peatlands.

RÉSUMÉ

L'URSS renferme les plus vastes étendues de tourbières et de terrains boisés excessivement mouillés du monde. Elle compte près de 5,5 millions d'hectares de forêts drainées où les réseaux de fossés sont efficaces et un autre million d'hectares de forêts plus anciennes, mais mal drainées en raison d'un engorgement secondaire. Les travaux de drainage ont donné de meilleurs résultats dans les pays baltes et en Ukraine. Même si l'efficacité du drainage forestier dans la République socialiste fédérative soviétique de Russie est, dans bon nombre de cas, de 30 à 40 % inférieure aux prévisions, le drainage est toutefois considéré comme un traitement important pour améliorer la productivité des forêts. L'inefficacité du drainage est attribuable à : 1) l'insuffisance du réseau de drainage; 2) des fossés de piètre qualité; 3) des réseaux routiers insuffisants; 4) la présence de

tourbières qui réagissent mal au traitement en raison de leur équilibre nutritif précaire, du manque d'arbres ou de l'âge ou de la composition défavorable des peuplements; 5) un manque d'entretien du réseau de drainage.

La proportion annuelle de nouvelles forêts drainées a diminué parce que les terres situées près des stations d'assainissement le sont déjà. La nécessité de reconstruire les anciens réseaux de drainage a également entravé le processus. De plus, la reconstruction de ces vieux réseaux est ralentie par le manque d'engins capables de creuser des fossés qui ne bordent pas des routes.

Il reste plusieurs problèmes à aborder, plus précisement : 1) l'elaboration de méthodes rationelles d'assainissement des régions autrefois drainées que se sont engorgées; 2) l'élaboration des paramètres optimaux pour les résaux de drainage et la révision des normes actuelles de construction; 3) la surveillance des secteurs drainés grâce à la télédétection; 4) l'évaluation des effets environnementaux du drainage forestier; et 5) la diffusion de l'information afin de favoriser des attitudes plus objectives chez le public à l'égard de l'utilisation rationelle de tourbières.

INTRODUCTION

The area of excessively moist forests and peatlands (Fig. 1) in the USSR accounts for about 21.8% of forest land, i.e., about 245,000,000 ha (Sabo et al. 1981). Although forest drainage in the USSR has been undertaken since the beginning of the 19th century, it is only in the second half of the present century, after World War II, with the introduction of excavator ditch digging, that the process has assumed major importance. As can be seen in Figure 2, the rate of forest drainage in the USSR increased sharply between 1960 and 1980. However, in the 1980s, the area drained decreased annually, to a low of 149,000 ha in 1988. Further decreases are expected in 1989 and 1990.

In recent years we have experienced major economic difficulties in the USSR. This situation has affected forest drainage activities, partly because of the lack of special digging machinery and unsatisfactory maintenance and repair of equipment. In addition, commercial machines for repairing ditches along which there are no roads are not available. Ditches dug some time ago require reconstruction. The areas close to equipment stations have been drained for the most part, but reforestation of drained areas is insufficient. Economic incentives for forest drainage development have not yet been introduced. In short, if forest drainage is to become a major silvicultural activity in the USSR, proper planning, adequate funding and suitable equipment are essential.

EFFECTIVENESS OF DRAINAGE

The drained forest area with an active ditch network in the USSR amounts to 5,500,000 ha. The effectiveness of drainage in different regions varies. In regions in which drainage has been effective and road networks have been properly placed for intensive forestry, overall benefits in terms of increased wood production have been high, as expected. For instance, in Latvia (Bush and Zalitis 1983), maximum efficiency was achieved over 49% and minimum efficiency over 13% of the total area drained (4211 km^2). In addition, 9.8 km of passways (simple roads) were constructed per 100 ha of drained area. This permitted intensive forestry activities and yielded an annual profit of 6,000,000 roubles, including 2,400,000 roubles as a result of additional wood increment from the drained area.

Forest drainage operations were less effective in the Russian Republic, where less intensive drainage was planned, and where drainage was not always carried out at the required rate. The per-hectare drainage cost was low, half the cost of that in the Ukraine or in the Baltic area. According to estimates made by research and operational institutions, the benefit from drainage in the Russian Federation was only two thirds of what had been expected, and no increase in the current season's wood increment was observed over 19% of the drained area. The main reasons for this insufficient response were the inferior quality of the initial operations, early failure of ditches, an insufficient degree of drainage, lack of roads,

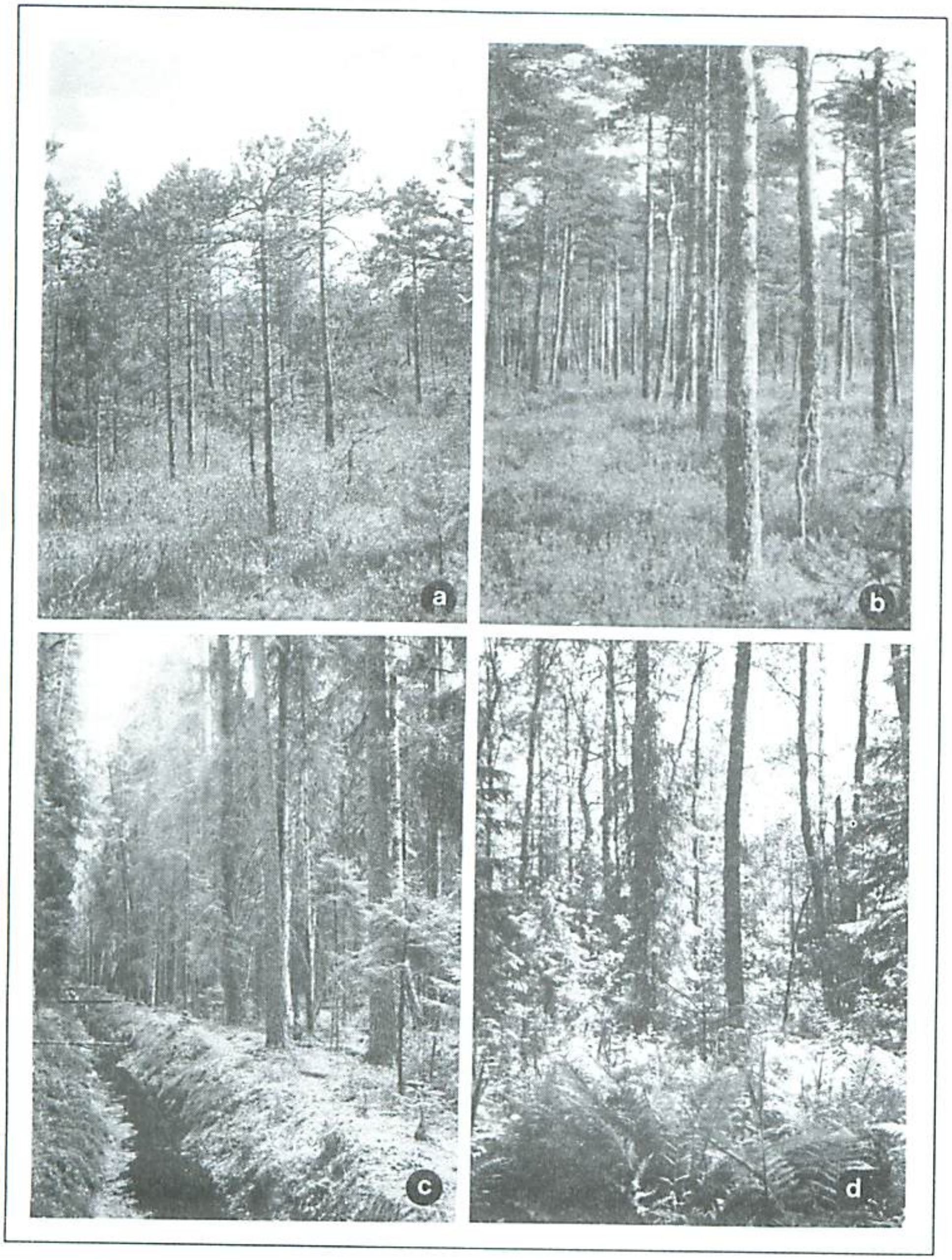

Figure 1. *Some peatland forests on which drainage has been undertaken (Zapadnaia Dvina Experimental Station, central part of the USSR forest zone, 56°N, 32°E): a) oligotrophic* Sphagnum *cotton-grass dwarf-shrub pine bog; b) oligo-mesotrophic dwarf-shrub* Sphagnum *pine bog; c) mesotrophic grass-sedge hardwood-spruce-pine swamp; d) eutrophic herb-rich black alder fen.*

SOME RESEARCH NEEDS

In some cases, the inefficiency with which forest drainage is undertaken in the USSR is due to inadequate research. Methods employed in redraining areas and recovering old drainage networks, the equipment available for these activities, procedures for reconstructing stands of little value, and improvement cuttings in peatland forests are poorly developed. Our experience in drainage operations, accompanied by fertilization, cultivation or improvement cuttings, is very limited. Remote sensing techniques for observation of drained areas and evaluation of the efficiency of drainage over large areas have not been elaborated in the USSR. The typology and classification of excessively moist forests and peatlands need to be improved. Forest drainage does not seem to be beneficial in regions with deeply frozen peat soils, which are slow to melt in summer (i.e., in the northwest areas of the European part of the Russian Republic and in Siberia). The need to understand the ecological impact of forestry practice on peatlands, and to assess probable negative effects of peatland drainage on the environment, has increased sharply. Finally, the need to monitor the dynamics of natural and drained forests in view of the probability of man-induced climatic changes has emerged. These and other problems are being examined in a number of countries, including the USSR.

and drainage of woodless peatlands and bogs with unfavorable stand composition. Striving to drain larger areas at lower cost often leads to a lower net benefit. Nevertheless, despite all the shortcomings of drainage practice, the value of drainage is recognized everywhere in the Russian Republic.

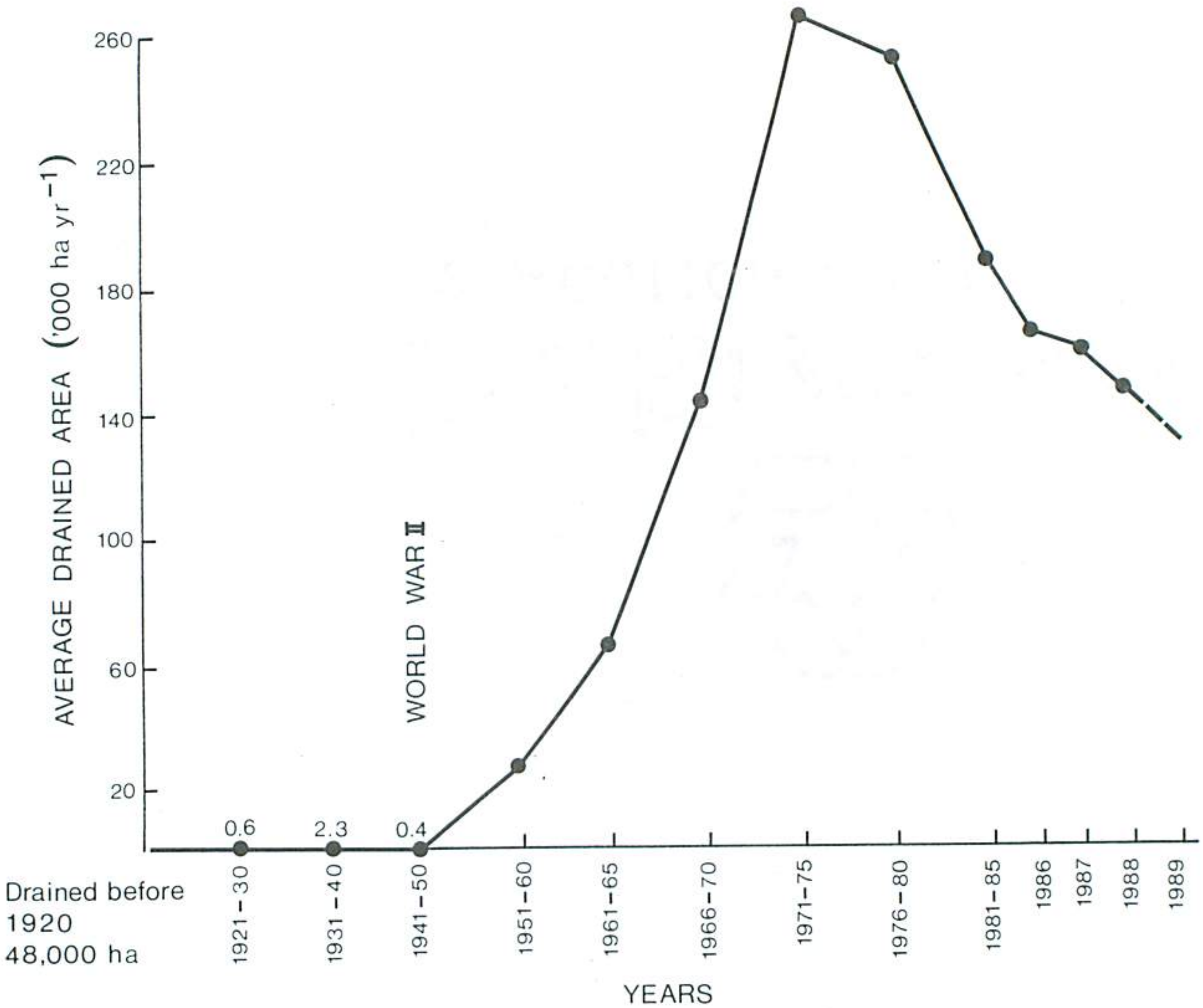

Figure 2. Dynamics of the average rates of forest drainage in the USSR.

ENVIRONMENTAL IMPACT

In addition to the ecological situation, public opinion about forest drainage in the USSR plays an important role in its development. Environmental groups, including those in the USSR, often oppose peatland drainage. In the past, mistakes were made in the use of peatlands both in agriculture and in forestry. For instance, in the Karelian Autonomous Republic, there is a fairly large area of poorly drained woodless peatlands that has not been fertilized or cultivated. Sometimes peatlands that are a valuable source of cranberries or are difficult to develop in any economically beneficial way have been drained. Frequently the quality of drainage has been unsatisfactory. Consequently, there has been considerable opposition to drainage.

Figure 3 represents an attempt to systematize the effects of forest drainage on the environment (Vompersky 1982). Feedback and trophic chains have been omitted for simplicity. A complete description of this model, with all the pathways, is presented elsewhere (ibid.).

Unfortunately, the majority of the effects have been studied insufficiently from the quantitative point of view, particularly the change in total evaporation, ground water flow to and from the drained area, peatland radiation balance, and carbon dioxide and oxygen balance in the air layer near the surface.

In the USSR and elsewhere, the effect of forest drainage on water resources, river runoff, and the productivity of naturally drained forest adjacent to artificially drained peatlands has been intensively studied (e.g., Heikurainen 1972, Sabo 1972, Ivanov 1977, Starr and Paivanen 1981). The effect of drainage on river runoff will be discussed in another paper in these proceedings; it is based

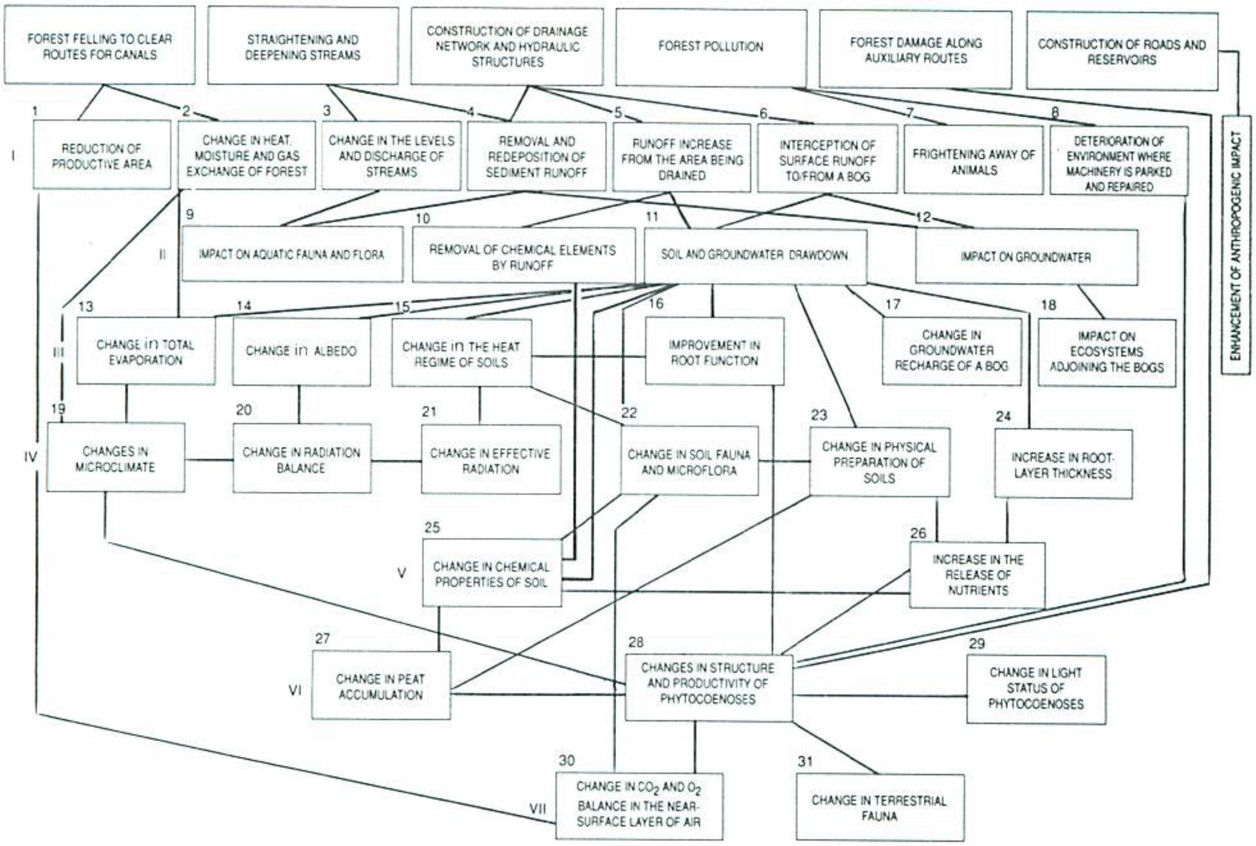

Figure 3. The chains of direct impact of peatland forest drainage on the environment and its consequences. The upper row = types of drainage operations: Roman numerals indicate successive levels of consequences, whereas the numbers of consequences are shown as Arabic numerals. The chains of impact extend from top to bottom, with horizontal chains indicated by arrows.

on research results obtained in collaboration with Dr. Sirin and Dr. Nazarov. As for the assessment of the effect of peatland drainage on adjoining dry-land forests, relevant publications contain highly varying estimates—positive, negative, and neutral. The variation in estimates of effects results from the variability of the different geographic settings being judged—varying land forms, soils, moisture balances, etc. However, as far as we know, if peatland drainage has an effect on the surrounding dry-land forest, that effect is limited to a small area immediately adjacent to the peatland. Nevertheless, this problem deserves more detailed analysis.

SCALE OF DRAINAGE AND CONSERVATION

The question of the optimum scale of peatland drainage in individual river basins and regions is still being debated. Experts in the USSR believe that, if the waterlogged portion is less than 10% of the area, forest drainage should not be undertaken. Where the waterlogged portion accounts for 20-30%, one third of the peatlands may be drained; where it accounts for 40%, half to two-thirds of the peatlands may be drained. Of course, when draining peatlands one should keep in mind the need to preserve the natural diversity of biogeocoenoses, good berry patches, pharmaceutical plant grounds, and special planting areas. Data on the negative effects of large-scale forest drainage are lacking and this problem should be studied further. Where forest drainage is undertaken in the USSR, the area that is being left undrained, for various reasons, until the end of this century varies from 45 to 80% of the excessively wet forest areas that are potentially drainable (including shallow peatlands and mineral hydromorphic lands).

It is essential, also, to preserve the natural diversity of peatland forests and peatlands, and to establish priorities for the use of these lands. More intensive research into the effects of drainage on the environment and dissemination of objective information to the public about this use of our natural resources are needed. However, by the end of the 1970s only a little more than 1% of the peatland areas had been classified as reserves (Boch and Mazing 1979). The figure has probably doubled by now, but precise statistical data are not available.

Opponents of forest drainage do not distinguish between the use of drained peatland in agriculture and that in forestry. The loss of peat in agricultural use is due primarily to erosion by wind as a result of plowing. In addition, during intensive agricultural activities, large amounts of material are removed annually by the crops, and their compensation by fertilization stimulates further the decomposition of peat and removal of its products. Peatland use in forestry activities differs qualitatively from that in agricultural activities.

LONG-TERM ECOSYSTEM CHANGES

According to my observations and calculations, stemwood removed by cutting accounts for only 15-20% of the phytomass produced by the peatland forest over a 100-year cycle, and 80-85% of the phytomass consists of litterfall and root components that remain on the site. The supply of matter to the ecosystem in the form of dust from the atmosphere and matter produced as a result of nitrogen-fixation is an order of magnitude higher than that removed in the stemwood during the 100-year cycle.

Of course, in order to determine the total effect of forest drainage on peatland, it is necessary to know all the quantities of organic matter and inorganic elements in all components of the biocoenosis before, and for some time after, drainage. Then it is important to establish the rates and magnitude of change of all these components, both within the system and as they enter and leave the system.

My preliminary general conclusions about this problem are as follows. The transformation of peatland ecosystems into forest ecosystems proceeds for several decades. This transformation is accompanied by some organic matter loss resulting from peat mineralization and the loss of decomposition products. However, in drained forest, there is usually a net gain in organic matter because of the considerable increase in litterfall and its slow decomposition.

In my opinion, the process of organic matter accretion and removal in an old drained forest will eventually become balanced, provided that environmental conditions are constant. The net changes in the system become more or less balanced. Destabilization of organic matter exchange processes may result from subsequent, more intensive drainage or secondary waterlogging, and from other human activities. Of course, this problem, and a number of others touched upon in this paper, suggest the need to deepen our knowledge and develop concepts of the structure and function of peatland and forest biogeocoenoses.

CONCLUSION

It should be stressed that I regard the current crisis of forest drainage in the USSR as a temporary phenomenon. Many drawbacks of forest drainage result from its excessively rapid development in the 1970s. Further elaboration of the basic scientific principles of forest drainage, its methods and technology will undoubtedly increase its role in the rational use of excessively moist forest lands.

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PEATLAND FORESTRY IN SWEDEN

B. Hånell
Department of Forest Site Research
Faculty of Forestry
Swedish University of Agricultural Sciences
Umeå, Sweden

ABSTRACT

The peatlands in Sweden are a major resource for forest production. In spite of a long tradition in forest drainage, this resource has been poorly utilized to date.

About 8.4 million ha, one-fifth of the total land area of Sweden, consists of peatland and wet mineral-soil sites. Effective use of these wetlands for forest production requires drainage. On poor peatland sites it is also necessary to add NPK (nitrogen, phosphorus, potassium) or PK fertilizer. Despite the fact that forest drainage has been carried out in Sweden for about 140 years, no more than one million hectares of the peatland area have been drained. Forest fertilization on peatlands is minimal. About 4% of the drained peatlands have been fertilized.

The peatlands are classified into eight site types on the basis of forest productivity after drainage. Approximately half of the peatland area is regarded as suitable for forest production after drainage. More intensive use of this area could sustain forest production equal to more than a 15% increase in the total forest growth in the country.

RÉSUMÉ

Les tourbières de la Suède revêtent une grande importance à l'égard de la productivité des forêts. Elles ont été peu utilisées jusqu'à maintenant, malgré une longue tradition de drainage forestier dans ce pays. Près de 8,4 millions d'hectares, soit le cinquième de la superficie totale de la Suède, se composent de tourbières et de stations à sol minéral mouillé. Il faudra drainer ces terres humides pour y permettre un aménagement forestier efficace. Les tourbières pauvres devront être également fertilisées à l'aide d'engrais à l'azote, au phosphore et au potassium (N, P et K) ou au PK. Même si la pratique du drainage forestier en Suède date d'environ 140 années, un million d'hectares de tourbières tout au plus ont été drainés et seulement 4 % de la superficie drainée a été fertilisée.

Les tourbières sont classées selon le type de station (8 au total) établi à partir de la productivité forestière après le drainage. Près de la moitié de la superficie des tourbières est jugée propre à l'aménagement de forêts après leur drainage. Une utilisation plus intensive de ces terres pourrait se traduire par une augmentation d'au moins 15% de la superficie boisée productive du pays.

INTRODUCTION

In spite of its northerly location, between latitudes 55° and 69°N (Fig. 1), Sweden has a fairly mild climate. This is a result of the moderating effects of the Gulf Stream, which provides the country with relatively warm winds from the west and southwest. Because of this variation in latitude, and also because of the variation in altitude (from 0 to 2000 m above sea level), climatic conditions in Sweden differ a great deal from north to south and from west to east. The growing season (i.e., the period during which the mean daily temperature is above 5°C) is longest (about 240 days) in the southwest, and shortest (less than 120 days) in the northwest. In all regions, the mean temperature during the warmest month exceeds 10°C, a basic condition for forests with elevated canopies.

Figure 1. Map of Sweden, superimposed on a section of eastern North America at the corresponding latitudes.

Precipitation varies considerably in different parts of the country, but is sufficient for tree growth everywhere. In most regions it ranges from 600 to 900 mm/yr. It is higher in the southwest (about 1200 mm/yr) and in the Scandinavian mountains in the northwest (up to 1800 mm/yr). Throughout the year, precipitation exceeds evapotranspiration in all parts of the country. Consequently, the Swedish climate is humid and the conditions for peat formation are favorable.

Peatlands are common in practically all parts of the country. In northern Sweden they are more extensive, but less deep, than in the southern regions, where sites with peat several metres deep are common. The Swedish forests are dominated by pure and mixed stands of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). These two species account for 85% of the total timber supply. The remaining 15% are deciduous trees, mainly birch (*Betula pubescens* and *B. pendula*), mixed with conifers.

PEAT-COVERED AREAS

The major part (57%) of the total land area of Sweden (40.9 million ha) is productive forest land. One fifth, or 8.4 million ha, is covered by shallow or deep peat. *Wet mineral soils* have a shallow peat layer, less than 30 cm; on *peatlands* the peat depth is 30 cm or more. Wetlands are classified, according to present forest productivity, as either nonproductive (open or sparsely forested) (<1 m^3/ha/yr) or productive (>1 m^3/ha/yr). There are areas of productive and nonproductive land on both wet mineral soils and peatlands. The proportion of nonproductive wetland, in both the wet mineral soil and the peatland categories, increases with elevation (Fig. 2). Most of the peatland area is currently nonproductive, whereas the wet mineral-soil area is dominated by productive forest land (Table 1).

FOREST PRODUCTION ON PEATLANDS

In the boreal coniferous forest zone, the most important method of improving forest production on peatlands is to lower and control the groundwater table. The primary goal of forest drainage is to achieve better soil aeration so as to improve tree-root respiration. Swedish peatlands have been used for forest production since the middle of the nineteenth century, although in the beginning, production was minimal. It was not until the turn of the century, because of an increasing demand for industrial wood, that large-scale forest drainage was undertaken (Fig. 3).

The period of most intensive drainage coincides with the economic depression in the 1920s and 1930s, when private landowners were given state subsidies to carry out forest drainage in order to reduce unemployment. A peak was reached in 1933, when almost 10,000 km of ditches, affecting an area of approximately 50,000 ha, were dug. (For comparison, it should br noted that almost 300,000 ha/yr were drained during the period of most intensive drainage in Finland, where peatland resources and climatic conditions are similar.)

Until the 1950s, all ditches were dug by hand. Since then, drainage operations have been fully mechanized. *Traditional* forest drainage was aimed at increasing the productivity of the site. However, since the 1970s, the aim has increasingly been to prevent the water table from rising after clearcutting by means of *remedial* drainage, mainly on mineral soils. In recent years, traditional forest drainage has been replaced by remedial ditching.

It is estimated that 50% of Sweden's 8.4 million ha of peat-covered wetlands could be used for forestry. To date, about one million ha of these wetlands have been drained (Fig. 4).

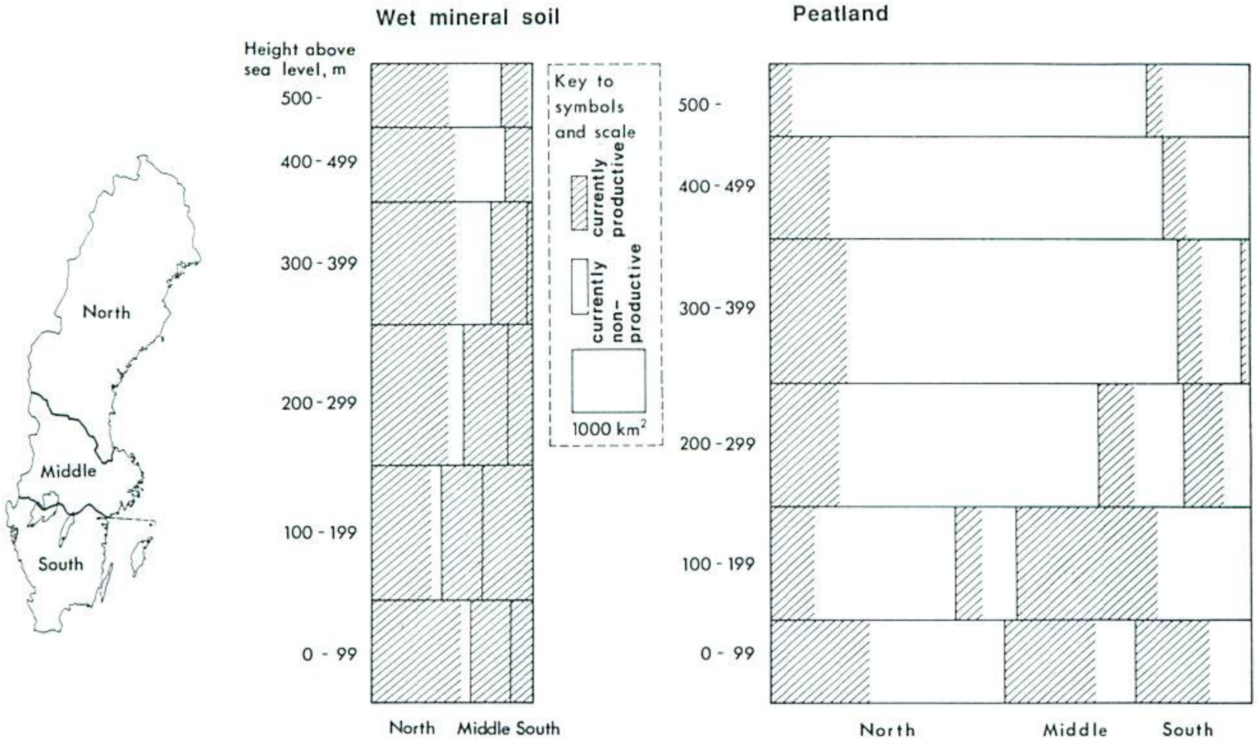

Figure 2. Wet mineral-soil and peatland area distributed according to elevation classes.

As a result of weathering, mineral soils are continuously supplied with nutrients. Since this process does not take place in peat soils, these are characterized by small amounts of mineral nutrients, like phosphorus (P) and potassium (K). On the other hand, the amount of nitrogen (N) present is commonly large. However, the supply of N that is easily available to plants, the ammonium and nitrate nitrogen, is most often small. As for the micronutrients, boron (B) deficiencies are also observed on trees growing on peatland. Prolonged, good forest growth can be achieved after drainage only, provided that the supplies of P and K (from the soil surface and 20 cm down) are at least 150 and 75 kg/ha, respectively. In well humified, herb-rich sedge peat the amounts are often twice as high. The total amounts of P and K in weakly decomposed *Sphagnum* peat, however, are not more than about 50 kg/ha (Holmen 1964). Accordingly, the addition of PK or NPK fertilizer promotes good tree growth on many peatland sites (Malmström 1935, Holmen 1980). Nevertheless, forest fertilization on peatlands has been minimal in Sweden. In all, about 40,000 ha of peatlands have been fertilized since this measure became common in the 1960s, and currently the level is less than 1000 ha/yr.

Table 1. Area of peat-covered wetlands in Sweden, by region (values in '000 ha)

	North		Middle		South		All Sweden		Total
	Prod.	Non-Prod.	Prod.	Non-Prod.	Prod.	Non-Prod.	Prod.	Non-Prod.	Prod.+Non-prod.
Peatland	776	3528	405	678	593	388	1774	4594	6368
Wet mineral soil	967	335	444	15	257	6	1668	356	2024
Sum	1743	3863	849	693	850	394	3442	4950	8392
Total Prod. +Non-prod.	5606		1542		1244		8392		

Prod. = productive forest land with productivity ≥ 1 m^3/ha/yr

Non-prod. = nonproductive wetlands, open or sparsely forested, with productivity < 1 m^3/ha/yr

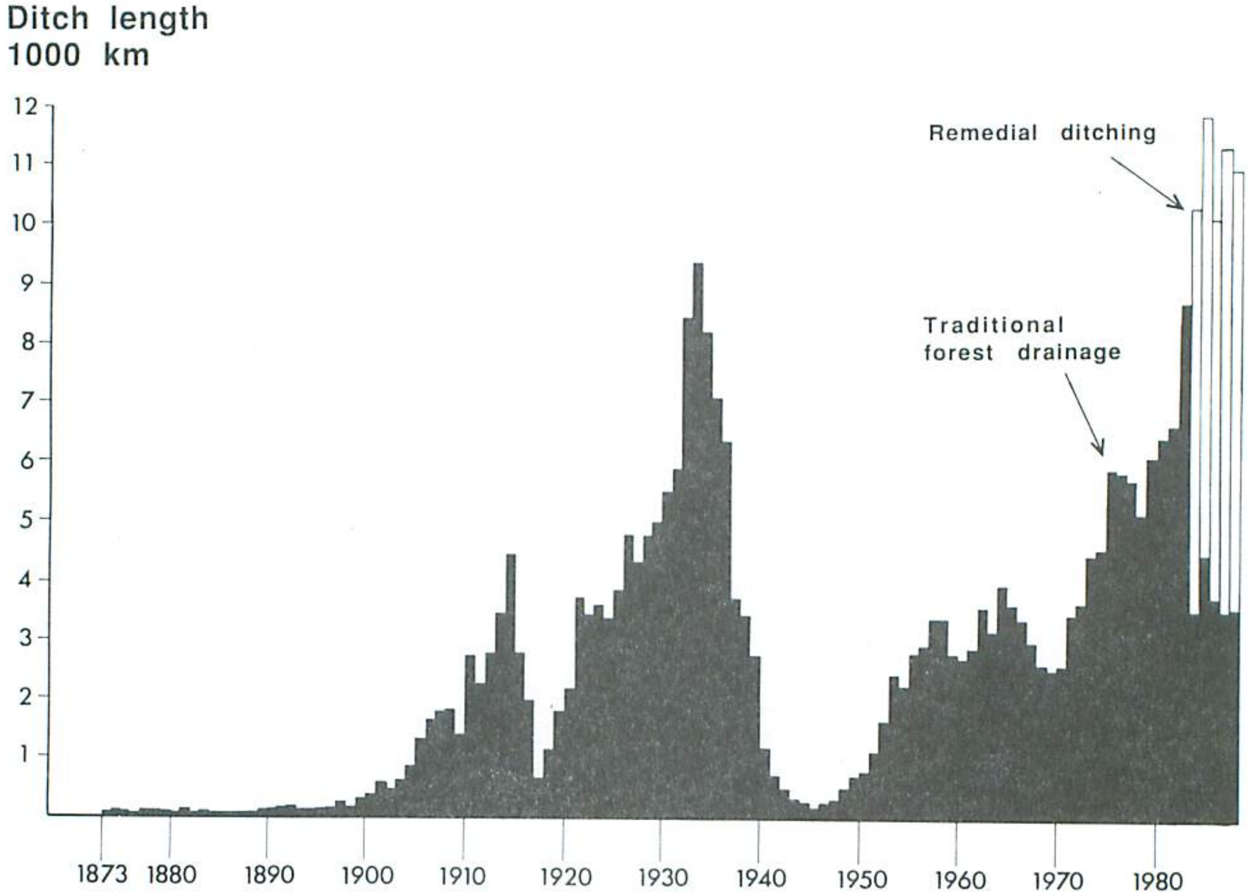

Figure 3. Forest drainage in Sweden, 1873-1987.

PRESENT SITUATION AND FUTURE POSSIBILITIES

The main reason for the minimal use of peatlands for forest production up to this point has been the fact that, in the past, there has been a surplus of wood fiber and therefore no obvious need to expand the forest base. Another reason is that forest drainage conflicts with other forms of peatland use. An extensive, national plan for forest drainage still needs to be worked out.

At present, one-sixth of the current annual increment as well as the total wood volume from Swedish forests originates in peat-covered wetlands. The opportunities to increase forest production by more intensive use of these wetlands are obvious. The size of such an addition depends on the quantity and quality of the sites selected for drainage. The expected increase from a certain selection of sites can be calculated from information on the areal extent of peat-covered wetlands in various parts of the country, and predictions of the forest productivity of peatlands after drainage (Fig. 5). The growth response from fertilization, over and above the effect of drainage, has yet to be investigated thoroughly. At present, only preliminary predictions, based on results from practical experience, can be made (Table 2).

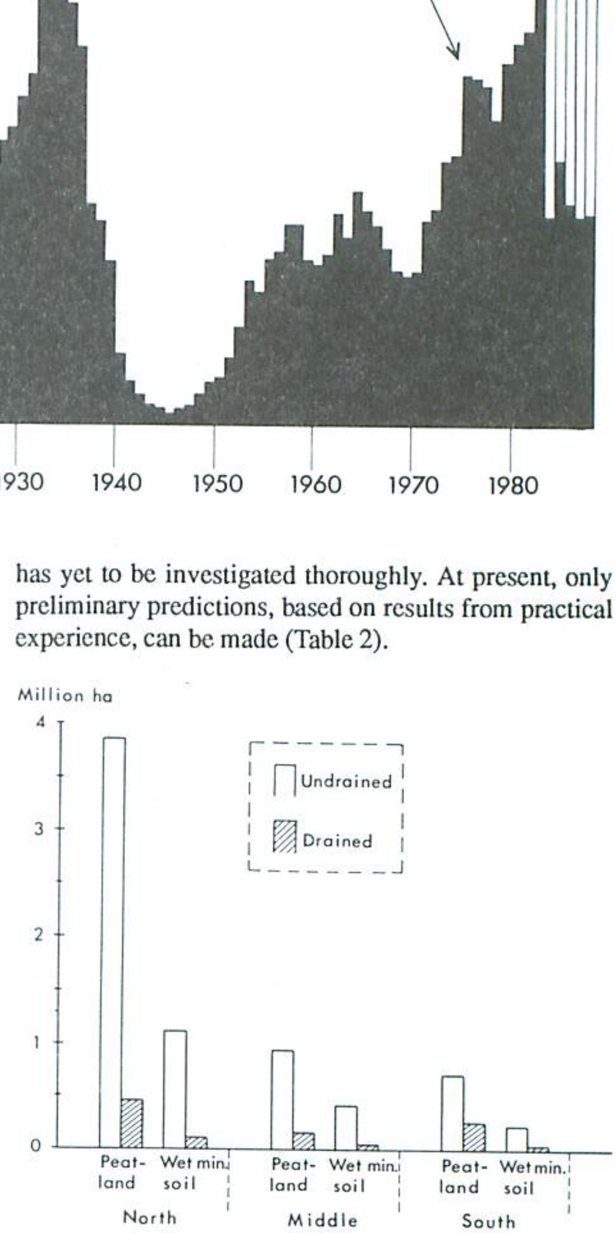

Figure 4. Undrained and drained area of peatland and wet mineral soil.

Original site type	Temperature sum, degrees 600	700	800	900	1000	1100	1200	1300	1400	1500	1600
	Post-drainage forest productivity, $m^3/ha/yr$										
1. *Aconitum-Filipendula/* **tall-herb** type											
spruce+hardwoods	3.2	4.2	5.2	6.3	7.4	8.4	9.3	10.2	10.8	11.2	11.4
2. *Maianthemum-Viola/* **low-herb** type											
spruce+hardwoods	2.9	3.9	4.8	5.7	6.7	7.7	8.7	9.5	9.9	10.2	10.3
pine+spruce+hardw.	2.4	2.8	3.3	3.8	4.4	4.9	5.6	6.3	6.9	7.3	7.5
3. *Vaccinium myrtillus/* **bilberry-horsetail** type											
spruce+hardwoods	2.6	3.3	4.1	4.9	5.8	6.7	7.6	8.4	8.9	9.2	9.4
pine	1.8	2.1	2.5	2.9	3.6	4.2	4.8	5.4	5.9	6.4	6.8
4. *Carex rostrata/* **tall-sedge** type											
pine+spruce+hardw.	2.0	2.3	2.6	3.1	3.7	4.3	4.8	5.4	5.9	6.2	6.3
pine	1.1	1.3	1.5	1.7	2.0	2.4	2.9	3.4	3.7	3.8	3.9
5. *Ledum palustre/* **dwarf-shrub** type											
pine+spruce+hardw.	1.7	1.9	2.3	2.7	3.2	3.8	4.4	4.8	5.2	5.3	5.4
pine	1.5	1.7	2.0	2.4	2.9	3.4	3.9	4.3	4.6	4.7	4.8
6. *Carex globularis* type											
pine+spruce+hardw.	1.2	1.5	1.7	1.9	2.2	2.6	3.1	-	-	-	-
pine	0.9	1.1	1.2	1.4	1.6	2.0	2.6	-	-	-	-
7. *Eriophorum vaginatum/* **low-sedge** type											
pine+spruce+hardw.	0.9	1.1	1.2	1.4	1.6	1.9	2.3	2.7	3.1	3.3	3.5
pine	0.7	0.8	0.9	1.0	1.2	1.5	1.9	2.2	2.5	2.8	3.0
8. *Calluna vulgaris/* **Marsh Andromeda-cranberry** type											
pine	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5

Figure 5. Post-drainage forest productivity of peatlands in Sweden (from Hånell 1988).

Table 2. Expected growth response from PK or NPK fertilization, over and above that resulting from drainage

Site type	Response m³/ha/yr
Tall herb	0.0 – 1.0
Low herb	0.0 – 1.5
Bilberry-horsetail	1.5 – 2.5
Tall sedge	1.5 – 2.5
Dwarf shrub	2.0 – 4.0
Carex globularis	1.5 – 3.0
Low sedge	1.5 – 3.0
Marsh-*Andromeda*-cranberry	1.0 – 2.0

The distribution of the wet mineral-soil and peatland areas in relation to site types and regions, based upon the National Forest Survey (Hånell 1989), is shown in Figure 6. These area estimates, combined with the predictions in Figure 5 and Table 2, were the basis for calculations of potential growth response after drainage alone, and after drainage and fertilization. In these calculations, it was assumed that half of the peatland and wet mineral-soil areas (except for the least productive marsh-*Andromeda*-cranberry site type, which is excluded) could be used for forestry, i.e., 50% of the area of each region. Furthermore, the North, Middle and South regions (of Sweden) were assigned average climatic conditions corresponding to temperature sums of 900, 1300 and 1400 degree-days, respectively.

The results of the calculations are summarized in Figure 7. The expected increase in forest growth from drainage alone on selected sites is 8.5 million m³. Almost twice that much can be attained after proper fertilization. These two levels of growth response correspond to 11 and 20% increases in the country's total forest growth.

CONCLUSIONS

The peat-covered wetlands in Sweden constitute a major but poorly used resource for forest production. More intensive use could make a substantial contribution to forest growth in the country.

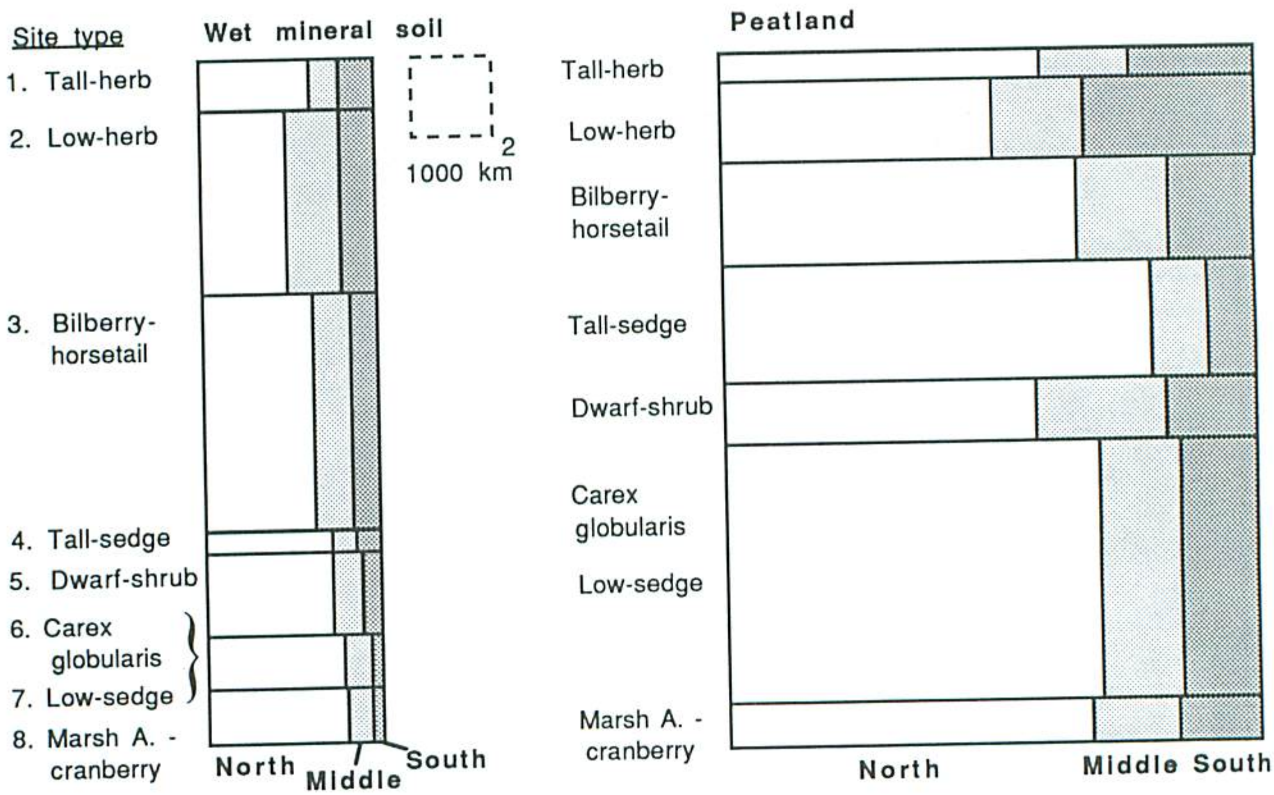

Figure 6. Wet mineral-soil and peatland area divided into forest-productivity classes and regions.

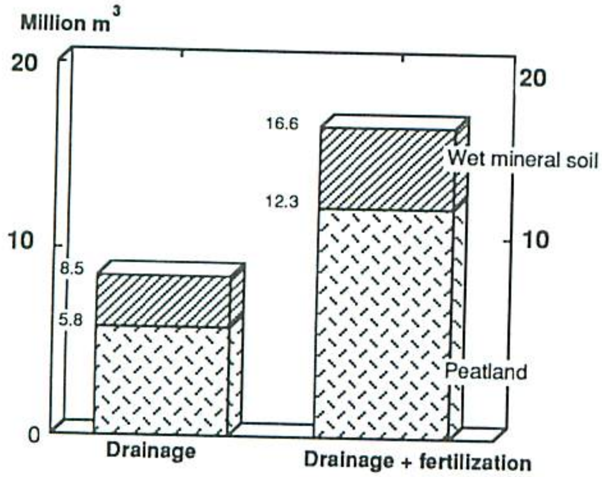

Figure 7. Increased forest growth from drainage and from drainage plus fertilization.

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THE USE OF SWAMP FOR FORESTRY IN THE NORTHEAST MOUNTAINS OF CHINA

W. Zhang and Q. Liu
Changchun Institute of Geography
Academia Sinica
Changchun, Jilin, China

ABSTRACT

The Da Hinggan, Xiao Hinggan and Changbai mountains are the most important areas for forestry in northeast China. About 6% of the forest land in these areas consists of swamp[1]. The environmental and forest conditions of swamp that is used for forestry vary considerably. Experience has shown that drainage of both treed and treeless swamp can be very profitable. In developing swamps for forestry, one must consider drainage, fertilization, selection of suitable tree species, and changes in environmental factors.

RÉSUMÉ

Les zones montagneuses de Da Hinggan, Xiao Hinggan et Changbai sont les régions les plus importantes pour la foresterie dans le nord-est de la Chine. Environ 6% des terres forestières de ces regions sont des tourbières. Les conditions environnementales et forestières des tourbières utilisées pour la foresterie varient considérablement. L'expérience a démontré que le drainage des tourbières boisées aussi bien que non-boisées peut être très profitable. Dans le développement des tourbières à des fins de foresterie, on doit considérer le drainage, la fertilisation, la sélection des essences forestières souhaitables, et les changements des facteurs environnementaux.

INTRODUCTION

In the past 20 years China has made considerable progress in forestry. About 12% of the total land area is previously unforested land that has been reclaimed for forestry. However, the average forested area per person is still only 0.13 ha, and it is clear that the forest resources in China are very valuable.

Conditions for peat accumulation are not uniform throughout China. Swamp is found primarily in the mountains in the northeast, but even there, the proportion of swamp is not high. For example, swamp constitutes only 3.0% of the area controlled by the Yakesi Forest Control Bureau in Inner Mongolia, 11.3% of the area controlled by the Da Hinggan Mountains Forest Control Bureau in Heilongjiang Province, and 4.0% of the area in the Changbai Mountains. The proportion of forested swamp is very small at the present time. Forested swamp land represents only 5.0% of the total area controlled by the Yichun Forest Control Bureau, 0.6% of the total area controlled by the Yakesi Bureau, and 0.3% of the total area controlled by the Da Hinggan Bureau. Many forest control bureaus have carried out drainage and other improvement work on swamp lands, and have obtained some good results.

CHANGES CAUSED BY THE USE OF SWAMP LAND FOR FORESTRY

Progress has been made in the use of swamp land for forestry in recent years. The work carried out by the Dailing Forest Experiment Bureau has attracted attention from researchers both in China and abroad. In addition, more than 20 forest bureaus have achieved successful results in the drainage of forested swamp land and afforestation of open swamp land (Table 1). Drainage in swamp land has caused changes in the soil environment, and influenced tree growth.

[1] In this paper, the term "swamp" is used in the sense of both treed and treeless wetlands, with both deep and shallow peat overburden.

Table 1. Indices of change in stands after forestry development in swamp land

Location[a]	Treatment[b]	Number of trees/ha	DBH (cm)	Mean height (m)	Stand volume (m^3)	Species[c]	Years since treatment
X1	Y1	2219	9.7	10.7	90.4	Z1	13
X2	Y1	3280	7.9	9.7	89.7	Z2	15
X3	Y2	1400	8.7	8.2	63.4	Z3	15
Y3	1600	6.3	5.4	29.5	Z1		
X4	Y2	6.5	7.8	45.5	Z1	18	
Y3	3.0	3.9	17.5	Z1			
X5	Y1	(2970)	13.2	11.2	166.8	Z1	17

[a] X1 Shuangfeng Forest Bureau
X2 Dailing Forest Bureau
X3 Hongxing Forest Bureau, Tanghongling Forest Farm
X4 Keyihe Forest Bureau, Likeshi Forest Centre
X5 Dashitou Forest Bureau

[b] Y1 Drainage and afforestation
Y2 Drainag
Y3 Control

[c] Z1 *Larix*
Z2 *Larix, Betula*
Z3 *Larix*, small quantity of *Betula*

Changes in Trees after Drainage

Root systems

Research has shown that, after drainage, the weight of the root system, the depth of the main root, the maximum diameter of side roots, the minimal distance from root to ground surface and the root angle are all increased, whereas the maximum length of side roots is reduced. Root respiration is improved by drainage, and exchanges of materials increase.

Stem, bark and branches

After drainage, trees became larger, taller and straighter. In the Xiao Hinggan Mountains after 15 years, mean tree height had increased by 2.8 m, DBH by 2.3 cm; in the Da Hinggan Mountains after 18 years, increases were 4.0 m and 3.5 cm, respectively. After drainage, branch growth spread laterally, and crown coverage doubled. Twigs in the middle of the lower branches became heavier and were hanging down, and bark changed from rough and flaky to smooth.

Cones

The average number of cones on two-year-old live branches increased from 30 to 35.8. The average length of cone increased by 1.7 cm.

Environmental Changes after Drainage

Soil water content

The specific gravity of the peat increased by 0.05 g cm^{-3}, and the porosity decreased by 11%. Water content of the peat soil before drainage ranged from 330 to 606%, and two years after drainage from 113 to 218% (at Dailing). Hence, the water storage capacity has been improved.

Soil temperature

On the north slope of the Xiao Hinggan Mountains, the ground temperatures rose after drainage. Drainage in swamp land deepened the seasonal melting layer in permafrost, and promoted microbial activity.

Soil nutrients

After drainage there were decreases in pH and K_2O, whereas for humic acid, N, and P_2O_5 there were increases (Table 2).

Vegetation

After afforestation in non-forested swamp land the vegetation changed from open wetland, mainly with *Sphagnum* and *Carex*, into forested wetland with larch

(*Larix* spp.), birch (*Betula* spp.) and poplar (*Populus* spp.). After drainage in forested swamp land, *Sphagnum* tended to decrease, and growth and canopy cover of pine (*Pinus* spp.) and birch increased. Forests consisting of old, slow-growing trees were converted into forests with much better height and diameter growth.

Table 2. Comparison of chemical properties of soil before and after swamp improvement at Likesi Forest Centre (Keyihe Forest Bureau).

	Depth (cm)	pH	Humic acid (%)	Dry Weight (%) N	P_2O_5	K_2O
Before drainage	0-17	5.50	54.69	1.74	0.47	1.06
	17-27	5.80	8.94	0.26	0.19	2.33
	27-40	5.54	5.46	0.17	0.17	2.80
After drainage	3-30	5.21	67.76	1.81	0.55	1.00
	30-46	5.58	66.06	1.91	0.48	1.01
	46-51	5.51	8.96	0.08	0.20	2.76

Some Problems in Using Swamp Forest

Sapling Selection

In selecting saplings, we need to judge what is practical for each local situation. For example, the effects of drainage in the northern region of the Da Hinggan Mountains are not very good; secondary paludification often follows. Hence, we should do experimental work first before undertaking large-scale reforestation with special seedling stock.

The regional forests in the northern Da Hinggan Mountains are mainly *Larix gmelini* and *Pinus sylvestris* var. *mongolica*, a mixed conifer forest characteristic of a frigid temperate zone (Table 3). The forests in the Xiao Hinggan and Changbai Mountains are conifer and broadleaf mixedwoods characterized mainly by *Pinus koraiensis*. *Larix gmelini* is located only in low-lying lands, often mixed with *Picea* species. Saplings should be selected according to species distribution and swamp characteristics. At present, *L. gmelini* is the main species selected in northern China. Some fast-growing, high-yield species, such as *Populus* and *Salix*, are being planted experimentally in swamp land in the north.

Table 3. Dominant tree species in the study area

Species	I[a]	II[b]	III[c]
Larix gmelini	x	x	x
Pinus sylvestris var. *mongolica*	x	x	x
Picea obovata	x	x	x
Pinus koraiensis			x
Picea jezoensis		x	x
Quercus mongolica	x	x	x

[a] I Eastern Siberia area

[b] II Da Hinggan Mountains

[c] III Xiao Hinggan Mountains, Chang Bai Mountains

Drainage

Drainage is the main method used in improving swamp land for forestry. Drainage provides numerous benefits, e.g., it lowers the groundwater level, reduces soil moisture, raises soil temperature, improves soil aeration, and accelerates decomposition of organic matter.

Drainage ditches are usually constructed perpendicular to contour lines. There are also drainage systems with lateral ditches extending from the main ditches at angles of 45 to 60°.

Length and Spacing of Drainage Ditches

Ditches should be short in well forested swamp land, and longer in poorly forested or open conditions. It is suggested that a suitable distance between drainage ditches is 30 to 60 m in *Carex*-dominated flood land, 60 to 70 m in flood land with mixed grass and *Carex*, and 100 m in gently sloping mountain swamp cutovers. The density of the drainage network should be 150 m/ha in flood-land swamps and 100 m/ha in cutover swamps with gentle slopes.

Ridging and Mounding

In addition to the above-mentioned drainage systems, we use other systems of site preparation for afforestation. One such system involves the excavating ditches at relatively close intervals and alternating them with ridges created from the excavated material. Dimensions for these systems are given in Table 4. The widths of the ridges are typically between 80 and 100 cm.

Table 4. Dimensions for closely spaced drainage ditch and ridge systems

Location	Ditch spacing (m)	Ditch width (cm)	Ditch depth (cm)
Hongxing	20	120	30
Dailing	3.3	120	60
Keyishe, large ditch	–	120	80
Keyishe, small ditch	2	70	40
Dashitou, medium ditch	2-4	100	40-60
Dashitou, small ditch	1.5	60-70	30

Two other methods are used in northern China. The first involves the construction of high platforms. These may be shaped as equilateral triangles 30 cm high and 1 m on a side, or as squares 50 cm high, and ranging from 40 to 100 cm on a side. The distance between platforms ranges from 1 to 2 m. The second method involves the construction of earth dikes, with 3-m spacing between.

Fertilization

At present we do little fertilization on swamp land for forestry. Application of fertilizer must take into account the characteristics of the swamp soil. We have found that phosphate and potash fertilizers are effective. The application of trace elements (copper, boron and zinc) should be investigated more fully, and more attention should be paid to the effect of fertilization.

RESEARCH IN CHINA

Several areas need to be addressed in research on swamp land forestry in China. We need to establish a classification system that is suitable for forestry; to predict forest changes and potential productivity after improvement; to strengthen research in drainage methods; to describe changes in drainage ditches, and determine how to maintain the ditches in good condition for different soil conditions; to establish fertilization experiments and develop methods for afforestation; to determine nutrient requirements of major species; to conduct research on the function of microorganisms and their influence on nutrient release; to conduct research on soil temperature and freezing; to develop guidelines for the selection of saplings in swamp land; and to measure changes in soil properties after drainage and fertilization.

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PEATLAND POTENTIALLY AVAILABLE FOR FORESTRY IN CANADA

V.F. Haavisto and J.K. Jeglum
Forestry Canada
Ontario Region
Sault Ste. Marie, Ontario
Canada

ABSTRACT

Canada has an estimated 1.11 million km^2 of peatland; however, precise figures for the area of productive and nonproductive forest on peat are not readily available. Owing to the size of the country and the resultant diversity in geography, soils, and climate, the peatland types and potential for forest production are highly variable. A province-by-province estimate of peatland area, and a summary of forestry activities on peatland, are presented. An accurate inventory of forest land on peat and on shallow-peated, wet mineral soils in Canada is urgently required.

RÉSUMÉ

Selon les estimations, le Canada compte 1,11 million de km^2 de tourbières; toutefois, on ne possède pas de chiffres précis sur la superficie des forêts turficoles productives et non productives. En raison de la superficie du pays et de la diversité résultante de la géographie, des sols et du climat, les types de tourbière et le potentiel d'exploitation forestière sont très variables. Une estimation de la superficie des tourbières, par province, et un résumé des activités forestières dans les tourbières sont présentés. Un inventaire des terres forestières à sols tourbeux et à sols minéraux humides à mince couche de tourbe doit être effectué dans les plus brefs délais.

INTRODUCTION

The second largest country in the world, Canada has a total area of 9.98 million km^2. Approximately 4.40 million km^2 are considered forest land (Bonner 1982), and of this area, about 61% is considered productive, i.e., capable of producing a merchantable crop of trees in a reasonable length of time (Table 1). Almost half of this productive forest land is found in areas far removed from large-scale commercial forestry operations. Owing to its climate (summers are short and warm, winters are long and cold, and precipitation can exceed evapotranspiration), Canada abounds in peatlands (Zoltai and Pollett 1983, Haavisto et al. 1989).

Peatlands are a predominant wetland type, and very abundant in the Boreal Forest Region (Rowe 1972), which stretches from coast to coast in Canada (Fig. 1). In this region, black spruce (*Picea mariana*) is the predominant tree species on peatlands (Fig. 1). In some parts of the country, tamarack (*Larix laricina*) and lodgepole pine (*Pinus contorta*) are also harvested from peatlands. Several other species specific to west coast peatlands are of economic importance.

The forests of the Boreal Forest Region are important for the economic well-being of many northern communities. In Ontario, and elsewhere in Canada, black spruce is the major source of fiber for the pulp and paper industry; a high proportion of the volume of this species comes from forested peatlands, and guidelines for the management of black spruce ecosystems on peatlands are being developed (Haavisto et al. 1988).

The word "peatland" has a different connotation depending on the purpose for which an inventory is being done. Usually, the primary focus of inventories is on the peat, and on open, treeless peatlands. Some of the inventories include sparsely treed peatlands, but not those on which good forests are growing. Hence, estimates of peatland areas can vary considerably. Radforth

Table 1. Distribution of various classes of land by province or territory in Canada

Province or territory	Land area (km²) Total	Forest[a] land	Productive forest[a]	Area of peatland[b]
Yukon Territory	478,000	242,000	73,000	12,980
Northwest Territories	3,246,000	615,000	143,000	251,110
British Columbia	931,000	633,000	515,000	12,890
Alberta	644,000	349,000	234,000	126,730
Saskatchewan	570,000	178,000	89,000	93,090
Manitoba	548,000	349,000	139,000	206,640
Ontario	891,000	807,000	426,000	225,550
Quebec	1,357,000	940,000	848,000	117,130
New Brunswick	72,000	65,000	62,000	1,200
Nova Scotia	53,000	41,000	29,000	1,580
Prince Edward Island	6,000	3,000	3,000	80
Newfoundland	371,000	142,000	85,000	64,290
Canada	9,167,000	4,364,000	2,641,000	1,113,270

[a] Areas according to Bonner (1982)
[b] Areas according to Tarnocai (1984)

(1968) stated that "Canada has an estimated 500,000 square miles [1.295 million km^2] of peatland," but noted that an accurate inventory is essential. He alluded to the Forest Resources Inventory in Ontario (Dixon 1963), according to which, in the Hudson Bay Lowlands alone, there are more than 100,000 km^2 of peatland. Rennie (1976), in his address to the Sixteenth Muskeg Research Conference, stated that the estimate of 1.3 million km^2 of peatland in Canada is conservative, and "an appreciable amount of this underlies areas of forest land, some of which is non-producing or marginally so". At the Sixth International Peat Congress, Kivinen and Pakarinen (1980) estimated that Canada has 1.7 million km^2 of peatland. According to Tarnocai (1984), there are an estimated 1.11 million km^2 of peatland in the country.

A proportion of these peatland sites is forested or sparsely treed, and is, or could be, important to forestry in Canada. In addition, there are considerable areas of waterlogged mineral soil or shallow-peated sites that are important. Both peatlands and forests on waterlogged mineral soils could be improved by forest drainage, possibly accompanied by fertilization, and made suitable for forest production. In this paper we attempt to summarize, on a provincial or territorial basis, the areal extent of peatlands in Canada. In addition, we briefly summarize current silvicultural and forest drainage activities.

PEATLAND AREA ESTIMATES AND FORESTRY ACTIVITY

Table 1 summarizes the areal extent of land, forest land, productive forest land (Bonner 1982), and peatland (Tarnocai 1984) on a provincial or territorial basis for all of Canada. The following information has been obtained from published material and personal communications. The figures presented are not necessarily accurate, but provide a first approximation of the areal extent and distribution of forest on peat and wet mineral substrates across Canada.

Yukon Territory

The Yukon Territory has a land area of 478,000 km^2 (Table 1), about 50% of it forest land (Bonner 1982). Only about 6.5% of the area is considered productive (Heartwell 1988). Approximately 13,000 km^2 of peatland are found in the Yukon. The area of forested peatland is not known. Because silvicultural work in theYukon is minimal[1], no silvicultural effort is put into peatlands. Although there may be some potential for increasing wood production on peatland sites in the Yukon, mineral-soil uplands have greater potential for wood production.

[1] J. Hanrath, Department of Indian and Northern Affairs, Whitehorse, Yukon Territory (pers. comm.).

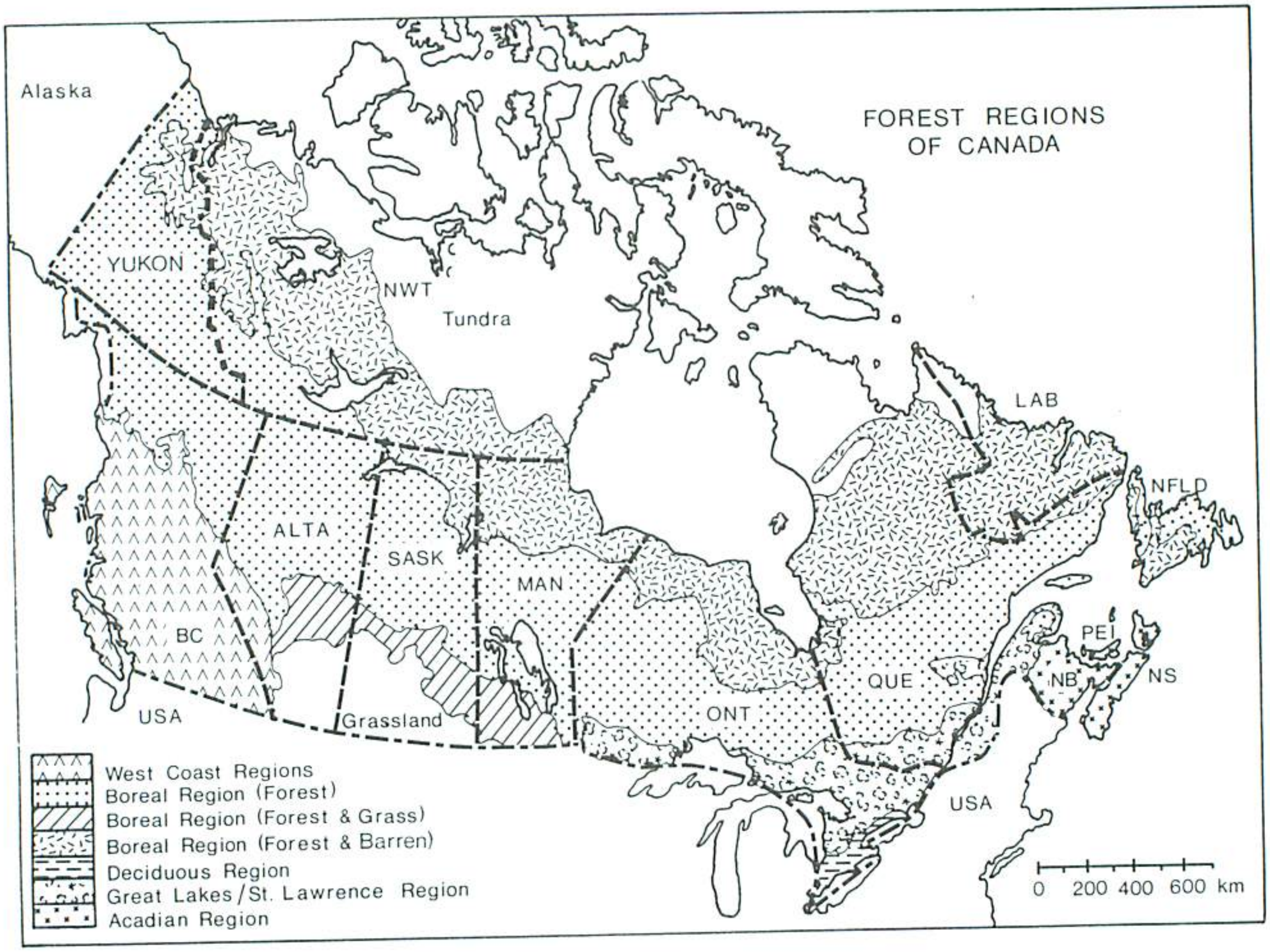

Figure 1. Forest Regions of Canada (modified from Rowe, J.S. 1972).

Northwest Territories

The Northwest Territories have a total land area of 3.25 million km^2, of which about 19% can be considered forest land (Table 1). Less than one quarter of the latter is productive (Bonner 1982), and yields are very low. The Territories contain an estimated 25.1 million ha of peatland, most of which is tundra-like and open. As in the Yukon Territory, silvicultural work is not done on any site type, and it is not anticipated that forest improvement work will be undertaken, especially on peatland sites.

British Columbia

Owing to the mountainous terrain and its effects on climate, both vegetation and site types vary considerably in British Columbia. Of the total land area, 91% is considered productive forest land (Table 1). Peatlands comprise about 13,000 km^2 (61%), an area similar in size to that of peatlands in the Yukon (Tarnocai 1984). Very little commercial forest land is found on peat, and most of this is in the northeastern part of the province. Occasional pockets of black spruce swamp occur in the Interior Region of the province, but these have not been exploited commercially to any extent.[2] Organic soils over bedrock, common on Vancouver Island and the Queen Charlotte Islands, are waterlogged owing to excessive amounts of precipitation and poor drainage. The potential for improving forest production on wet sites is considerable. However, because the better drained and highly productive sites are much more important economically, there is little reason to manage true peatland forest types.

Alberta

According to Hillman (1987), there is concern in the province of Alberta about the decrease in the productive land base. About 36% of the total land area of Alberta is productive forest land (Table 1). Tarnocai (1984) estimated that there are about 127,000 km^2 of peatland in the province. The area of productive and nonproductive forest on this peatland is not known. Considerable quantities of black spruce, and some tamarack and lodgepole

[2] G.D. Lloyd, Regional Silvicultural Officer, B.C. Ministry of Forests, Prince Rupert Forest Region, Smithers, B.C. V0J 2N0 (pers. comm.).

pine, are being harvested from peatlands every year. Apart from conventional regeneration methods, such as site preparation and planting, silvicultural work on peatlands is done on an operational trial basis. It has been estimated that about 40,000 km^2 could be drained to improve tree growth or to convert the area into productive forest land (Hillman 1987). Since 1975, eight systematic peatland drainage trials, covering an area of 1144 ha, have been established to ascertain the most suitable ditch depths and spacings on a variety of peatland sites. Several research projects have been undertaken to evaluate hydrological processes, nutrient dynamics, and tree growth.

Saskatchewan

Of the total land area of Saskatchewan, about 27% is forest land (Table 1), and 89,000 km^2 are considered productive. Some of this land is situated in the central Aspen Woodlands Zone, but most is in the Boreal Forest Region in northern Saskatchewan. The province contains about 93,000 km^2 of peatland (Table 1). It is not known how much of this is forested and productive. Almost all of the northern half of the province is situated in the Continental High Boreal Wetland Region. It is characterized by peat plateau bogs, palsa bogs with collapse scars (Anon. 1986), and veneer bogs, all of which have no commercial forestry value. On the other hand, a band of Continental Mid-Boreal Wetlands across the province to the north of the Prairie Zone has treed bogs and fens on broad flats and in confined basins. Because the average annual harvest for the whole province is only 146 km^2 (Brace and Golec 1982), forestry activity on peatlands is insignificant. Furthermore, no interest has been shown in improving productivity on peatland sites.

Manitoba

Although half of the total area of the province of Manitoba is considered forest land, only about 21% is productive (Table 1). Much of the annual harvest (averaging 8.5 million m^3, 75% conifers) comes from the spruce working group (Brace and Golec 1982). There are 207,000 km^2 of peatland in the province (Table 1). The Forestry Branch of the Manitoba Department of Natural Resources has estimated that about 15,000 km^2 of the province's black spruce forests are in poorly drained peatland areas[3]. The total area of forest on peatlands has not been calculated, and no effort has been made to drain or fertilize peatland forests.

[3] Woons, F.J.M. Jr., 1988. The feasibility of draining stands of black spruce to increase growth rates in southeastern Manitoba. Univ. Man., Nat. Resour. Inst., Winnipeg. M.Sc. Practicum. 103 p.

Ontario

More than 90% of the 891,000 km^2 of land in the province of Ontario is forest land, about half of it productive (Table 1). Much of the nonproductive forest land is in the inaccessible northern areas. Using summaries from the Ontario Forest Resource Inventory, Ketcheson and Jeglum (1972) estimated the areas of various classes of land on peat substrates. They ascertained that almost half of the province (434,000 km^2) could be categorized as peatland, 78% of it treed and 22% treeless (Table 2). Of the treed portion, only 80,000 km^2 were considered productive peatland forest dominated by black spruce. The remainder was nonproductive "treed muskeg" (black spruce up to 3 m high and fewer than 1000 stems/ha) and "stagnant stands" (black spruce primarily, up to 7 m high, 10 cm DBH at 150 years, and 2200-2500 stems/ha). On the other hand, Tarnocai (1984) estimated the total wetlands of the province to be about 292,000 km^2, and about 226,000 km^2 of these to be peatlands (Table 1).

Peatland forestry in Ontario has been described by Jeglum et al. (1983b). On average, an estimated 281 km^2 of black spruce-dominated peatland are cut each year, and yield about 20% of all roundwood harvested in Ontario (Haavisto 1980). Harvesting techniques are changing so that less physical damage will be done to the sites, and well established stems of advance growth will be protected. Alternate strip clearcutting, block cutting, and seed tree groups have been used in an effort to regenerate these areas by natural seeding. Site preparation (e.g., winter shear-blading) is being carried out to remove excessive amounts of slash and competing vegetation, and to prepare spruce for planting and natural or direct seeding. The number of black spruce planted increased from 17-18 million seedlings/year in the early 1980s to about 64 million in 1987 (Anon. 1988). Some drainage trials have been established for research purposes. The earliest of these was established in 1929 in the Abitibi drainage area (Payandeh 1973) and the most recent in 1984 in the Wally Creek drainage area (Rosen 1986). To date, about 1000 ha have been drained in the province for forestry purposes. On peatlands, fertilization has been experimental only. **A Silvicultural Guide for the Spruce Working Group in Ontario** (Arnup et al. 1988) summarizes management techniques for use with white spruce (*Picea glauca*) and black spruce, and describes the most up-to-date management methods within a framework of ecological site classification (*see also* Jeglum et al. 1983a, Jones et al. 1983). Rosen (1989) describes the installation of the Wally Creek Drainage Area, which was done according to Finnish standards.

Table 2. Inventory of different classes of land in Ontario

Class of land	Area (km^2)
Total land area	884,780
Nonforested area	80,910
Forest land	804,790
Nonproductive	377,890
Productive	425,980
Total peatland	434,840
Treed peatland	340,360
Productive black spruce	79,690
Cedar- and larch-dominated	2,450
Muskeg and stagnant stands	507,980
Other treed peatlands	18,720
Treeless peatlands	94,480
Open muskeg	31,080
Bogs	63,400

Excerpted from Ketcheson and Jeglum (1972).

Quebec

Quebec is the largest province in Canada (Fig. 1). The area that is important for forestry is in the southern third of the province. About 61% of the total land area is forest land (Table 1). Only about two thirds of the 850,000 km^2 of productive forest land have been inventoried. Tarnocai (1984) estimated that there were 117,000 km^2 of peatland in the province, but in view of the fact that the province is largely boreal, this may be a low estimate. Bolghari (1986) estimated that, south of the 50th parallel of latitude, about 27,000 km^2 of productive forest lands on peat soils are economically accessible. Furthermore, between the 50th and 60th parallels there are an additional 48,000 km^2. Most of this area is dominated by black spruce, which is the primary source of raw material for a thriving pulp and paper industry.

Silvicultural operations are similar to those in Ontario. Other than in the Clay Belt area of northwestern Quebec, only limited effort is expended on peatland. Drainage has been attempted at the Valcartier Experimental Station (Stanek 1970), and fertilization has been tried in conjunction with drainage (Stanek 1976). More recently, Nadeau and Parent (1982) showed that growth response to drainage was positive, and that a return on investment could be expected if drainage were undertaken. On the basis of their results and of some field evaluations (Trottier 1990a, 1990b), the province of Quebec provided a monetary incentive for private forest land owners to undertake drainage on black spruce-dominated peatlands.[4] The intention was to increase wood production close to the mills. By the end of 1988, a total of 135 km^2 had been drained. A forest drainage manual, summarizing operational drainage methods in Quebec, has been published (Trottier 1989).

New Brunswick

The province of New Brunswick encompasses both the Atlantic Boreal and the Eastern Temperate wetland regions (Anon. 1986). Of the total area (72,000 km^2), 90% is considered forest land, almost all of it productive (Table 1). About half of this is privately owned, largely by forest industries. There are only about 1,200 km^2 of peatland in the province (Table 1). Keyes et al. (1983) suggested that there are 1,400 km^2 of peatlands and stated further: "The prevailing attitude in the Province is that there are many higher quality sites available for forestry use at present and there appears to be a low probability that peatland forestry will be attempted in the near future." Some drainage work has been done to obtain basic information on response to drainage (e.g., Wetmore 1972, Smissaert[5]). Because of the relatively wet climate in some parts of the province (105-115 cm annual precipitation), there are considerable areas of waterlogged mineral soils, but estimates of their size are not available. Some drainage work has been attempted recently in these areas[6], but more for the purpose of providing access to the wet sites for harvesting and silvicultural work than for increasing the productivity of the trees.

Nova Scotia

Nova Scotia is completely surrounded by water (Fig. 1), and except for a small part of Cape Breton Island, the entire province is in the Atlantic Boreal Wetland Region (Anon. 1986). Of a total land area of 53,000 km^2, about 41,000 km^2 have been designated forest land, over half of it productive (Table 1). About 75% of the forest land is privately owned. With an average annual precipitation ranging from 110 to 135 cm, there is much waterlogged mineral soil, and it has been estimated that 25% of the forest lands of the province are imperfectly or poorly drained (Anon. 1989). Tarnocai (1984) estimated that there are 1,580 km^2 of peatland in the province. The Forest Research Section of the Nova Scotia Department of Lands and Forests (Anon. 1989) estimated that only 2.5% (102,500 ha) of the province's forest lands are on peat substrates. No large-scale operational drainage is being undertaken, but some research trials have been established. To evaluate the effectiveness of water removal and the growth performance of trees, about 9 km

[4] F. Trottier, Ministère de l'Energie et des Ressources, Direction de la Sylviculture, 200-B, Chemin Ste-Foy, Québec, Qué. G1R 4X7 (pers. comm.).

[5] Smissaert, C.D. 1984. A report on the installation of open-ditch drainage and its effects on groundwater fluctuations in a poorly drained forest soil. Univ. N.B., Fac. For., BScF Thesis. 51 p.

[6] P. Etheridge, J.D. Irving Limited (pers. comm.).

of ditches have been dug on a variety of sites ranging from waterlogged sands underlain by iron pans to well humified, deep organic soils[7].

Prince Edward Island

This island province (Fig. 1) has a land area of only 6,000 km^2 (Table 1), half of it productive forest land. With an annual harvest of about 1,600 ha and regeneration amounting to 108 ha (Brace and Golec 1982), forestry is not a major consideration in the province as a whole or on its estimated 80 km^2 of peatlands.

Newfoundland

The province of Newfoundland is made up of three bioclimatic regions (Fig. 1): the island of Newfoundland, having on its periphery an oceanic climate; a central portion of the island, which is colder and more continental; and a large peninsula (Labrador) connected to the mainland, with much colder winters, considerably cooler summers and much less precipitation (95-100 cm annually). The total land area of the province is 371,000 km^2, of which 38.3% is forest land and only 22.9% (85,000 km^2) is productive (Table 1). Tarnocai (1984) estimates that Newfoundland has about 64,000 km^2 of peatland. Päivänen and Wells (1978) calculated that insular Newfoundland has about 25,000 km^2 of peatland (22% of the land area), about 7,000 km^2 of it "scrub-forested" and an additional 7,000 km^2 treeless but reclaimable for forestry. According to Päivänen (1985), treed peatlands have not been included in any inventory of peatlands. Six experimental areas have been ditched since 1966, mostly on treeless peatlands; various species have been planted for the purpose of evaluating their potential for afforestation (Wells 1986). No trials have been established on treed peatlands. Considerable areas of waterlogged mineral soils would be good candidates for drainage (Päivänen 1985).

DISCUSSION

Of the 9.2 million km^2 of land area in Canada, almost half is considered forest land (Bonner 1982). Only about 29% of the total land area is productive forest land. Some of this, especially the portion on peat soils, is producing wood at less than the optimum rate because of excessive moisture in the rooting layer. In the exploitable forest zone, severe waterlogging can result in forest land that is nonproductive. Much nonproductive forest land is found in the inaccessible and inhospitable north (Fig. 1). The foregoing account has shown that peatlands are important for forest production in Canada.

In none of the provinces has an intensive inventory been undertaken to ascertain the area and distribution of the various peatland types. However, inventories have been undertaken and estimates specific to certain interests, e.g., peat production, have been made. There is great variation in these inventories because each has been conducted for different purposes and according to different criteria. For this reason, we question the validity of even the most recent estimates, such as those of Tarnocai (1984).

We previously alluded to the major differences in estimates of peatland in Ontario. Tarnocai (1984) stated that there are 226,000 km^2 of peatland in this province. According to the published Forest Resource Inventory data for the province of Ontario (Dixon 1963), there are 94,000 km^2 of treeless peatlands, 166,000 km^2 of "treed muskeg", and 73,000 km^2 of stagnant stands. In addition, Ketcheson and Jeglum (1972) estimated that there are 80,000 km^2 of productive black spruce forest on peatland, and an additional 21,000 km^2 of other treed peatlands (a total of 340,000 km^2 of treed peatlands). Why the significant discrepancies? Might there be similar discrepancies in the other provinces?

As the area and distribution of the types of peatland economically treated for forestry purposes are not readily available, we urge that a complete inventory be undertaken (cf. Päivänen 1985). The information is also essential for forest management planning. Harvesting is usually the first forestry activity carried out on peatlands in Canada, and it can have the most far-reaching consequences (Jeglum et al. 1983b, Haavisto et al. 1988). We need to know which harvesting methods, types of site preparation, and forest improvements should be undertaken on different sites and under different stand conditions to ensure regeneration success and improved forest growth. For example, under what site, stand, and climatic conditions would drainage be biologically and economically effective? According to our survey, the diversity of forestry activities on peatlands across Canada indicates that drainage could be implemented effectively on many forested peatlands and wet mineral-soil sites, especially in areas with climates similar to or warmer than those of the middle of the Boreal Forest Region.

CONCLUSIONS

Canada has much forest land on peat. An inventory carried out on a site-type basis is essential. According to experts from the Scandinavian countries, the potential for significantly increasing rates of tree growth and bringing more area into production through the judicious

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[7] P. Neily, Nova Scotia Department of Lands and Forests (pers. comm.).

use of drainage and fertilization has not been recognized in Canada. To date, fewer than 25,000 ha have been drained in Canada for forestry purposes. Prescriptions based on biological principles have been prepared for similar sites in countries such as Finland, and we should test and modify some of these for use on our sites, under our stand conditions, and with our tree species. Numerous guidelines have been prepared (e.g., Päivänen and Wells 1978; Heikurainen 1980; Rosen 1986, 1989; Haavisto and Wearn 1988; Haavisto and Päivänen 1987; and Trottier 1989), but much more needs to be done.

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Section II
Research Programs: Progress Reports

RESEARCH IN FOREST PRODUCTION AND SILVICULTURE ON WETLANDS IN SWEDEN: THE RESEARCH PROGRAM IN WETLAND FORESTRY AT THE SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES, UMEÅ

B. Hånell and A. Sugg
Departments of Forest Site Research and Silviculture
Faculty of Forestry
Swedish University of Agricultural Sciences
Umeå, Sweden

ABSTRACT

More information is required on the establishment, treatment and renewal of forests on wetlands in order to realize the full potential of these areas for forestry. This paper points out some of the information deficiencies and introduces the reader to some of the issues involved in this research by outlining a program that has been initiated at the Swedish University of Agricultural Sciences.

A series of experiments has been set up in different areas of the country to study stand harvesting and renewal on highly productive peatlands; stand establishment on open wetlands, abandoned agricultural peatlands and excavated peatlands; intermediate treatment of stands with emphasis on suitable intensities of thinning; and wetland forest-regeneration techniques. Components and dynamics of the nutrient cycle in a developing forest ecosystem on wetlands are also being studied carefully and fundamental information on the supply of oxygen to trees and soil is being obtained for different types of wetland.

RÉSUMÉ

Il faut recueillir un plus grand nombre de données sur l'établissement, l'entretien et le renouvellement des forêts occupant des tourbières si l'on veut pleinement tirer profit du potentiel forestier de ces milieux. Le présent article décrit certaines lacunes dans nos connaissances et familiarise le lecteur avec quelques-unes des questions visées par cette recherche en présentant les grandes lignes d'un programme qui a été entrepris à l'Université des sciences agricoles de Suède.

Une série d'expériences ont été mises sur pied dans différents endroits de la Suède afin d'étudier la récolte et le renouvellement des forêts occupant des tourbières très productives, l'établissement de peuplements dans des tourbières ouvertes et des tourbières agricoles abandonnées, le boisement des tourbières qui ont été exploitées (extraction de la tourbe), les soins à apporter dans l'intervalle aux peuplements, l'accent étant mis sur un dosage convenable des éclaircies et les techniques de régénération des forêts occupant des terres humides. Les composantes et la dynamique du cycle des éléments nutritifs dans un écosystème forestier de terres humides en développement font également l'objet d'études et des données fondamentales sur l'approvisionnement en oxygène des arbres et du sol sont également compilées pour différents types de terres humides.

INTRODUCTION

Wetlands have been considered important areas for the conservation of delicate ecosystems; they have also been exploited for agriculture and as sources of peat for energy and soil conditioning. The terms "wetland" and "peatland" are often used interchangeably, but there are some important differences. Although it is true that peatlands constitute a large portion of the wetland area in northern boreal countries, peatlands have a minimum depth of peat, generally 0.3 m; wetlands, on the other hand, include not only ecosystems in which peat has accumulated, but also wet forests, shrublands and more open areas with a very shallow peat layer or no peat at all. In the context of this article and for the purpose of developing wetlands for forestry, it is only those wetlands that are covered with peat that are under consideration.

Wetlands also constitute a potentially huge forest resource for northern boreal countries. Certain countries have already realized the importance of this resource because they have had to make use of available land for forestry. For example, wetlands constitute about 30% of the land area of Finland, where almost all potentially productive peatlands have been developed for forestry. On the other hand, the economic viability and potential environmental effects of such development remain open questions with respect to the future expansion of wetland forestry in other countries.

Sweden is pursuing a policy of developing wetland forestry at a cautious pace. Silviculture on wetlands is a subject that has been given high priority in a long-range proposal for forest research that has recently been accepted by the government. Despite the fact that wetland drainage has been carried out in Sweden for well over a century, the emphasis on wetland forestry is relatively recent.

About 20% of the land area of Sweden is peat-covered wetland (Hånell 1989), which is roughly equivalent, in proportional terms, to the situation in Canada. In a country with an area less than half that of Ontario, there is a need not only to increase timber production on productive forest land but also to expand available land for forestry. Approximately half of the more than 8 million ha of wetland in Sweden have been deemed suitable for drainage. It has been estimated that these areas could sustain 12 to 15 million m^3/yr of forest production after drainage and proper forestation. For the entire country this could eventually mean an increase in annual allowable harvest of no less than 10%. More than one million ha, or about one-third of the potentially drainable area, has been ditched and developed for forestry. However, this is a poor indication of the actual progress of wetland forestry: on a large portion of the drained area, perhaps as much as half, the results are unsatisfactory on account of sparse or poorly located ditches and poor selection of areas.

Research into forestry on peatlands in Sweden has, for the most part, dealt with methods of site classification and the importance of nutrients for tree development. Attempts to determine how forests should be established and treated after drainage have been minimal. Wetlands that have been ditched constitute unstable ecosystems, in which water and nutrient distribution are in constant transition. The use of silvicultural techniques on such land requires knowledge about the unique qualities and processes of different site types. If the exploitation of wetlands for forestry is to be increased, our knowledge of site conditions, stand development and appropriate stand treatments must be expanded. The potentially detrimental effects of wetland forest production on ecosystems and the environment need to be considered carefully as well.

The research program "Forest Production and Silviculture on Wetlands" was established in 1985 to develop guidelines for initial establishment, stand treatment and forest renewal on wetlands so that a consistently high level of timber production could be maintained in these areas. Parts of the program will be carried out over several decades throughout the country. The seven projects that constitute the program are outlined in the following sections.

Components and Dynamics of Nutrition in a Forest Ecosystem on Peatlands

This project is included in a joint Nordic effort to increase our knowledge of the supply, redistribution and losses of nutrients in typical Scandinavian peatland ecosystems. The project will be carried out in three experimental areas, one in each of Sweden, Finland and Norway. The purpose of the investigation is to work out the nutrient budget for a typical peatland ecosystem and thus acquire insight into the basis and need for fertilization. There will be special emphasis on determining the amount of nutrition supplied by air pollution.

A relatively large part of these efforts will be concentrated on a scientific description of the ecosystem. This includes observations and nutrient analysis of tree, shrub, field and ground layers, litter from the trees and field layers, roots, peat, precipitation, groundwater and runoff. In addition, the groundwater levels as well as the temperatures in and above the ground will be recorded. The ecosystem will be described before and after fertilization.

A key question about the efficacy of fertilization and about environmental impact concerns the destination of the added nutrients. The Swedish part of the investigation is being carried out on a bog that was ditched in the 1940s and subsequently in 1986. It was originally an *Eriophorum vaginatum*/low sedge type and has since been overgrown by a 40-year-old pine (*Pinus* spp.) stand. The experimental area is situated in southwestern Sweden, where there are high levels of precipitation and air pollution.

Subsurface Gas in Forest Wetlands

The purpose of this project is to increase our knowledge of the composition of and variation in soil gas. Oxygen supply and continuous access to water and nutrition are fundamental needs of all higher plants. The primary goal of forest drainage is not simply to eliminate too much water but rather to achieve better ground aeration. Wetlands with moving groundwater, which do not accumulate peat, are generally high in oxygen. In wetlands with stagnant groundwater or moderately to highly decomposed peat, there can at times be a serious oxygen deficiency well above the groundwater level. In addition to oxygen, nitrogen and carbon dioxide, the gases in soil may contain nitrogen oxides, methane and hydrogen sulfide. The latter two gases occur only in anaerobic environments. All of these gases influence tree survival and development.

At present, we have very little information on oxygen supply to the tree and prevailing gas concentrations in the soil. The times of year during which oxygen deficiency can occur, and the degree to which it affects trees and plants, are important issues that have not received much attention.

The main focus of this project is on analyzing the distribution of soil gases and the variation in gases during the vegetation period. The project is being conducted on certain productive peat-covered wetlands with well defined site conditions. The connection between the reduction in development of trees, tree mortality and oxygen deficiency in new stands established on wetlands is also being studied. The aboveground development of trees is monitored concurrently with gas concentrations in the soil near the roots.

Forestation of Open Wetlands

The objective of this project is to develop site-specific methods for stand establishment both on open wetlands and on abandoned agricultural land located on peat.

In the 1960s and 1970s some forestation and fertilization experiments were begun on open wetlands. In the present project, a series of experiments dealing with optimal ditch spacing, tree species, planting methods and fertilization is being undertaken. These experiments are being set up across the country.

About 30 years ago, approximately 200,000 ha of peatland were used for agriculture. A large proportion of this area has been or will be abandoned in the near future, because of a domestic surplus of agricultural products that has resulted from better production methods.

Much of this land has a high production capacity and, if properly taken advantage of, it should be well suited to forest production. Forestation efforts have often failed because of frost, competing vegetation, drainage difficulties and, sometimes, nutrient deficiency.

An experiment that employs different forestation methods has therefore been initiated in nine areas located in three different regions of the country. Different tree species are being examined and, in the case of Norway spruce (*Picea abies*), different seedling sizes are also being tested. The seedlings are planted in plowed soils or mounds, or without any site preparation. Weeding and fertilization are included in the experiments.

Forestation of Excavated Peatland

The project has been set up with the aim of determining the prerequisites for stand establishment on excavated peatlands so that a system will be in place for the forestation of areas after the peat has been stripmined.

As a result of efforts to find alternative sources of energy, peat is being excavated from a large peatland area. If areas that are under protection are taken into account, about 300,000 ha of peatland (areas >50 ha) are suitable for large-scale harvesting. In 1987, about 6,000 ha of flammable peat were excavated and by 1990 the amount is expected to triple.

The company that is responsible for the excavation of a given area must also see to suitable restoration of the land when the work is finished. Forestation is a desirable option; however, domestic experience in this area is very limited.

In 1982 a forestation study with pine on excavated peatland was begun in central Sweden. A similar study is being established on a similar site in the south. In addition, research results and practical experience gained from Finnish efforts are being examined.

Certain conditions for regeneration on excavated peatlands are significantly different from those that apply to normal peatland. The focus in this project will be on three major differences. First, the surface peat layer, which contains more nutrients than the lower layers and consists of less decomposed material, no longer exists. What remains is a highly decomposed material that is low in nutrients and more difficult to drain. Second, the surface level has been lowered, which renders the outflow of water difficult and results in a poorer microclimate. Finally, on the positive side, competing vegetation remains absent for some time after peat harvesting.

Stand Harvesting and Forest Renewal

The purpose of this project is to determine suitable methods for harvesting and renewing mature spruce (*Picea* spp.) forests on highly productive peatlands. There are at present about one million ha of good peatland sites that support more than 150 million m^3 of trees, or about 5% of the national timber inventory. Areas that have been cut so far have had major regeneration problems, including unacceptable increases in the groundwater levels, fast-growing competition, high degrees of frost and considerable damage to wildlife.

The project includes research with different regeneration methods in nine experimental areas in the country. Each location is divided so that half the area is completely clearcut, while the other half consists of seed trees at densities of 140 and 200 trees/ha. Large bare-root Norway spruce seedlings are being used for planting.

Stand Treatment and Forested Wetlands

This project is intended to determine the effect of different thinning intensities on wood and total growth of stands on drained wetlands and also the effect of subsequent ditching with high levels of thinning.

Silviculture in stands on drained wetlands is often neglected. This is because of uncertainty about how a stand should be treated, and also because of poorly developed thinning techniques for wetlands. The level of thinning influences factors such as the level of groundwater after thinning, the risk of snow and wind damage, and the economic return. Intensive thinning may be desirable for release of birch (*Betula* spp.) and suppressed trees, and for higher economic returns, but it may create a need for ditch cleaning or complementary ditching. Low levels of thinning may be preferable to maintain a well balanced ecosystem in the stand and thus avoid an unacceptable increase in the groundwater level, and to reduce the risk of windthrow.

The experiment has been established at six locations in southern Sweden in stands that have undergone single thinnings. All of the locations have old ditch systems; there are five sample plots (measuring 25 x 40 m) on each, with different thinning intensities. The degree of thinning varies from 20 to 50% of the basal area. In the case of the most intensive thinning, complementary ditches are also being tested. The level of groundwater is regularly being measured on all sample plots.

Silvicultural Techniques

This project deals with methods of ditching and forest regeneration on wetlands.The purpose is to develop a basis for improved techniques.

Forest-regeneration techniques in Sweden are based on analysis of the demands of rocky ground with stumps and slash. In the case of wetlands, forest-regeneration techniques are influenced by other conditions, especially those related to soil texture and ground strength. There should be better possibilities for the development of suitable planting spots on wetlands than there are on most other types of land because peat and sediment are easier to manipulate. Since wetlands are typically flat and often lack impediments such as stumps and rocks, the conditions for mechanical planting are very favorable.

The project will concentrate on an analysis of conditions for ditching, site preparation and planting. The analysis will be expanded to include a description of how forest-regeneration techniques should be carried out on different types of wetlands, and a discussion of how existing techniques in Sweden and other countries meet these demands.

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FOREST DRAINAGE IN NOVA SCOTIA

P. Neily
Nova Scotia Department of Lands and Forests
Truro, Nova Scotia
Canada

ABSTRACT

In Nova Scotia, there has been no large-scale operational drainage of forest lands. Approximately 25% of these forest lands are classified as imperfectly or poorly drained, and a further 2.5% are classified as peatland. Trials are under way to evaluate the effect of drainage on site productivity in Nova Scotia. In the absence of results from these tests it is assumed that an average increase of 3 m^3 ha^{-1} yr^{-1} could be achieved by draining imperfectly and poorly drained soils. This increases the potential forest production by approximately 3.0 million m^3 yr^{-1} (1.5 million cords yr^{-1}). While the potential gain will never be achieved for a variety of reasons, substantial gains are nevertheless possible.

RÉSUMÉ

Il n'y a eu aucun drainage opérationnel important de terres forestières en Nouvelle-Écosse. Environ 25% de ces sols sont classés comme étant mal drainés, et 2,5% sont classés comme tourbières. Des essais sont en cours pour évaluer l'effet du drainage sur la productivité en Nouvelle-Écosse. Faute de résultats de ces essais, on suppose qu'il serait possible d'obtenir une augmentation moyenne de 3 m^3/ha par année en drainant les sols mal drainés en Nouvelle-Écosse. Cela permet d'augmenter la production possible des forêts d'environ 3,0 millions de mètres cubes par an (1,5 million de cordes par an). Bien qu'il soit impossible d'atteindre la production nominale pour diverses raisons, des gains importants sont néanmoins possibles.

INTRODUCTION

Nova Scotia is one of Canada's most heavily forested provinces. Productive forests occupy 69% of the total area or 3.845 million ha. Non-productive forest land comprises only 3.5% of the total area, or 193,000 ha, of which 132,700 ha are classified as peatland. The climate is strongly influenced by the Atlantic Ocean, which is no further than 60 km from any point of land. Nova Scotia receives 1300 mm of precipitation and accumulates 1700 degree-days (> 5°C) annually.

In many parts of the world, drainage of wetlands has long been recognized as a relatively economical means of increasing forest productivity. Finland alone has increased the growth of its forests by 7 to 8 million m^3 per year by drainage of 5.7 million ha. Other countries in which significant forest areas have been drained include Sweden, Norway, the United Kingdom, and the USSR.

Drainage of peatlands for forest use will never be a major silvicultural treatment in Nova Scotia because of the small area available. However, with almost 1 million ha of poorly drained mineral soils, drainage schemes can be designed to improve water movement in these soils. The strategic location of ditches can be prescribed to increase site productivity and improve early conifer establishment on harvested sites. Because most poorly drained areas already support mature forest stands, improvement of drainage could be a treatment prescribed after harvesting. Drainage may also be used as a remedial effort to counteract poor harvesting practices. Water ponding is caused by the deep rutting of harvesting machinery, but the water can be drained off site by ditching.

DRAINAGE STUDIES

Since 1986, several forest drainage experiments have been established on imperfectly and poorly drained mineral soils in Nova Scotia. A variety of mechanical equipment, including a tracked excavator (11,000 m of ditches) and the Lännen ditching tractor (5,000 m of ditches), has been used. These experiments were undertaken to: 1) determine the most effective ditch spacing on wet, poorly drained mineral-soil sites, 2) determine the effects of ditching on plantation survival and growth, and 3) assess the capability of tracked excavators and the Lännen S-10 ditching tractor under Nova Scotia conditions.

Four clear-cut sites were selected for study; three contained imperfectly drained, fine-textured soils over a compacted subsurface layer. The other site was also imperfectly drained and underlain by a compacted layer, but had coarse-textured soils. Ditches were established at 12-, 20-, 25-, 30- and 50-m spacings and were dug to a depth of 45-60 cm and a width of 1 m. Sediment ponds were established at the ends of all main ditches. A control or untreated area was reserved on each site. Wells to measure water level were placed throughout the drained and control areas. Permanent sample plots were established at all sites to monitor the effect of drainage on crop-tree growth.

The monitoring wells to measure water levels consisted of plastic pipes 1.2 m long and 2 cm in diameter, placed in the ground to a depth of 1 m. Holes were drilled at 15-cm intervals along the pipe to allow easy water movement. Water levels in these wells were measured by blowing air down a graduated copper pipe. When the pipe hit the water, bubbles were heard and the measurements were recorded.

RESULTS AND DISCUSSION

After two seasons of measuring water levels on the drained and undrained sites, preliminary analysis indicated that ditching of imperfectly drained mineral soils affected water levels during the growing season. However, the effect of this lowering of the water level on tree seedling growth and survival has yet to be determined quantitatively. Data gathered from the permanent sample plots over the next five years may indicate the degree of increase to be expected from draining of wet mineral soils.

Ditching specifications used in Quebec (Trottier 1986) may have similar application in Nova Scotia. It is recommended in the interim, until more information is available from trials in Nova Scotia, that a ditch spacing of 30-50 m and a ditch depth of 50-70 cm be adopted for draining imperfectly and poorly drained mineral soils. Ditches should be established with a V-shaped bucket on all sites. Sediment ponds should be established at the ends of all main ditches and consideration should be given to establishing sediment ponds midway along ditches of extraordinary length or slope. Continued evaluation of ditching trials will allow refinement of the ditching specifications to reduce losses caused by erosion and adverse effects on water quality.

Drainage of peatlands can increase productivity from 1 to 8 m^3 ha^{-1} yr^{-1} (Mikola 1967, Smissaert[1], Kusnierczyk[2]). Andreáson (1978) reported that drainage of poorly (imperfectly) drained mineral soils and peatlands will raise the productivity of the site so that it equals that of surrounding well drained sites. Trottier (1986) expects an increase in productivity of 3-7 m^3 ha^{-1} yr^{-1} by draining peatlands and paludified (poorly drained) mineral soils in Quebec.

It is estimated that drainage could increase the productivity of Nova Scotia's forests by 3.0 million m^3 yr^{-1}. However, because of ownership patterns (small private holdings account for 50% of the productive forest lands, large industrial holdings account for 25%, and the remainder is publicly controlled), and for a variety of other reasons, it is unlikely that this level of productivity increase will be achieved.

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THE WALLY CREEK AREA FOREST DRAINAGE PROJECT IN ONTARIO'S CLAY BELT: PROGRESS REPORT

J.K. Jeglum
Forestry Canada
Ontario Region
Sault Ste. Marie, Ontario
Canada

ABSTRACT

The Wally Creek area has provided a focus for a major, multiagency, cooperative program of research into peatland forest drainage. The main contributors are the Ontario Ministry of Natural Resources and Forestry Canada, Ontario Region, but several other agencies are also participating. The project objectives are to demonstrate the installation and workings of a systematic drainage network, to provide an economic evaluation of forest growth response, to develop a set of operational prescriptions, and to supply scientific information for environmental assessment. Numerous studies have been initiated and some are already completed. This presentation provides an overview of the Wally Creek Area Forest Drainage Project, and a progress report on the results of the individual studies.

RÉSUMÉ

Le secteur du ruisseau Wally a été le siège d'un programme de recherche majeur conjoint entre plusieurs organismes sur le drainage des tourbières arborées. Le ministère des Richesses naturelles de l'Ontario et Forêts Canada, région de l'Ontario, en ont été les principaux artisans mais plusieurs autres organismes y ont également participé. Le projet avait pour objectifs de démontrer la mise en place et le fonctionnement d'un réseau de drainage systématique, d'évaluer la croissance obtenue en terme économique, d'élaborer un ensemble de modalités de fonctionnement et d'obtenir des données scientifiques à des fins d'évaluation de l'état de l'environnement. De nombreuses études ont été entreprises et certaines sont déjà complétées. Le présent article donne un aperçu du projet de drainage forestier du secteur du ruisseau Wally et rend compte de l'état d'avancement des travaux des différentes études.

INTRODUCTION

In 1984, a cooperative forest drainage project was initiated by the Ontario Ministry of Natural Resources (OMNR) and Forestry Canada, Ontario Region (FCOR) (Haavisto 1984; Rosen 1985b, 1986a, 1986b; Wearn 1984). Preliminary work by FCOR at Wally Creek in the early 1970s (Silc 1973) had provided a contour survey for part of the area. Since it is located on a provincial highway only 26 km from Cochrane, Ontario, the area is ideal for demonstration purposes for forest managers, researchers and the general public.

The study area is in the Northern Clay Section of the Boreal Forest Region (Rowe 1972) of northeastern Ontario (Fig. 1). It consists of 1,099 ha of lowland black spruce (*Picea mariana*) forest. Part of this forest was cut over about 1930 by ground cutters using horses to skid to the roadside. This method left much advance growth, including saplings and small trees, and the area regenerated naturally to a fully stocked forest. At the time of drainage, in the fall of 1984, the forest had grown for 55 years since cutting. It was uneven-aged, some trees originating after the cutting, others being present at the time of the cutting and hence more than 55 years old. Other parts of the area had not been cut over, and the forest here was 120+ years old. Part of this was stunted black spruce and/or tamarack (*Larix laricina*) in the wet, low depressions, and part was productive black spruce that was not in the harvest allocation.

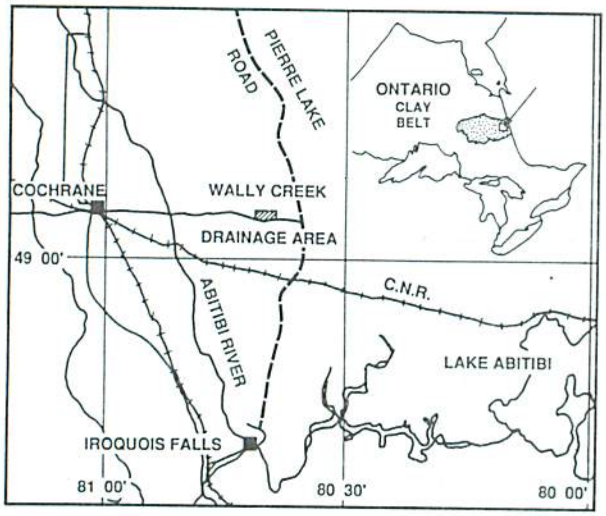

Figure 1. The study area in the Northern Clay Section of the Boreal Forest Region of northeastern Ontario.

A Finnish drainage expert, Ilka Koivisto, was hired to design and oversee establishment of an operational drainage trial (Haavisto 1984). He also trained an OMNR Project Forester, M.R. Rosen, so that the knowledge and experience gained could be passed on to others in Canada. Two Finnish Lännen S-10 digging machines were brought to Ontario, along with two experienced Finnish operators (Härkönen 1986). Koivisto (1984, 1985) has reported on his experiences in planning and implementing the drainage system.

The overall project objectives were as follows: (1) to demonstrate the installation and workings of a systematic drainage network; (2) to provide an economic evaluation of forest growth response; (3) to develop a set of operational prescriptions; (4) to supply scientific information for an environmental assessment; and (5) to provide a land area, management and coordination for research on and development of peatland forestry (Rosen 1986a). A summary of studies and projects up to 1986 was included in a Management Plan developed by the Cochrane District office of the OMNR (ibid.) and in two published papers (Rosen 1986b, 1986c), and a workshop was held at Wally Creek in 1986 (Jeglum 1986). The present paper updates the studies and activities, and summarizes their results. A comprehensive list of all reports and articles published on Wally Creek is provided in the Literature Cited section.

RATIONALE FOR DRAINAGE

In Ontario, there is not enough planting stock to regenerate every hectare cut, and it is necessary to rely on less expensive methods such as direct seeding, or to hope for natural regeneration. It is commonly held that the best land, closest to the mill, should receive the highest level of investment and the most intensive treatment. If planting stock is not available, less expensive, more extensive methods of regeneration, such as direct seeding and modified harvesting, should be used. The poorest land and the land furthest from the mill should either receive inexpensive treatments or be left after harvest to regenerate naturally. Since peatland forests are in the category of poorer or poorest lands, many foresters do not think that drainage has much place in current forest management.

However, there are certain forest industry timber limits with a high proportion of peatland or wetland forests, where the improvement of fiber production is very important for mill supply. As well, in certain situations, peatland forests may represent a good investment, e.g., where they are close to the mill so that transportation costs for the harvested wood will be low. The most attractive peatland forest sites for drainage are those that show moderately good growth, are moderately rich in terms of soil nutrient regime, are already well stocked with a usable species so that no fill-in planting costs are involved, are in mid-rotation so that only 15 to 20 years are required to a final cut, and may require a rather low intensity of forest drainage ditches for effective drainage.

From the above discussion, it appeared that drainage could be utilized in two ways (Koivisto 1986): (1) clear-cut, drain and plant; (2) drain mid-rotation stands. These methods have been incorporated into the Wally Creek Area Forest Drainage Project.

EXPERIMENTAL DESIGN

In all, 306 ha of mid-rotation black spruce forest and 69 ha of planted cutover, most of it on organic soil, have been drained. There are 87 km of open ditches draining the area. The ditches are mostly 90 cm deep and 1.2 m wide, but collector ditches are deeper and wider, and some ditches are shallower (about 70 cm) where the peats are shallow and close to mineral-soil uplands.

In the Clay Belt, a Forest Ecosystem Classification system has been developed (Jones et al. 1983) that has proved very useful to forest managers in a variety of situations (Jeglum 1985a). In the summer just before drainage, the Forest Ecosystem Classification Operational Groups (FEC-OGs) in the Wally Creek area were surveyed under contract (Arnup 1985). This survey provided the basic stratification into site types that were used to locate experimental plots and lines. The main OGs were OG8, OG11, OG12 and OG14; OG8 is a mineral-soil type, whereas OG11 to OG14 are on organic soils. (Small amounts of OG9 and OG5 were also present.)

The drained forested area consisted primarily of OG11, with some OG12; ditches here were mainly 40 to 45 m wide. Wider ditch spacings of 55 to 60 m were used in a predominantly upland block, consisting mostly of OG8, with some OG5 and OG11. Narrow spacings of 20 to 25 m were used in OG14. For the most common site type, OG11, it was possible to install a range of ditch spacings from about 20 to 75 m wide. For OG11, four modal widths for ditches were 26, 39, 45 and 56 m (Berry and Jeglum 1988).

The clearcut area consisted primarily of OG12, with lesser proportions of OG11 and OG8. In the clearcut area for each of the four subexperiments, the main ditch spacings were 30 m, but a few narrower (15 m) and wider (60 m) strips were included.

In the clearcut area four site-preparation/regeneration treatments were applied:

(1) tree-length logging, shearblading and planting;

(2) tree-length logging, shearblading and natural regeneration with seed-tree groups;

(3) tree-length logging, prescribed burning, and planting;

(4) full-tree logging, no site preparation and planting.

STUDIES AND ACTIVITIES

Numerous studies, trials and activities were undertaken in the area, and a summary of these was provided at an early stage of the project (Rosen 1986d). Most of these were research studies, but others were less formal trials or demonstrations, or consisted of baseline data collection (the weather station), or public awareness activities (e.g., the self-guiding trail). The following is an updated list of studies and activities. Reports or publications are shown in bold type.

Ontario Ministry of Natural Resources (OMNR)

The studies are being supervised by OMNR's Northern Technology Development Unit[1], and conducted by Project Foresters located at OMNR's Cochrane District Office[2].

1. Assessment of the economics of forest drainage.

   The cost of peatland forest drainage in the Claybelt of Ontario *(Rosen 1986e, 1987).*

   Economic evaluation of forest drainage and fertilization in northern Ontario peatlands with an investment decision model *(Payandeh 1988).*

   Cost-effectiveness of forest drainage and fertilization in northern Ontario peatlands *(Payandeh 1990).*

2. Assessment of the growth and yield of untreated, uneven-aged, 55-year-old cutovers of black spruce, naturally regenerated, and virgin forests more than 120 years of age.

3. Assessment of growth response of black spruce to drainage (including variation owing to ditch spacing) and fertilization (total NPK).

4. Foliar nutrient response to drainage and fertilization.

5. The influence of drainage and fertilization on survival and growth of planted conifer seedlings, and ingress of natural regeneration in the group seed-tree area, in the peatland cutover.

   Wally Creek area forest drainage project: A preliminary analysis of the seedling assessment data *(Abraham 1989).*

6. Assessment of natural regeneration in the group seed-tree area.

7. A self-guided interpretive trail and accompanying pamphlet.

   The Wally Creek Project Trail *(Rosen 1985a).*

8. The development of drainage prescriptions.

   Forest drainage manual *(Rosen 1989).*

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[1] For further information, contact the Ontario Ministry of Natural Resources, Northern Technology Development Unit, 60 Wilson Avenue, Timmins, Ontario P4N 2S7.

[2] For further information, contact the Ontario Ministry of Natural Resources, Cochrane District Office, P.O. Box 730, Cochrane, Ontario P0L 1C0.

Forestry Canada, Ontario Region

The objectives of the work by Forestry Canada are (1) to evaluate hydrological changes associated with forest drainage[3], and (2) to elucidate ecological changes in drained forested and clearcut areas and relate these to growth responses by trees and seedlings.[4]

1. The influence of drainage on groundwater depths.

   Water table profiles of drained forested and clear-cut peatlands in northern Ontario, Canada *(Berry and Jeglum 1988).*

   A probe for measuring depth to water surface in wells *(Bodley et al. 1990).*

2. The influence of drainage on groundwater nutrient content.

3. The influence of drainage on streamwater quality.

   Effects of forest drainage on surfacewater quality of black spruce peatlands *(Berry 1990).*

4. The influence of the drainage system on streamflow.

5. The influence of clearcutting on groundwater depths.

6. Vegetational changes associated with drainage.

   Vegetation analysis of peatland drainage sites at Cochrane and Hearst *(Browning 1986).*

7. Foliar nutrients before and after drainage.

8. Weather data collection with an automatic data-logger at an on-site weather station.

9. Assessment of the influence of drainage and clear-cutting on soil temperatures.

   Climate, water, and drainage in peatland *(Haavisto et al. 1989).*

10. Peat substrate environments on drained and un-drained peatlands.

    Substrate environments on drained and undrained peatlands, Wally Creek Experimental Drainage Area, Cochrane, Ontario *(Rothwell 1990).*

11. Vegetation-soil-site relationships for the permanent growth plots.

12. Cellulose decomposition and oxidation rod studies in relation to drainage.

13. Black spruce outplantings: survival and growth response to drainage, seedbed, and alder (*Alnus* spp.) competition.

14. Ectomycorrhizal colonization and root growth of outplanted container seedlings.

    Root growth and ectomycorrhizal colonization of outplanted containerized **Pinus banksiana** *(Browning and Whitney 1987).*[5]

Other agencies

1. Supplementary aerial photography and thermo-graphy. Ontario Centre for Remote Sensing.[6]

   The use of airborne thermography in the design of ditch networks for forest drainage programs *(Senese 1985).*

   Detection of micro-drainage patterns for ditching in forest environments *(MacIver and Senese 1985).*

2. Characterization of the microfauna of black spruce swamps, and influence of drainage. Agriculture Canada.[7]

   Soil microfaunal densities following drainage of peatlands *(Tomlin 1988).*

3. Airborne detection of water vapor and CO_2 flux in drained peatlands. Agriculture Canada.[8]

4. Cone and seed yields in mid-rotation black spruce stands.[9]

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[3] For further information, contact G.J. Berry, c/o Forestry Canada, Ontario Region, P.O. Box 490, Sault Ste. Marie, Ontario P6A 5M7.

[4] For further information, contact J.K. Jeglum, Forestry Canada, Ontario Region, P.O. Box 490, Sault Ste. Marie, Ontario P6A 5M7.

[5] For further information, contact M.H.R. Browning, c/o Forestry Canada, Ontario Region, P.O. Box 490, Sault Ste. Marie, Ontario P6A 5M7.

[6] For further information, contact E.M. Senese, Ontario Centre for Remote Sensing, CIL House, 90 Sheppard Ave. E., 4th Floor, North York, Ontario M2N 3A1.

[7] For further information, contact Dr. A. Tomlin, Agriculture Canada, London Research Centre, University Sub Post Office, London, Ontario N6A 5B7.

[8] For further information, contact Dr. R. Desjardins, Agricul-ture Canada, Central Experimental Farm, Ottawa, Ontario K1A 0C6

[9] For further information, contact V.F. Haavisto, Forestry Canada, Ontario Region, P.O. Box 490, Sault Ste. Marie, Ontario P6A 5M7.

5. Evaluation of testate amoebae (Rhizopoda: Protozoa) for peatland forestry as indicators of soil moisture and oxygenation in peat soils. University of Waterloo.[10]

   Distribution and abundance of testate amoebae: (Protozoa) in the Wally Creek watershed, Ontario (Warner 1990)

6. Wildlife assessment of a peatland drainage project. McGill University.[11]

   Wildlife assessment of a peatland drainage project (Bérubé 1988).

CONCLUDING COMMENTS

The status of peatland forestry in Ontario (Jeglum et al. 1983, Rosen 1986f) and Canada (Päivanen 1985, Haavisto and Jeglum 1990) has been reviewed in several recent papers. Forest drainage has considerable potential in Ontario, especially in view of the need to manage the better lands closer to the mills more intensively. One of the main purposes of drainage is to shorten rotation of mid-rotation stands by accelerating growth. Seedling outplantings on drained clearcuts can grow faster, and rotation age of the new forests can be reached considerably earlier. This may help to bridge the age-class gap that is predicted in the next 20 to 30 years, when the old forests have been harvested and there are not enough second-rotation forests available to meet the projected demand. Although growth response is the main goal of drainage, there are other potential benefits. Drainage before harvesting could reduce the amount of mucking-up damage to the site, and improve accessibility for subsequent planting activities and the next harvest.

In Finland it is emphasized that the peatlands with the most potential are those on shallower peats and those that are richer, i.e., the herb-rich types (Jeglum 1985b). In the current program of identification of 'prime lands', it is quite possible that some of the peatland sites and shallow peated sites could be among the most productive lands if they were drained. On certain timber limits, drainage of some of the richer peatlands near the mill may be a very attractive choice, as it could yield the highest returns on investment. It is important to set up a number of operational trials in northern Ontario, in particular to determine the optimum spacing of ditches for different OGs, as choosing the spacing is the major question to be settled if we are to reach an acceptable compromise between biological effectiveness and the cost of drainage.

The Wally Creek experiment is the first significant step towards the development of peatland management prescriptions in Ontario. However, one trial will not answer all questions about forest drainage. More trials are required in Ontario to gain broader information on the optimum spacing of ditches for each of the main OGs. As well, trials are required to show how thinning of stands at the time of drainage can be used to improve the productivity of the stands, and the size of the stems at final harvest. Finally, more fertilization trials are required with the full range of combinations of N, P and K, and also micronutrients.

At this time we should collect as much information as possible about drainage so that we are prepared for a potentially rapid increase in drainage activity. Peatland drainage in Finland grew rapidly in the 1950s, and unfortunately, the necessary research had not yet been done. Consequently, many mistakes were made. In Ontario, we have the opportunity to provide information and guidelines before the big drainage push occurs, as I believe it will. This means capitalizing on the Wally Creek drainage project. It also means setting up other well designed trials to gain more experience, especially in designing the drainage layouts.

This project demonstrates how a well designed experimental forest can provide the focus for a multitude of different activities and research studies and thus multiply by many times the experience and information gained from that area. This project is unusual in that it is one of the few that is providing comprehensive information on management of a particular type of site, the peatland forest, in advance of the time when it will be needed.

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[10] For further information, contact Dr. B.G. Warner, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario N2L 3G1.

[11] For further information, contact Dr. J.R. Bider, Biology Department, MacDonald College of McGill University, Ste. Anne de Bellevue, Quebec.

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THE CANADA-ALBERTA WETLANDS DRAINAGE AND IMPROVEMENT PROGRAM FOR FORESTRY: AN UPDATE

G.R. Hillman
Forestry Canada
Northwest Region
5320-122 Street
Edmonton, Alberta
Canada

ABSTRACT

In 1986, 135 ha were ditched near Goose River, one of the three experimental drainage areas set up under the Canada-Alberta Wetlands Drainage and Improvement Program. The average depth to water table after ditching was between 38 and 53 cm. Ditching had little impact on the physical and chemical quality of stream water during periods of low flow. The data were insufficient for determining the effects of ditching on water quality during periods of high flow. At a Fort McMurray site, which was drained between 1975 and 1980, drainage significantly increased growth rates of young black spruce (*Picea mariana*). Average height, diameter at breast height and volume of trees in the drained area were respectively 1.8, 2.3 and 5.0 times greater than for trees in the undrained control. For trees in the drained area, the average annual-ring width for the postdrainage period was 4.3 times that for the predrainage period. It was 3.3 times that of the average annual-ring width of trees in the undrained area for the corresponding post-drainage period. On portions of the drained area, a dense growth of deciduous species, attaining the same height as the spruce, has grown up with the spruce.

RÉSUMÉ

En 1986, des fossés ont été aménagés sur 135 hectares près de la rivière Goose, l'un des secteurs de drainage expérimentaux créés dans le cadre du programme Canada-Alberta d'assainissement et d'amélioration des terres humides. Une fois les travaux terminés, la profondeur moyenne de la nappe phréatique variait de 38 à 53 cm. L'aménagement de fossés a eu peu d'incidences sur les caractéristiques physiques et chimiques de l'eau de la rivière en périodes de faible débit. Les données n'étaient pas suffisantes pour déterminer les effets de l'aménagement de fossés sur la qualité de l'eau en périodes de débit élevé. Le drainage du site de Fort McMurray, qui a eu lieu entre 1975 et 1980, a fait énormément augmenter le taux de croissance des jeunes épinettes noires (*Picea mariana*). La hauteur moyenne, le diamètre à hauteur de poitrine et le volume des arbres du secteur drainé étaient respectivement 1,8, 2,3 et 5,0 fois supérieurs à ceux des arbres de la station témoin non drainée. La largeur moyenne des cernes d'accroissement annuel après les travaux était 4,3 fois supérieure à celle d'avant les travaux et 3,3 fois supérieure à la largeur moyenne des cernes d'accroissement des arbres de la station témoin pendant la période postérieure aux travaux correspondante. Une végétation dense composée d'essences feuillues qui ont atteint la même hauteur que les épinettes est apparue dans certaines parties de la station assainie.

INTRODUCTION

The Canada-Alberta Wetlands Drainage and Improvement Program is in its fifth year of operation. It was initiated by the Canadian Forestry Service (now Forestry Canada) and the Alberta Forest Service under the Canada-Alberta Forest Resource Development Agreement (Anon. 1984). The reasons for implementing the program, its objectives, the research plan, and the methodology were described earlier (Hillman 1987, 1988a,b).

In the summer of 1985, a Canadian Forestry Service-Alberta Forest Service team selected Goose River, McLennan 28 and Wolf Creek wetland areas as experimental drainage sites. Subsequently, instrumentation and permanent sample plots were installed on the sites to measure changes in the water-table levels of groundwater, ground temperatures, stream-water quality, ground-vegetation composition and tree growth.

These and several other forested wetland drainage projects were recently implemented in Alberta (Hillman 1987, Toth and Gillard 1988), but too little time has elapsed since drainage for meaningful data on tree growth response to be available. Consequently, data from a drainage project established by the Alberta Forest Service near Fort McMurray in 1975 were used in obtaining estimates of tree-growth response to drainage.

The purpose of this paper is to outline some of the results obtained so far — namely, the effects of drainage on groundwater levels and stream-water quality at Goose River, and on tree growth at Fort McMurray.

SITE DESCRIPTIONS AND TREATMENTS

The sites investigated are located in the mixedwood boreal forest region of Alberta (Rowe 1972). In each case, existing vegetation grew in after fire. Legal descriptions and other details for the Goose River and Fort McMurray sites are provided in Table 1.

The Goose River experimental drainage area is a swamp situated about 35 km southeast of Valleyview (54° 54'N, 116° 45'W) at an elevation of 850 m. The swamp supports a black spruce (*Picea mariana*) stand 40 to 50 years old and a shrub understory dominated by Labrador tea (*Ledum groenlandicum*). Peat depth is less than 1 m. Ditching at Goose River was started in June 1986 and completed in September 1986. A more detailed description of the Goose River site and its treatment is given by Hillman (1988a).

The 89-ha Fort McMurray project area is a coniferous swamp located 11 km south of Fort McMurray (56° 34'N, 111° 19'W), adjacent to Highway 63 in the Athabasca Forest at an elevation of 400 m. Vegetation, established after a wildfire in 1953, consists of a dense cover of black spruce and a Labrador tea, feathermoss (mainly *Pleurozium schreberi*) and sphagnum moss (*Sphagnum* spp.) association.

Between 1975 and 1980 the Alberta Forest Service imposed a number of different treatments on the area to remove excess soil water and thereby enhance forest growth. Although different treatments were applied to separate portions of the area to test three drainage intensities, data collected from only one of the drained areas was used in the tree growth analyses described in this paper — the 25-ha area that was most intensively scarified[1] and ditched, and that lies adjacent to the 16-ha control (undrained) area. Preliminary analyses (Alberta Forest Service, unpublished reports) indicated that the effects of drainage were most pronounced on this site. Further information on site description and treatments is provided by Hillman (1987; unpublished report, 1989). The drainage took place over a six-year period, from 1975 to 1980; hence, for the purpose of analysis, the postdrainage period was arbitrarily defined as extending from 1979 to 1988.

[1] Scarification consisted of blading the vegetation and upper layer of peat with a bulldozer; this resulted in bladed strips 7 m wide alternating with spoil rows and undisturbed strips 3.5 m wide.

Table 1. Details of the Goose River and Fort McMurray drainage areas

Site (legal description)	Total area (ha)	Drained area (ha)	Date completed ($d\ m^{-1}yr^{-1}$)	Total ditch length (km)	Nominal ditch spacing (m)	Ditch spacings evaluated (m)	Drainage ditch density ($m\ ha^{-1}$)
Goose River (14-68-19-W5[a])	320	135	30/09/86	40	40	30, 40, 50	294
Fort McMurray (24-87-9-W4)	89	25[b]	1980	–	10	10	–

[a] Section 14, Township 68, Range 19, west of 5th meridian.

[b] Data from only a portion of the drained area at Fort McMurray were used in this study.

METHODS

Groundwater

Water-table configurations for groundwater at Goose River were monitored by means of between 7 and 12 wells, each 5 cm in diameter, which were installed, before drainage in 1986, perpendicular to ditches at three different ditch spacings. Two wells were installed on the undrained control. Depth to water table was obtained with a carpenter's tape measure once or twice a month.

Stream-water Quality

At Goose River, sediment loads and inorganic chemicals in water were monitored periodically at one location upstream and two locations downstream from points at which water from the drainage network's longest main ditch enters the creek. Sampling station D1 was located 300 m downstream from the upstream station (U) and 100 m from the nearest main ditch. Station D2 was located 1700 m downstream from station U and downstream from three main ditches. Sediment samples were collected in a DH-48 sediment sampler. The total suspended sediment was determined by methods described in Anon. (1971). "Grab" samples of water containing inorganic chemicals were collected in 250-ml plastic bottles and analyzed for total concentrations of Ca, Mg, Na, K, Al, Ti, Pb, As, Cu, Fe, Mn, Zn, Ni, S, P and N, according to the methods described by Hillman (1988a,b).

Tree Growth

Predrainage tree growth data were obtained from three transects established on the Fort McMurray site in the spring of 1976. Leader growth for 1975, total tree height and age were recorded for each tree sampled.

Four 0.25-ha plots were installed in the undrained area and in each of the drained areas in 1980. In 1981, one plot in each area was thinned to 1730 stems ha^{-1}, one plot was fertilized with nitrogen, another was fertilized with phosphorus and the fourth plot served as a control. In each plot, about 30 trees were measured for total height and leader growth each spring from 1981 through 1985. Leader-growth data for the 4-year period were analyzed by 2 x 4 (two site and four treatment conditions) factorial analyses of variance[2]. Duncan's multiple-range test (P = 0.05) was used to compare the means.

In August 1988, 42 trees were randomly sampled along transects crossing the drained and undrained areas. Twenty-two trees in the drained area and 20 in the undrained area were sectioned and measured. Disks were cut from the top of each tree section and were later used for age and ring-width determinations.

The disks were measured with a Holman Digimicrometer tree-ring increment measuring system and television camera. The resulting data sets were processed by means of the DUFFNO and STEM computer programs developed by Kavanagh (1983). The STEM program carried out stem analyses and provided tables showing mean annual increment and periodic annual increment for height (pahi), DBH, basal area and volume (pavi).

Paired and nonpaired t-tests were run on data from the destructively sampled trees to test the hypothesis that there were no differences between means for the drained and undrained areas, or between the means for the predrainage and post-drainage periods. Age and ring widths at 0.3 m height were compared, together with total height, leader length, DBH, volume per tree, pahi and pavi.

RESULTS

Groundwater

Data on the Goose River groundwater table are for May through October, from 1986 to 1988. The 1986 data constitute the predrainage measurements and the remainder are post-drainage data. The updated average water-table profiles of the pre- and post-drainage periods for the 30-, 40- and 50-m spacings (Fig. 1a, 2a and 3a, respectively) are not very different from previously presented profiles (Hillman 1988a) for 1986-1987. The average drops in water-table levels across the profiles after ditching were 27, 24 and 18 cm, respectively (Fig. 4). In contrast, on the undrained control, the average depth to groundwater table for the postdrainage period was 13 cm greater than that for the predrainage period. The average drops in water-table levels are greater than those reported previously (Hillman 1988b).

At Goose River, precipitation from May to October was 396, 337 and 392 mm, respectively, in 1986, 1987 and 1988. The corresponding total annual precipitation was 561, 439 and 540 mm. Of the three years, 1987 was the driest; during that year, lower average levels of groundwater table could be expected. At a lookout tower at Sweathouse, located adjacent to the Goose River experimental area, the 30-year (1951 to 1980) average precipitation for May to October was 444 mm (Anon. 1987).

[2] The two primary treatments were 'drained' and 'undrained'. To facilitate the analyses of variance, thinning and nitrogen/phosphorus fertilization were considered secondary treatments.

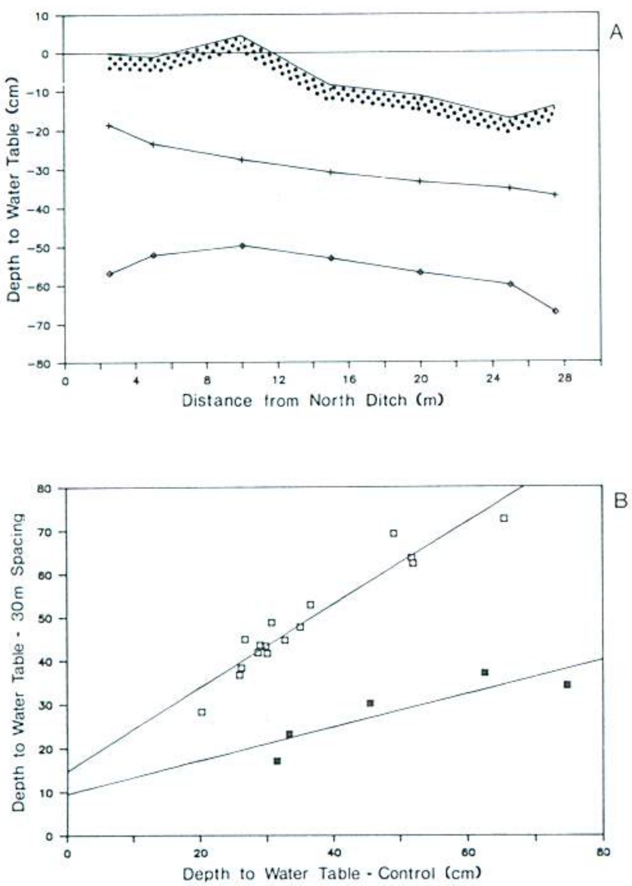

Figure 1. Goose River, 1986-1988, 30-m spacing. Depth to mineral soil is 93 cm. A) Average water-table profiles before (+) and after (♦) drainage. B) Regression lines before (■) [$y = 0.38x + 9.53$, $r^2 = 0.77$] and after (□) [$y = 0.95x + 14.84$, $r^2 = 0.92$] drainage.

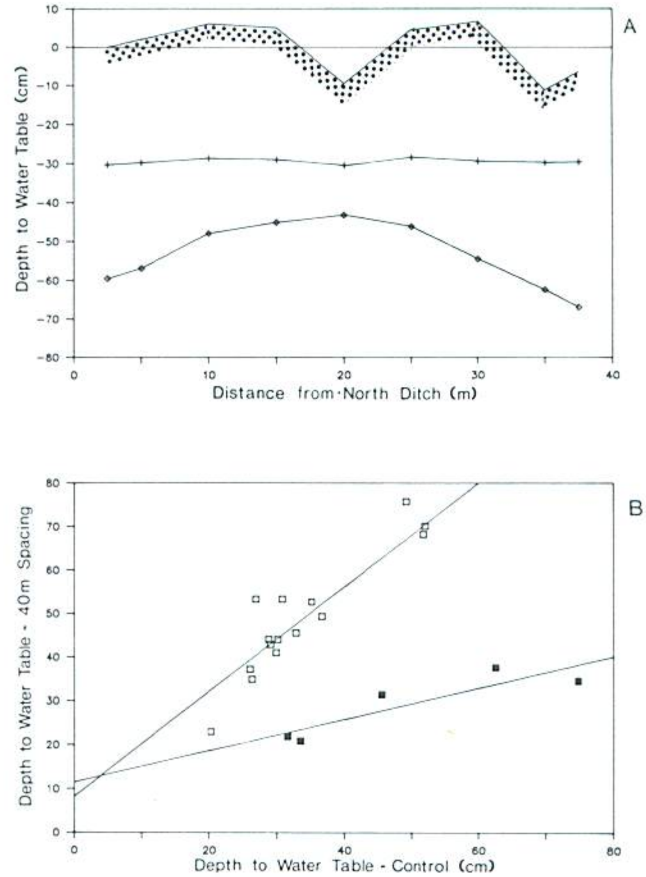

Figure 2. Goose River, 1986-1988, 40-m spacing. Depth to mineral soil is 96 cm. A) Average water-table profiles before (+) and after (♦) drainage. B) Regression lines before (■) [$y = 0.36x + 11.54$, $r^2 = 0.79$] and after (□) [$y = 1.20x + 8.36$, $r^2 = 0.87$] drainage.

To minimize the confounding effects of dry years on levels of groundwater table, regression analyses were carried out on values for depth to groundwater tables for the undrained control and for each ditch spacing. The results (Fig. 1b, 2b and 3b) indicate that, in each case, the post-drainage relation is distinct from the predrainage one; consequently, the drainage treatment had a greater impact on average levels of groundwater table than did the drier climatic conditions of 1987. The slopes of the post-drainage graphs are about three times those of the predrainage graphs.

Streamwater Quality

In 1986, concentrations of Cu, Ni, As and P in downstream water samples were always below detection limits for these elements. Concentrations of Ti, Pb, and Zn at these locations were also frequently below the detection limits. The highest concentrations of Ti, Pb and Zn detected in the downstream samples were 0.01, 0.04 and 0.04 mg kg^{-1}, respectively. The large number of zero values did not allow for statistical analysis of data for these elements.

Analyses of the 1986 data on suspended sediment and chemicals in water (Table 2) showed that there were no significant differences between upstream and downstream concentrations for suspended sediment, total N, Ca, Mg, Na, Mn, S and specific conductance. The differences were significant for K and Fe. In the case of aluminum (Al), differences between the upstream mean and the mean for the first downstream station (D1) were significant, but differences between the upstream mean and the mean for the second downstream station (D2) were not. The upstream means were significantly greater for K and Al. Both downstream means were significantly greater for Fe.

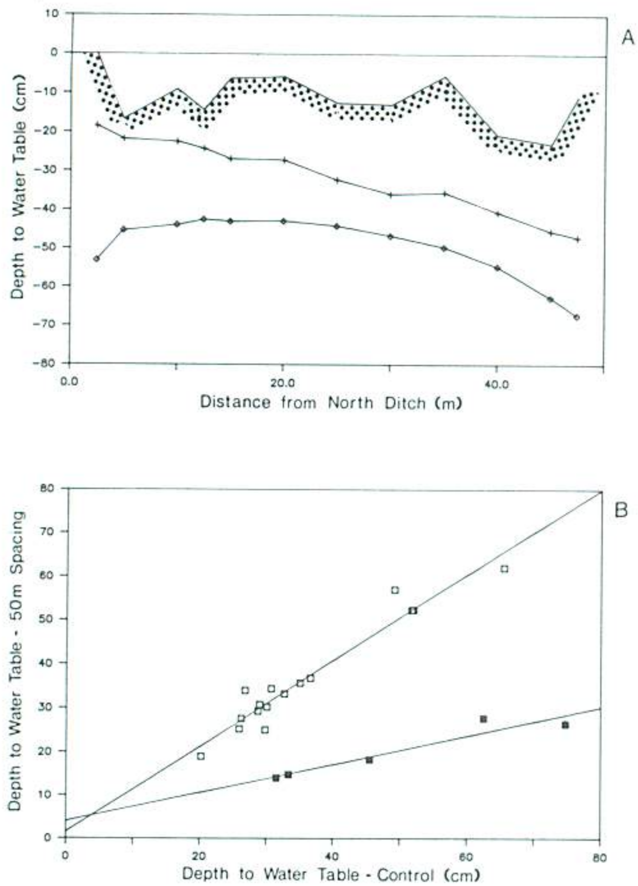

Figure 3. Goose River, 1986-1988, 50-m spacing. Depth to mineral soil is 80 cm. A) Average water-table profiles before (+) and after (♦) drainage. B) Regression lines before (■) [$y = 0.33x + 3.95$, $r^2 = 0.91$] and after (□) [$y = 0.98x + 1.43$, $r^2 = 0.93$] drainage.

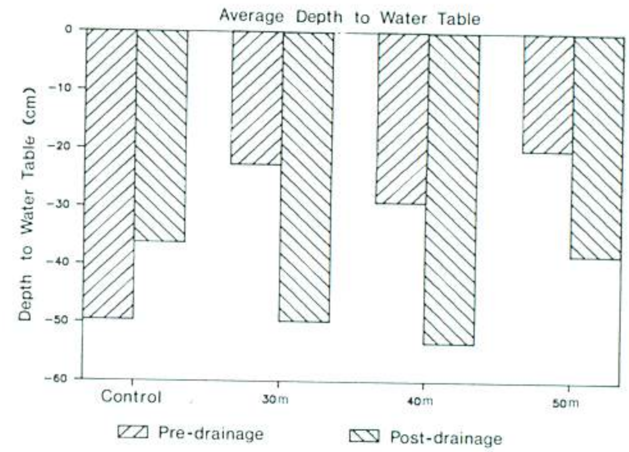

Figure 4. Goose River, 1986-1988. Average depth to water table before and after drainage for the control and for the 30-, 40- and 50-m ditch spacings.

Tree Growth

The results cited here are treated more fully in an unpublished report[3]. The pretreatment data indicated that, before drainage, the height growth of black spruce in both the treated and the untreated areas was poor. There were no significant differences in age, total tree height and leader length between the two sites. The average age for all trees measured in 1976 was 15.4 years. The clearing and scarification treatment greatly reduced stocking in the drained area.

The average annual leader growth for black spruce in the drained area, 6-9 years after treatment began, was 3.8 times that for black spruce in the undrained area. Neither the fertilizers nor the thinning had a significant effect on tree leader growth in the drained area but nitrogen did have a significant effect on leader growth in the undrained area; leader growth on the nitrogen-treated plots was nearly three times that on the control plots.

The 1988 data from the 42 destructively sampled black spruce trees verified that drainage had a significant effect on leader growth. They also showed that the ratio of drained to undrained leader growth was being maintained at the same ratio as for the 1981-1985 period (3.8:1). The average leader growth on the drained area was 45 cm. Mean tree height, DBH and volume per tree were, respectively, 3.89 m, 4.1 cm and 0.0034885 m^3 in the drained area in comparison with 2.13 m, 1.8 cm and 0.0006947 m^3 in the undrained area. The difference was highly significant in each case.

[3] Hillman, G.R. 1989. Tree growth on drained forested peatland near Fort McMurray, Alberta. (Unpublished report).

Table 2. Specific conductance and mean concentrations of post-drainage suspended sediment and chemical elements for the creek at Goose River, 1986

Site[a]	Suspended sediment	N	Ca	Mg	Na	K	Al	Fe	Mn	S	Specific conductance
	mg kg^{-1}										(µS cm^{-1})
U	20.06	0.92	5.76	1.08	4.79	1.04	0.51	0.64	0.04	0.53	56.66
D1	14.63	0.97	8.04	1.70	7.08	0.11	0.23	1.04	0.04	0.48	74.68
D2	5.23	0.78	8.87	2.00	6.69	0.27	0.31	1.01	0.03	0.55	74.65

[a] U = Upstream, D1 = Downstream 1, D2 = Downstream 2

In the undrained area, there were no significant differences in average ring width at a height of 0.3 m or in pahi between the two periods investigated, 1969 to 1978 and 1979 to 1988. The pavi was significantly greater (2.6 times) during the latter period. In the drained area, ring width, pahi and pavi were all significantly higher for the later, post-drainage period than for the 1969 to 1978 interval. During the 1979 to 1988 period, ring width, pahi and pavi were respectively 4, 3 and 39 times greater than the corresponding averages for the earlier period.

Ring width, pahi and pavi for trees on the undrained site were compared with those for trees in the drained area for the same period. There were no significant differences in ring width or pahi during the predrainage period. During this period, the pavi of trees in the undrained area was more than twice that of trees in the drained area. (The difference was significant.) A similar comparison for the 1979 to 1988 post-drainage period showed that tree ring width, pahi and pavi in the drained area were 3.3, 3.8 and 7.2 times greater, respectively, than the corresponding values for the undrained area; these differences were significant.

Drainage also had a significant effect on growth of deciduous species. No attempt was made to quantify the growth of alder (*Alnus crispa*), willow (*Salix* spp.), aspen (*Populus tremuloides*), balsam poplar (*P. balsamifera*) or birch (*Betula pumila*), but it was evident that a dense growth of these species filled the space between the spruce and had attained approximately the same height as the spruce canopy. In contrast, in the undrained area, growth of willow, birch and black spruce was suppressed.

DISCUSSION

Groundwater

Results from Goose River so far indicate that drainage has increased the average depth (across the drained profile from ditch to ditch) to the saturated zone by between 18 and 27 cm, with the average water table lying between depths of 38 and 53 cm. These depths are comparable to the range of optimum depths recommended for different tree species that are found in forest-drainage literature (Heikurainen 1964).

It appears that acceptable depths to water table can be achieved with 50-m ditch spacings, but it is not known whether this spacing will result in the best growth of black spruce. This will be determined when the permanent sample plots on Goose River are remeasured. Economics and considerations of environmental preservation dictate that ditch spacings be as wide as possible, but they must also be narrow enough to promote acceptable improvement in tree growth rates.

The results tell us nothing about the residual water content in the unsaturated zone. Because trees must have an adequate water supply, it is important to know the water content in the rooting zone after drainage. An arid rooting zone is as undesirable as an excessively wet one. Preliminary results from McLennan and Wolf Creek indicate that drainage has caused water tables there to drop as low as, or even lower than, those at Goose River. Because of this and because of the complete lack of information on soil moisture conditions on these sites, soil-water sampling programs were begun in drained and undrained areas on all three experimental sites in 1989. This part of the program is a cooperative effort between Forestry Canada, the Alberta Forest Service, and the Forest Science Department at the University of Alberta.

Drainage reduces the capacity of peat to store water by introducing numerous hydraulic gradients into the natural system. Peat depth is between 80 and 100 cm in the ditch-spacing evaluation area at Goose river. It was previously reported (Hillman 1988a) that most of the water running into the lateral ditches came from the interface between the peat and mineral (clay) soils and that the ditch depth need not extend much below that level. Measurements from pressure transducers installed at Goose River before drainage have indicated that water table levels fell more rapidly after drainage than before drainage (Hillman 1988a). This change reflects the increase in hydraulic gradients as a result of drainage. The foregoing observations are related to a reduction in the water-storage capacity of the peat.

The strips between ditches may be considered a series of isolated hydrodynamic systems, and so long as the water levels in the adjacent ditches are lower than the water table level in the strips, Darcy's Law dictates that groundwater will move out of the strips into the open ditches. One aspect of conventional forest-drainage-ditch network design (used on Goose River) that enhances water movement out of the strips is the requirement that lateral ditches be oriented at a sharp angle to the contours. As a result, the strips are oriented almost perpendicularly to the slope, and the water flux through the strips has a strong downslope component.

There are two ways in which the water-storage capacity of peat in a drained area can be increased, and conversely, drainage effectively curtailed. Either the hydraulic gradients can be reduced or eliminated, or the saturated hydraulic conductivity can be reduced. The first will occur when water is backed up in the ditches and the second may occur over time with peat settlement and decomposition.

Streamwater Quality

It would appear from the results that, except for producing an increase in the concentration of iron and a reduction in the concentrations of potassium and aluminum, ditching had no effect on the chemical quality of water or suspended-sediment concentrations in the stream. An inspection of the sediment ponds and stream channel on 24 July 1986, however, revealed that sediment filled the sediment ponds and also covered the banks of the stream channel near each main ditch. This was the result of the 99 mm of rain that fell in a 9-day period during ditching earlier in July. It was evident that the sediment ponds were functioning well but needed to be cleaned out after a storm of that magnitude. Perhaps several larger ponds are needed to control sediment movement.

The sediment ponds at Goose River were cleaned out and enlarged in October 1988, but by mid-June, 1989 they were filled again. Once more, there was ample evidence of sediment along the banks of the stream channel. The sediment pond at Wolf Creek was also filled during the first year after drainage but, so far, sediment there appears not to have reached the stream channel.

It is clear that sampling only during the monthly service visits to each experimental area is inadequate for a proper assessment of changes in the physical and chemical quality of stream water that result from drainage. The results so far are probably indicative only of water-quality conditions that prevail during periods of low flow. Theoretically, sampling should also be timed to coincide with the spring runoff and with storms that occur during the remainder of the monitoring period — events during which high concentrations of sediment and chemical elements are most likely to be flushed into the stream channel. Future plans include the use of automatic water sampling devices linked to stage-measuring recorders that activate the samplers during storm-flow periods.

One of the main ditches at Goose River is degrading and is a major source of sediment. It is deeper than when first constructed and its banks have been undercut. It was dug in a natural, vegetated draw with a relatively steep slope of 0.007. The need to minimize this kind of erosion problem suggests that, for the purposes of ditch network design, a limit should be imposed on the degree of slope that can be tolerated in ditch construction.

Tree Growth

It is evident that lowering the water table in the study area near Fort McMurray affected tree growth. Trees were larger as a result, showing increases in height, diameter and volume. Although no measurements of groundwater table were taken, it is speculated that drainage caused the average water-table level to drop 50 cm. After drainage, periodic annual volume increment per tree in the drained area was more than seven times that in the undrained area.

Two important facts should be kept in mind when one is assessing the results from the Fort McMurray study. First, the ditch spacing (10 m) is unusually narrow for forest drainage; second, the trees are 30 years old or less.

The additional value of the Fort McMurray drainage study is the young age of the stand. If the study area is protected from further disturbance, growth measurements can be taken as the trees pass through different age classes. Such measurements will enable us to learn to what extent the improved growth rates can be sustained.

CONCLUSIONS

Preliminary results from Goose River indicated that the average depth to groundwater table after drainage was between 38 and 53 cm. Additional knowledge about water content in the unsaturated zone is required to relate ditch spacings to tree growth.

Data on streamwater quality showed that drainage had little effect on the physical and chemical quality of water during periods of low flow. Automatic sampling devices and procedures are needed to monitor water quality during spring runoff and storm-flow periods. Degradation of some main ditches indicated the need to specify in future ditch network design the maximum permissible slope for use in ditch construction.

At Fort McMurray, where the ditch spacing was about 10 m, young trees responded positively to drainage. Tree height, DBH and volume were greater in the drained area than in the undrained control. Deciduous species also grew vigorously in the drained area; if they should adversely affect black spruce growth, some form of weed control will be necessary.

ACKNOWLEDGMENTS

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Section III
Growth Responses
of Forests and Seedlings

THE STATUS OF PEATLAND FORESTS IN FINLAND, BASED UPON THE NATIONAL FOREST INVENTORY

E. Paavilainen
The Finnish Forest Research Institute
Unioninkatu 40A
Helsinki, Finland

ABSTRACT

A total of 5.8 million ha of peatlands and paludified mineral soils, corresponding to one-fourth of the total area of forest land, has been drained for forestry in Finland. From the 3rd (1951-1953) to the 7th (1977-1984) National Forest Inventory, the total volume of peatland stands increased from 252 to 291 million m^3 (15%). The corresponding estimates for annual increment are about 10 and 15 million m^3 (an increase of 51%). At present, it is estimated that drainage and fertilization of peatlands account for at least 7 million m^3 of tree growth annually. Most of the drainage areas are still at an early stage of development, but a considerable increase in annual production is to be expected by the end of the century. In the near future, problems connected with ditch maintenance and first thinnings have to be solved.

RÉSUMÉ

En Finlande, 5,8 millions d'hectares de tourbières et de sols minéraux turbidifiés, soit l'équivalent du quart de la superficie totale des terrains forestiers, ont été drainés à des fins d'aménagement forestier. Entre la tenue du troisième (1951-1953) et du septième (1977-1984) inventaire forestier national, le total du matériel sur pied des tourbières a augmenté, passant de 252 à 291 millions de mètres cubes (15%). Les estimations correspondantes de l'accroissement annuel sont d'environ 10 et 15 millions de mètres cubes (une augmentation de 51%). On évalue l'augmentation de la croissance des arbres attribuable aux activités de drainage et de fertilisation des tourbières à au moins 7 millions de mètres cubes par année. Les peuplements de la plupart des secteurs assainis en sont toujours à leur premier stade de développement, mais leur production annuelle devrait connaître une augmentation considérable d'ici la fin du siècle. Il faudra bientôt résoudre des problèmes relatifs à l'entretien des fossés et aux premières éclaircies.

INTRODUCTION

At present, about 5.8 million ha of peatlands and paludified mineral soils have been drained for forestry in Finland (Anon. 1988). The aim is to reach a total of 6.5 million ha.

Information about Finnish peatland forests is based mainly on the material gathered in connection with the national forest inventories. The results presented in this paper about the possibilities of using drained peatlands for timber production are based mainly on the 7th National Forest Inventory (NFI) (1977-1984). Calculations were made separately for southern and northern Finland (Fig. 1).

LAND CLASSES

One of the main purposes of forest drainage is to convert unproductive peatland into forest land. At the time of the 7th NFI the ca. 9.0 million ha of peatlands in Finland consisted of 53% forest land (i.e., mean annual increment, with bark, during a rotation of 100 years is at least 1 m^3/ha), 24% scrubland (mean annual increment 0.1 to 1.0 m^3/ha), and 23% wasteland (mean annual increment less than 0.1 m^3/ha). A considerable part of the scrubland and wasteland was still undrained (Table 1).

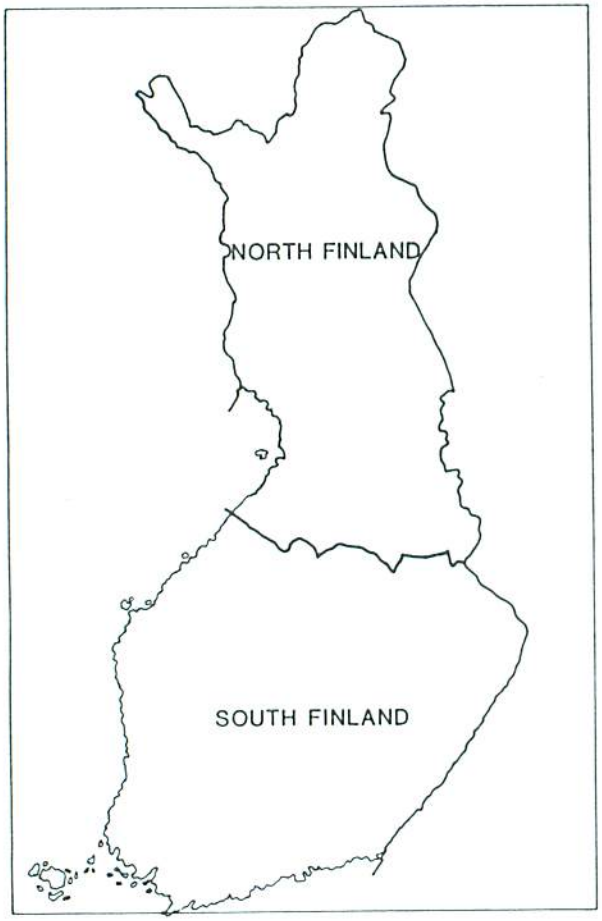

Figure 1. Research area.

Table 1. Division of the total peatland area into different land classes

Land class	Southern Finland		Northern Finland		Total	
	1000 ha	%	1000 ha	%	1000 ha	%
Forest land	2687	78	2075	37	4762	53
Scrubland	455	13	1708	31	2163	24
Wasteland	312	9	1791	32	2103	23

It should also be mentioned that some of the sites originally classified as shallow mires were reclassified in the 7th NFI in the group of drained mineral-soil sites, and are therefore not included in Table 1.

The proportion of forest land on peat soils was considerably higher in southern than in northern Finland (Table 1). This is because of the extensive peatlands (especially open mires) that are, for biological and economic reasons, unsuitable for draining in the climatic conditions of northern Finland.

Peatlands are divided in the Finnish classification system into three groups: open mires, spruce (*Picea abies* spp.) mires and pine (*Pinus sylvestris* spp.) mires. Each group is further divided into a number of different peatland site types. In the 7th NFI some of the spruce mires were included in the class of virgin peatlands (Table 2). Most of these sites, as well as some of the pine mires, are nutrient-rich swamps in which the water is constantly moving. Of the spruce mires, 14 and 32% in northern and southern Finland, respectively, were classified as transformed peatland that has reached full productivity as a result of drainage and contains ground flora similar to that of mineral sites. For the pine mires, the respective figures for transformed mires were only 3 and 11%.

TREES SPECIES AND DEVELOPMENT CLASSES

The dominant tree species on 51% of the area of spruce mires on forest land in southern Finland is Norway spruce (*Picea abies*) (Table 3). Birch (*Betula pubescens*) and other hardwoods are also quite common on spruce mires, especially in northern Finland. Scots pine (*Pinus sylvestris*) is the dominant tree species on 93-95% of the pine mires.

On average, 10 to 11% of the stands on spruce mires are classified as mature. On the pine mires, the proportion of "young thinning" stands is higher, and that of "advanced thinning" stands lower, than on spruce mires. Only 2 to 3% of the pine mires are mature stands.

The proportion of low-yielding stands (class 8) is rather high on spruce mires, especially in northern Finland (Table 4). The proportion of low-yielding stands on pine mires is only 2 to 4%.

VOLUME AND GROWTH

The volume of peatland forest stands is clearly dependent on the climatic region and the peatland site type (Fig. 2). For example, the stand volume on fertile spruce mires in southern Finland is more than 100 m^3/ha, whereas the volume of pine stands on poor sites in northern Finland is less than 20 m^3/ha.

Table 2. Distribution of the area of forest land classified as spruce and pine mires according to the state of drainage

State of drainage	Spruce mires				Pine mires			
	Southern Finland		Northern Finland		Southern Finland		Northern Finland	
	1000 ha	%	1000 ha	%	1000 ha	%	1000 ha	%
Virgin peatland	299	25	233	34	211	14	308	22
Newly ditched peatland[a]	80	7	47	7	184	12	140	10
Transforming peatland[b]	423	36	303	45	950	63	904	65
Transformed peatland[c]	381	32	98	14	159	11	42	3
Total	1183	100	681	100	1504	100	1394	100

[a] These can be either recently drained or older drainage areas in which the trees and ground vegetation show no or little response to drainage.

[b] An intermediate stage after drainage. The effect of drainage is perceptible in the growing stock and ground vegetation.

[c] These have reached full productivity as a result of drainage. Ground flora is comparable with that of mineral-soil sites.

Table 3. The dominant tree species on forest land (% of area)

Dominant tree species	Spruce mires Southern Finland	Spruce mires Northern Finland	Pine mires Southern Finland	Pine mires Northern Finland
Treeless	3	6	1	2
Picea abies	51	39	1	2
Pinus sylvestris	24	14	95	93
Betula and other deciduous spp.	22	41	3	3

Table 4. Development classes on forest land (% of area)

Development class[a]	Spruce mires Southern Finland	Spruce mires Northern Finland	Pine mires Southern Finland	Pine mires Northern Finland
1	2	3	1	1
2	5	3	6	4
3	13	12	31	41
4	31	29	42	39
5	28	17	14	8
6	10	11	3	2
7	1	0	1	1
8	10	25	2	4

[a] 1 = Open area or seed-tree stand
2 = Small seedling stand
3 = Advanced seedling stand
4 = Young thinning stand
5 = Advanced thinning stand
6 = Mature stand
7 = Shelterwood stand
8 = Low-yielding stand

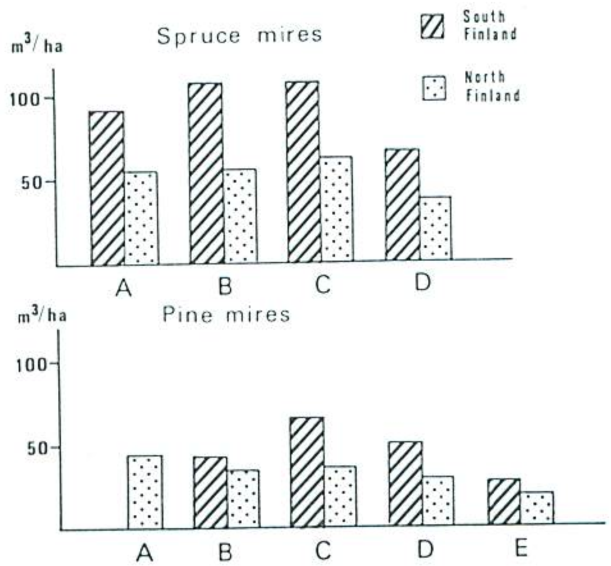

Figure 2. Mean stand volume on different peatland site types. A = peatland with eutrophic vegetation, B = herb-rich peatland, C = tall-sedge and Myrtillus *peatland, D = Small-sedge and* Vaccinium *peatland, E = cottongrass and dwarf-shrub peatland*

The total volume of peatland forests, according to the 3rd and 7th NFIs, is as follows:

Region	Stand volume, million m³ 3rd NFI (1951-1953)	7th NFI (1977-1984)
Southern Finland	161	194
Northern Finland	91	97
Total	252	291

The total volume has increased by 15% over a period of about 30 years. The increase is even higher if we take into account the fact that some of the sites originally classified as shallow-peated were assigned in the 3rd NFI to the peatlands category, but were included as mineral-soil sites in the 7th NFI.

The effect of climate and site type is very clearly reflected in the mean annual stand increment (Fig. 3). The highest annual increment under the best conditions was, on average, about 6 m^3/ha, and in poor cottongrass pine stands in northern Finland, only about 1 m^3/ha.

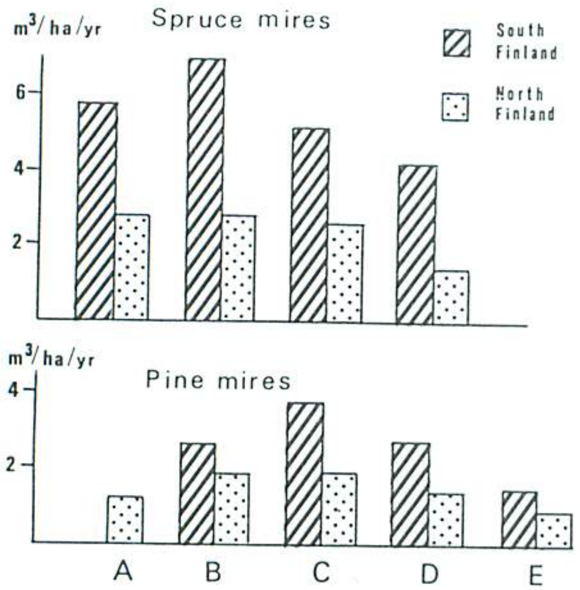

Figure 3. Mean annual increment on different peatland site types. A = peatland with eutrophic vegetation, B = herb-rich peatland, C = tall-sedge and Myrtillus *peatland, D = small-sedge and* Vaccinium *peatland, E = cottongrass and dwarf-shrub peatland*

The estimated total volume growth of all peatland forests according to the two different inventories was as follows:

Region	Annual increment, million m^3 3rd NFI (1951-1953)	7th NFI (1977-1984)
Southern Finland	6.49	10.65
Northern Finland	3.37	4.21
Total	9.86	14.86

The effect of drainage and fertilization on peatlands and the improved silvicultural condition of peatland forests are clearly evident in the difference between the two inventories. The increase in total volume growth over a period of about 30 years is 51%.

QUALITY OF STANDS AND THE NEED FOR CUTTING

As was mentioned earlier, some of the peatland forests were low-yielding and therefore under-productive. This can also be seen in Table 5, in which the stands are divided into different classes according to their silvicultural quality.

Table 5. The quality of stands on forest land (% of area)

Quality of stand	Spruce mires Southern Finland	Spruce mires Northern Finland	Pine mires Southern Finland	Pine mires Northern Finland
Good	23	11	44	33
Satisfactory	46	40	43	46
Understocked	8	12	8	14
Needs tending	12	12	3	3
With developmental potential	89	75	98	96
Under-productive	11	25	2	4
Total	100	100	100	100

The quality of the stands was good to satisfactory on the majority of the pine and spruce mires in southern Finland. Stands of good quality were not common on spruce mires in northern Finland, where only three-fourths of all the stands had sufficient development potential.

On average, 21 to 23% of the peatland forest stands were in need of cutting during the next 5-year period (Table 6). The proportion of stands in need of cutting during the second 5-year period was greater in the southern part of the country than in the north. The need for cutting was more urgent on spruce than on pine mires, primarily because of the high proportion of hardwoods on the former sites.

CONCLUSIONS

The results of the NFIs presented here, as well as some other recently published results (Keltikangas et al. 1986, Mattila and Penttilä 1988), clearly show that peatlands in Finland have great potential for timber production. Even now, when most of the drainage areas are still at an early stage of development, a considerable increase in the volume and growth of peatland forests has been achieved. Forest improvement work (drainage and fertilization of peatlands) and silvicultural measures are estimated to have resulted in an additional 7 million m^3 peatland forests annually.

Table 6. The need for cutting in peatland forests, expressed by development class (% of area)

Development class[a]	First 5-year period		Second 5-year period		After 10 years	
	Southern Finland	Northern Finland	Southern Finland	Northern Finland	Southern Finland	Northern Finland
1	3	34	10	53	87	13
2	12	6	6	6	82	88
3	9	5	2	2	89	93
4	16	12	18	11	66	77
5	28	31	23	12	49	57
6	65	76	27	14	8	10
7	42	25	46	53	12	22
8	72	70	3	2	25	28
All classes	23	21	14	7	63	72

[a] 1 = Open area or seed-tree stand
2 = Small seedling stand
3 = Advanced seedling stand
4 = Young thinning stand
5 = Advanced thinning stand
6 = Mature stand
7 = Shelterwood stand
8 = Low-yielding stand

However, before we can effectively utilize the potential of Finnish peatlands for timber production, problems in several areas will have to be solved. Suitable methods for the maintenance of drainage networks, which involve the repair of ditches and construction of new ditching systems to supplement existing ones, are not yet fully developed. The environmental effects of drainage will also have to be considered in this connection. Furthermore, there is not enough lightweight machinery suitable for first thinnings or for future harvesting on peatlands. Finally, the quality and quantity of silvicultural measures carried out on peatlands are not yet adequate. Special attention should be paid to first thinnings and the increased utilization of birch, and to the economical use of fertilizers in peatland forests.

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GROWTH RESPONSE OF PEATLAND STANDS TO DRAINAGE IN NORTHERN FINLAND

T. Penttilä
The Finnish Forest Research Institute
Rovaniemi Research Station
PB 16, Rovaniemi
Finland

ABSTRACT

The effects of drainage on the growth of peatland forests and especially on post-drainage timber volume are estimated for Finnish Lapland. The study area covers 32% of the land portion and 38% (34 000 km^2) of the peatland portion of Finland. In Lapland, the area of peatland drained for forestry is about 8,000 km^2. The distribution of the peatland area into land classes is based on data from the National Forest Inventories. The area of land in the categories "spruce mire", "pine mire" and "treeless mire", and the distribution of peatland area into trophic levels, are shown. The main stand characteristics, taken from the 7th National Forest Inventory, are examined. Estimates of mean annual increment for *Pinus sylvestris*, *Picea abies* and *Betula pubescens* on drained and undrained peatland sites are compared. The effect of site trophic level on growth response of conifer stands is examined with the aid of data obtained from permanent sample plots. The relative growth rates for coniferous stands on different peatland sites are compared with those on upland sites. The need for a modeling approach to the growth of peatland forests is emphasized.

RÉSUMÉ

Les effets du drainage des tourbières sur la croissance des forêts qui y poussent, notamment sur le volume de bois produit après les travaux, sont estimés pour la Laponie finlandaise. La région étudiée couvre 32% de la superficie émergée et 38% (34 000 km^2) de la partie couverte de tourbières de la Finlande. En Laponie, la superficie des tourbières drainées pour la production forestière est d'environ 8 000 km^2. La répartition des tourbières dans les diverses catégories de terrains se fonde sur les données collectées à la faveur des inventaires forestiers nationaux. La superficie classée dans les catégories <<marécage à épinettes>>, <<marécage à pins>> et <<marécages sans arbres>> ainsi que la répartition trophique des marécages sont montrées. Les principales caractéristiques des peuplements, tirées du septième inventaire forestier national, sont examinées. On compare l'accroissement annuel moyen estimatif de *Pinus sylvestris*, de *Picea abies* et de *Betula pubescens* dans les stations de tourbières drainées et non drainées. L'effet du niveau trophique stationnel sur l'accroissement des peuplements de conifères est examiné à l'aide de données obtenues dans des placettes d'échantillonnage permanentes. La vitesse relative de l'accroissement des peuplements de conifères dans les différentes stations de tourbière est comparée à la vitesse observée en terrain sec. Le besoin d'une modélisation de l'accroissement des forêts de tourbière est souligné.

INTRODUCTION

Climatic factors greatly affect the growth rate of forests in Finland. Hence, climate also affects the efficiency of treatments intended to increase tree growth, such as drainage of peatland forests. In the Finnish drainage directives, the climatic limit for profitable forest drainage is defined as a certain temperature sum for each peatland site type. Under the climatic conditions indicated by this critical temperature sum, drainage should, on average, result in future benefits equal to the costs of drainage at a certain rate of interest.

For most open bog and fen types, and for the ombrotrophic pine mires, the climatic limit for profitable drainage is found in the southern part of Finland. Most of the forested mire types, however, are considered suitable for drainage far into the north. The rationale for forest drainage – especially in northern Finland – has been continually discussed and criticized. The drainage directives in Finland are based mainly on research concerning post-drainage productivity on different mire site types (e.g., Heikurainen 1959, Heikurainen and Seppälä 1973). However, there is a lack of quantitative knowledge about the response of peatland stands to drainage.

This paper examines the effects of forest drainage on forest growth and stand characteristics for different peatland site types in northern Finland. A review of recent research reports and preliminary results of a continuing research project are presented. The aim of the paper is to give an estimate of the response of peatland stands to drainage in terms of mean annual increment and relative growth rates at different stages of stand development.

MATERIAL AND METHODS

The mean temperature-sum curves for northern Finland for the period 1941-1970 are shown in Figure 1a. Characteristics of peatland areas in northernmost Lapland (north of sub-region 2, see Fig. 1) were included in the results, whereas forest stand characteristics were excluded. This was done because of the marginal importance of peatland forests in northern Lapland.

The characteristics of peatlands and peatland forests in northern Finland discussed here are based mainly on the results of the Finnish National Forest Inventories (NFI) published by Mattila and Penttilä (1987) and by Paavilainen and Tiihonen (1988). The results of field surveys of peatlands drained for forestry between 1930

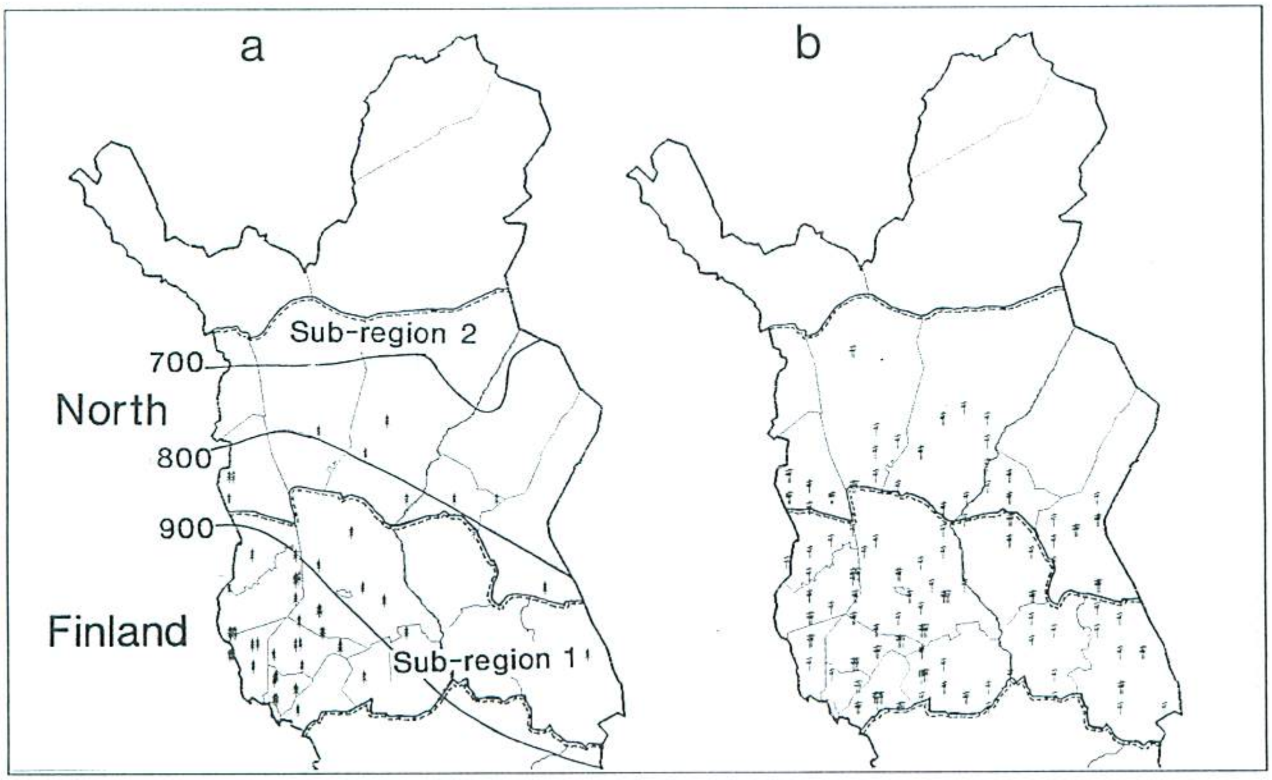

Figure 1. Sub-regions of the study area, the temperature sum (at a 5°C threshold) for the period 1941-1970, and the location of the SINKA permanent sample plots used in the study (a = stands dominated by Norway spruce, b = stands dominated by Scots pine)

and 1978 (Keltikangas et al. 1986) were used to describe the site-type distribution of drained peatlands in the study area.

The responses of peatland stands to drainage were examined in two different ways. Drained and undrained peatlands on forest land were compared in terms of mean annual volume increment (MAI), which was computed from the data of the 7th NFI (carried out from 1982 to 1984). MAI was calculated separately for Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), deciduous tree species (mainly birch, *Betula pubescens*), and for all tree species together. The growth responses were also examined by analyzing volume increment data from a network of permanent sample plots, the so-called 'SINKA'-plots (Penttilä and Honkanen 1986), on peatlands. Relative growth rates of SINKA stands, defined as stand volume increment divided by the initial stand volume, were compared with the results of growth and yield models for upland conifer stands.

The SINKA network was set up from 1984 to 1989 by the Peatland Forestry Department of the Finnish Forest Research Institute. It includes both drained and undrained peatlands in all land classes. Permanent sample plots were selected from the field sample of the 7th NFI, stratified by state of drainage, dominant tree species, and trophic level. Stands in which the height of dominants was less than 5 m, or in which the proportion of hardwoods was >50% of the stand volume, were excluded from the data. Volume increments of the stands were computed by a standard growth-analysis method (Heinonen 1981) based on DBH and height-growth measurements from the past 5-year period.

RESULTS

Peatland Area and Site Quality

Northern Finland covers 10 million ha, one third of the land area of Finland. The peatland area in northern Finland is 3.4 million ha, or 34% of the total peatland area in the country. The distribution of drained and undrained peatlands is shown in Table 1. According to the 7th NFI, 70% of the drained peatlands were classified as forest land, 24% as scrub land and 6% as waste land. Drained peatlands totaled 800,000 ha, 17% of the total drained peatlands in the country. Since the 1950s, some 200,000 ha of peatlands have been converted from waste land or scrub land to productive forest land. This trend is likely continuing, at least on recently drained areas.

Table 2 summarizes drainage conditions of peatlands classed as forest land according to the 7th NFI. Only 8% of these drained peatlands had reached the final 'transformed' state, in which the ground flora resembles that of mineral sites. Transforming peatlands accounted for 78% of these drained peatlands.

Table 1. Area of drained and undrained peatlands in northern Finland, by land class (from the 3rd, 5th, and 7th National Forest Inventories [NFI])

	Area (1000 ha)		
Peatland type[a]	NFI 3 (1952-54)	NFI 5 (1969-70)	NFI 7 (1982-84)
Forest land			
drained	4	206	539
undrained	613	352	310
Scrub land			
drained	25	181	193
undrained	1212	1086	1016
Waste land			
drained	19	89	44
undrained	1713	1644	1336
All peatlands	3586	3558	3438
drained	48	476	776
undrained	3538	3082	2662

[a] For forest land, scrub land, and waste land, mean annual increment (over bark, under optimal silvicultural conditions) was > 1 m^3 ha^{-1}, 0.1-1 m^3 ha^{-1} and < 0.1 m^3 ha^{-1}, respectively.

Table 2. Area of spruce mires and pine mires on forest land in northern Finland, by drainage condition

Drainage condition[a]	Area (1000 ha) Spruce mires	Pine mires	All mires
Undrained	147	161	309
Drained	198	339	539
Newly ditched	25	48	73
Transforming	139	282	422
Transformed	34	9	44
All	345	500	848

[a] Newly ditched land comprises recently drained land or older areas on which trees and ground vegetation have shown no response to drainage; transforming land is an intermediate stage, in which the effects of drainage are perceptible in the growing stock; transformed land has reached its full potential production as a result of drainage, and ground flora resembles that of mineral-soil sites.

The area of drained spruce mires was rather evenly distributed among four trophic classes (Table 3). However, drained pine mires are primarily oligotrophic sites. The drained waste land and scrub land classes are mainly open mires, open fens and bogs; this class totals 100,000 ha (Table 3).

Table 3. Area of drained peatlands, by trophic class, in northern Finland (derived from Keltikangas et al. [1986])

	Area					
	Spruce mires		Pine mires		Open mires	
Trophic class	1000 ha	%	1000 ha	%	1000 ha	%
Eutrophic	47	24	80	17	21	21
Mesotrophic	56	28	49	10	23	23
Oligo-mesotrophic	49	25	59	13	42	41
Oligotrophic	44	23	273	58	13	13
Poor oligotrophic			6	1	2	2
Ombrotrophic			4	1		
All	196	100	471	100	101	100

Stand Characteristics

On average, drained stands were less well stocked than undrained ones (Table 4). This results from the cutting of trees connected with drainage and the conversion of sparsely treed scrub land and waste land to forest land after drainage (Mattila and Penttilä 1987). On spruce mires, the proportion of hardwoods has increased after drainage whereas pine mires continue to be dominated by pine in all drainage-condition classes (Table 4).

The response of volume increment of peatland stands to drainage was first examined by using the estimates of MAI computed from the data of the 7th NFI (Table 5). Comparison of drained and undrained peatlands indicated a clear response in pine mires and hardwood-spruce mires in southern Lapland. There was no response in the northern sub-region.The responses of birch and Scots pine to drainage were better than that of Norway spruce.

Table 4. Mean volume and its distribution, by tree species, on peatlands on forest land in northern Finland

Drainage condition[a]	Tree species[b] (mean volume, $m^3\ ha^{-1}$)			
	P	S	B	All
Spruce mires				
Undrained	4.5	28.3	21.5	54.3
Newly ditched	3.8	12.8	13.5	30.1
Transforming	2.2	14.8	22.0	39.0
Transformed	3.5	18.8	41.1	63.4
Pine mires				
Undrained	21.1	3.5	4.1	28.7
Newly ditched	8.5	1.4	2.4	12.3
Transforming	16.7	1.6	2.6	20.9
Transformed	16.9	0.8	4.5	22.2

[a] Newly ditched land comprises recently drained land or older areas in which trees and ground vegetation have shown no response to drainage; transforming land is an intermediate stage, in which the effects of drainage are perceptible in the growing stock; transformed land has reached its full potential production as a result of drainage, and ground flora resembles that of mineral-soil sites.

[b] P = Scots pine, S = Norway spruce, B = birch and other deciduous spp.

Table 5. Mean annual increment on undrained and drained peatlands on forest land in northern Finland, by tree species (derived from Mattila and Penttilä [1987])

	Mean annual increment ($m^3\ ha^{-1}\ yr^{-1}$)							
	Undrained				Drained			
Site type[a]	P[b]	S	B	All	P	S	B	All
Pine mires								
sub-region 1	0.59	0.07	0.15	0.81	0.89	0.08	0.19	1.16
sub-region 2	0.49	0.07	0.05	0.61	0.66	0.05	0.06	0.77
Hardwood-spruce mires								
sub-region 1	0.15	0.68	0.59	1.42	0.20	0.74	1.63	2.57
sub-region 2	0.10	0.49	0.60	1.19	0.06	0.47	0.67	1.20
All mires								
sub-region 1	0.42	0.31	0.32	1.05	0.63	0.32	0.72	1.67
sub-region 2	0.26	0.32	0.38	0.96	0.45	0.20	0.28	0.93
northern Finland	0.35	0.31	0.34	1.00	0.58	0.29	0.61	1.48

[a] Sub-regions 1 and 2 are shown in Figure 1.

[b] P = Scots pine, S = Norway spruce, B = birch and other deciduous spp.

The inventory method of the 7th NFI used in northern Finland (Mattila 1985) does not permit reliable estimates of MAI for different tree species on different site types. Preliminary stand growth results from the SINKA plots are presented in Figures 2 and 3 to show the effect of site type and inferred trophic level on growth responses. Since the SINKA study was aimed mainly at tree growth models, data from the undrained strata are inadequate for relevant analysis of stand increment, especially on hardwood-spruce mires. Therefore, observations in undrained stands were first compared with the stand growth models for undrained peatland stands on forest land (Gustavsen and Päivänen 1986). The equations for the correlation between the annual volume increment over the past 5 years and the stand volume seemed to fit the SINKA data on the corresponding site types fairly well (Fig. 2). As reported by Gustavsen and Päivänen (1986), the variation in stand growth on undrained pine mire stands that appeared in the SINKA data did not seem to depend on the peatland site type (Fig. 2a). Hence, the equation for paludified pine forests (KgR) in northern Finland was chosen to represent the stand increment on all undrained pine mire sites. Similarly, the equations for undrained hardwood-spruce mires were used to represent growth for the site types represented in the SINKA data (Fig. 2b).

On pine mires, the relationship between stand volume and stand volume increment (i.e., relative growth) over the past 5 years indicated a clear growth response at all trophic levels (Fig. 3a-d). After drainage, relative growth rate was highest on mesotrophic and oligo-mesotrophic pine sites. The variation in relative growth rate was rather large, especially on mesotrophic and oligotrophic pine mires.

For hardwood-spruce mires, only the stands dominated by Norway spruce were included in the study material. According to Mattila and Penttilä (1987), 41% of the area of hardwood-spruce mires was dominated by Norway spruce. The relative growth rate of the stands indicated a clear growth response to drainage only on eutrophic and mesotrophic sites with a high stocking. On the oligo-mesotrophic sites, practically no response was shown (Fig. 3e,f).

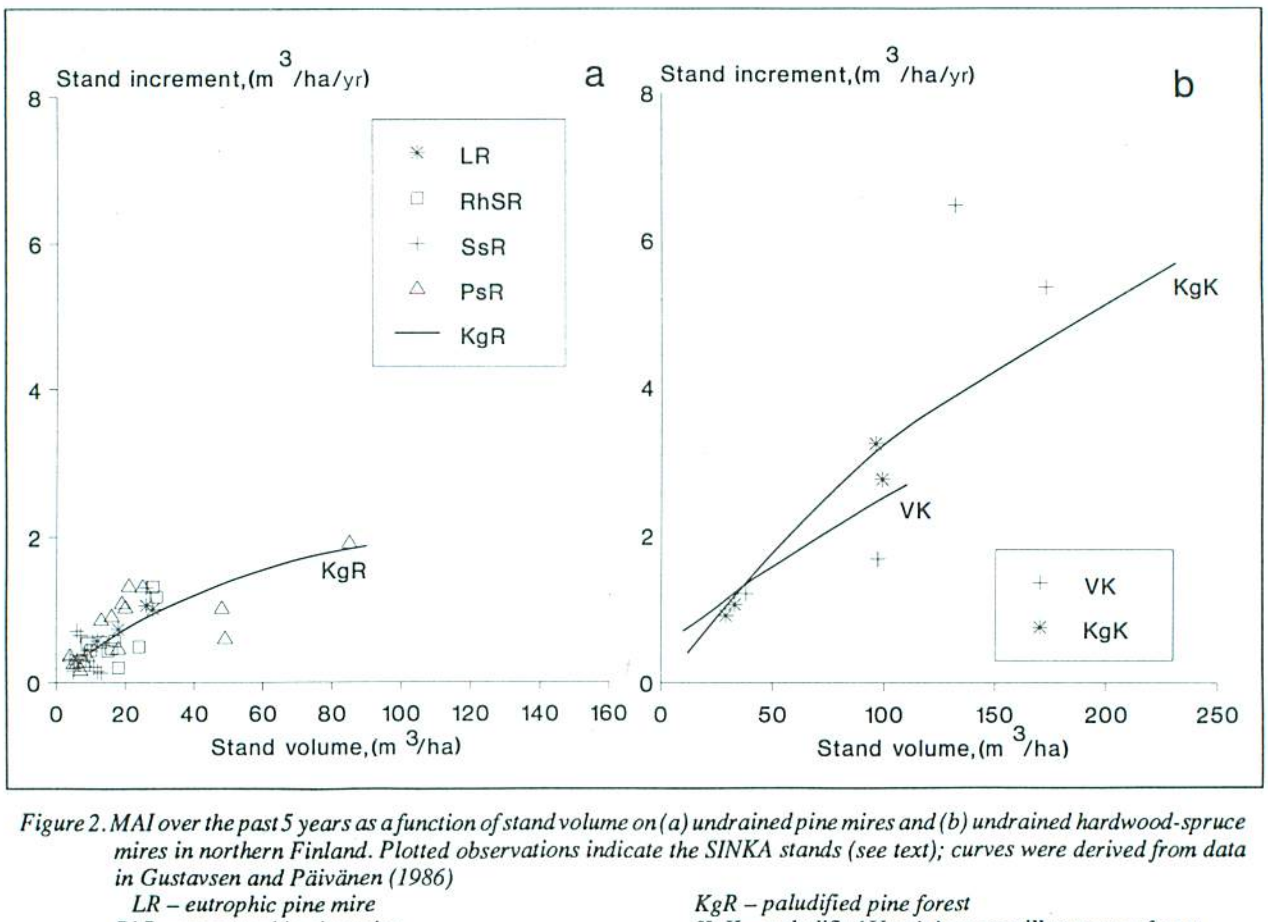

Figure 2. MAI over the past 5 years as a function of stand volume on (a) undrained pine mires and (b) undrained hardwood-spruce mires in northern Finland. Plotted observations indicate the SINKA stands (see text); curves were derived from data in Gustavsen and Päivänen (1986)

LR – eutrophic pine mire
RhR – mesotrophic pine mire
SsR – oligo-mesotrophic pine mire
PsR – oligotrophic pine mire
KgR – paludified pine forest
KgK – paludified Vaccinium myrtillus *spruce forest*
VK – V. myrtillus *or* V. vitis-idaea *spruce swamp*

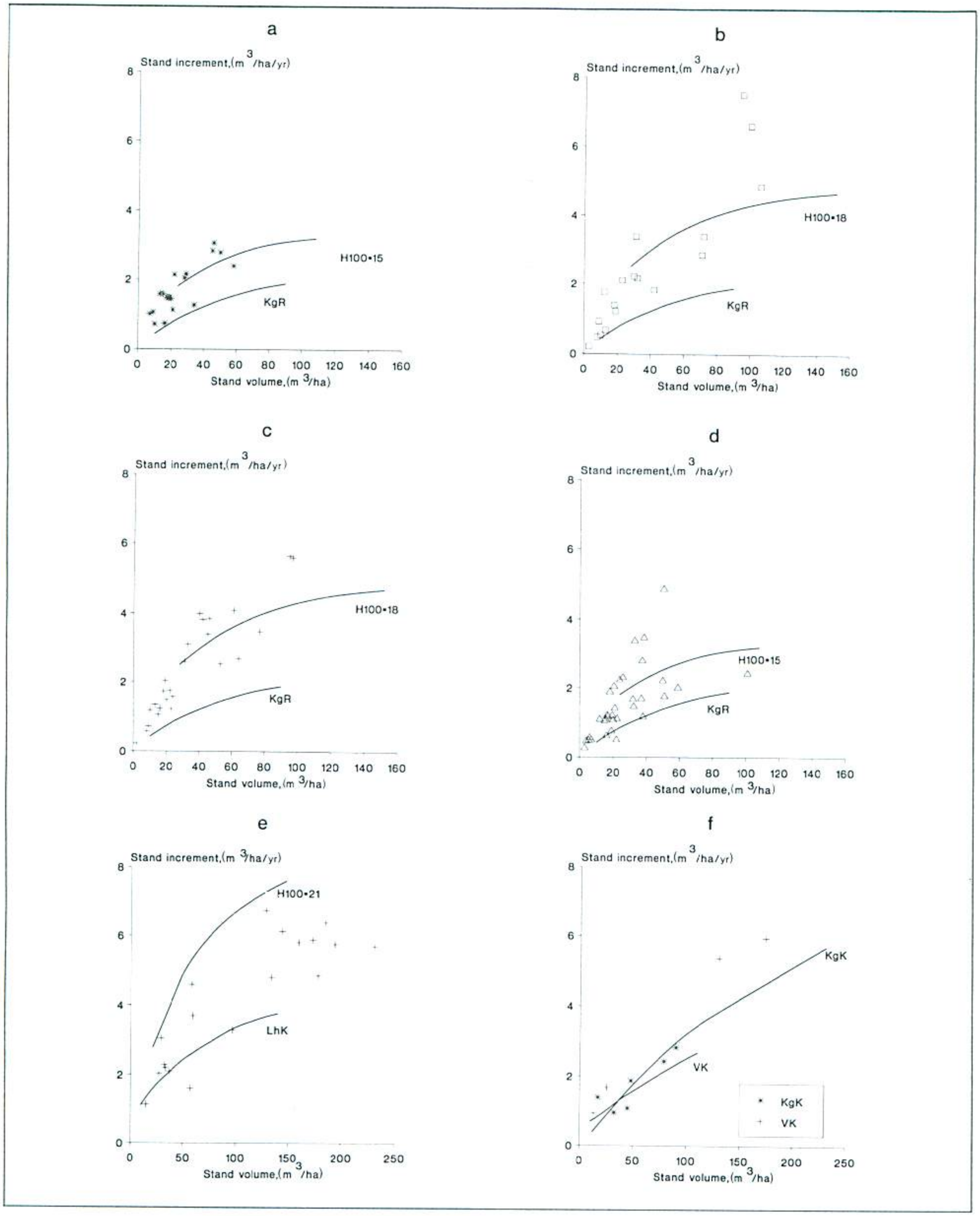

Figure 3. MAI observations for the drained SINKA stands compared with the curves for undrained peatland stands in northern Finland (Gustavsen and Päivänen 1986) and upland conifer cultures of different dominant height indices (Vuokila and Väliaho 1980). LhK indicates undrained eutrophic paludified hardwood-spruce forest; for KgR, KgK, and VK, see Fig. 2.

a – eutrophic pine mire (LR)
b – mesotrophic pine mire (RhR)
c – oligo-mesotrophic pine mire (SsR)
d – oligotrophic pine mire (PsR)
e – eutrophic and mesotrophic harwood-spruce mire (LK, LhK, RhK)
f – oligo-mesotrophic hardwood-spruce mire (VK, KgK)

The relative growth rates of stands on drained eutrophic, mesotrophic, oligo-mesotrophic and oligotrophic pine mires appeared to correspond, on average, to those of upland pine stands with dominant site indices of 15, 18, 18 and 15 m, respectively at an age of 100 years, (Fig. 3a-d). An applicable model for the relative growth rate of undrained pine mires is not found in the growth yield tables for conifers (Vuokila and Väliaho 1980). From an extrapolation of the growth and yield tables, the corresponding dominant site index would be no more than 12 m. This is confirmed by the stand characteristics of the virgin forested pine mires in northern Finland studied by Gustavsen and Päivänen (1986, p.11). According to Vuokila and Väliaho (1980), the difference between the stands with dominant-height site indices of 15 and 18 m, as well as between those with indices of 18 and 21, is about 1 m^3 ha^{-1} yr^{-1} in MAI during the rotation period. Hence, it can be estimated that the average increase in MAI as a result of drainage of pine mire stands in Lapland would be at least 1 m^3 ha^{-1} yr^{-1} on oligotrophic and eutrophic pine mires and 2 m^3 ha^{-1} yr^{-1} on oligo-mesotrophic and mesotrophic pine mires during the whole rotation period.

The relative growth rates of spruce-dominated stands on drained eutrophic and mesotrophic hardwood-spruce mire sites were generally lower than those of Norway spruce stands with a dominant height site index of 21 at 100 years (Fig. 3e), i.e., the lowest index given in the growth and yield tables by Vuokila and Väliaho (1980). The relative growth rates of stands on drained oligo-mesotrophic sites did not appear to differ from those in the model for corresponding undrained sites (Fig. 3f). In the early 1950s, the average dominant height on virgin forested spruce mires on productive forest land in northern Finland was from 11 to 14 m at ages of 109 to 135 years (Gustavsen and Päivänen 1986, p. 11). This provides a reference for the dominant height indices of undrained hardwood-spruce mire stands. Because of inadequate data and the lack of a reference point, it was not possible to estimate the magnitude of the response of hardwood-spruce mire stands to drainage during the rotation period.

DISCUSSION AND CONCLUSIONS

In northern Finland, forest drainage is not as common a practice as in the southern parts of the country. This is a natural consequence of the climatic conditions and the large proportion of open fens and bogs. Recent results of field surveys indicate that not all of the drainage activities in northern Finland have been undertaken on the optimal sites in terms of cost-efficiency. Large areas of treeless peatlands and poor pine mires have been ditched. In addition, because of the cold climate, a relatively small proportion of the total area of drained peatlands consists of transformed peatlands. However, the area of productive forest land on peatlands has increased significantly since the 1950s, when large-scale drainage began in northern Finland.

In the early 1980s the average growth response (MAI) to drainage in northern Finland was about 0.5 m^3 ha^{-1} yr^{-1} on the basis of estimates for all drained and undrained peatlands on forest land. The estimated MAI on drained peatlands, computed from the data of the 7th NFI, was very close to that reported by Keltikangas et al. (1986) for the same area. As well, the estimated MAI of undrained peatlands on forest land was quite close to that calculated from the data of the 3rd NFI (carried out in the early 1950s) (Mattila and Penttilä 1987).

From the results of the 7th NFI, the response of peatland stands to drainage in southern Lapland was superior to that in central Lapland. As well, the hardwood-spruce mire stands responded better than pine mire stands. In terms of MAI, birch responded better than Scots pine and Scots pine better than Norway spruce.

Data from a continuing growth and yield research project, SINKA, were used to show the effect of site trophic level on the relative growth rate and on the response to drainage of peatland stands dominated by conifers. In stands dominated by Norway spruce, there was a clear response to drainage on eutrophic and mesotrophic sites but none at all on more oligotrophic sites. The contribution of hardwoods to the growth response of mixed hardwood-spruce mire stands will remain unknown until more data are obtained from repeated measurements of the SINKA plots.

There was a lack of correspondence between peatland classification, when based on trophic levels, and the post-drainage productivity of stands on pine mires. On eutrophic pine mires, the post-drainage relative growth rates were clearly inferior to those of mesotrophic sites, as Keltikangas et al. (1986) had found. This is somewhat unexpected in view of the results of earlier studies (Heikurainen 1959, Heikurainen and Seppälä 1973), although it has long been known that the factors determining the trophic level of a site are not necessarily those that have the greatest impact on tree growth. This may contribute to the great variability of relative growth rates within trophic classes after drainage.

In general, drainage appears to increase tree growth on forested peatlands in northern Finland. The magnitude of the growth response to drainage evidently depends on the climate and nutritional status of the site, and also on tree species composition and stocking of the stand. In Finland, few quantitative studies have been carried out on the effects of all these factors. Although the drainage program in Finland is almost finished, modeling to estimate the growth rate of trees on peat is still essential as a planning tool for use in the management of peatland forests. This will be a major element of Finnish peatland forestry research in the near future.

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DRAINING WOODED PEATLANDS: EXPECTED GROWTH GAINS

F. Trottier
Service des traitements sylvicoles
Ministère de l'Énergie et des Ressources
Québec, Québec
Canada

ABSTRACT

A forest drainage trial was carried out in 1983 in the Beauséjour forest, 25 km southwest of Quebec City. The peatland type is a tall-sedge/larch (*Larix* spp.) swamp, in the sapling stage of development. Permanent sample plots were measured in 1983 and 1988 at 20-, 40-, 60- and 80-m ditch spacings, and in controls. The increase in diameter and height growth was proportional to drainage intensity. Diameters have increased 85% in the plots with 20-m spacing, in comparison with 15% in the control. The increase in height growth was 64% and 10%, respectively, in plots with 20-m spacing and in the control. After 5 years of observation, the results indicate a fast and strong reaction to drainage for eastern larch (*Larix laricina*).

RÉSUMÉ

Un réseau de drainage a été établi en 1983 dans une tourbière de la Forêt de Beauséjour, à 25 kilomètres au sud-ouest de la ville de Québec. Le site, une tourbière à sphaignes et à carex, est peuplé d'un mélézin (*Larix* spp.) au stade de gaulis. Des parcelles-échantillons ont été mesurées en 1983 et en 1988 dans des écartements de 20 m, 40 m, 60 m, 80 m et dans des secteurs témoins. Les résultats démontrent que les accroissements en hauteur et en diamètre sont proportionnels à l'intensité du drainage. Les diamètres se sont accrus de 24% dans les écartements de 20 m alors que l'augmentation ne fut que de 15% dans les secteurs témoins. La hauteur des arbres a augmenté de 64% dans l'espacement de 20 m et de 10% dans les secteurs témoins. Malgré seulement cinq années d'observation, les résultats témoignent d'une réaction rapide du mèlèze (*Larix laricina*) au drainage.

INTRODUCTION

In many European countries, forest drainage is recognized as an effective means of increasing the productivity of wooded peatlands (Heikurainen 1983). As a rule, a network of drainage ditches is established to collect surface and infiltration waters. Tree roots can thus draw the nutrients they require from a larger volume of better aerated soil. This improvement is translated into stem growth. Best results are obtained where the peatland is fertile, and where the site is covered with preferred species that have reached the development stage (as saplings or young trees) (Heikurainen and Kuusela 1962).

At the beginning of the 1980s, nearly 0.5 million ha of peatland in Europe were drained each year for silvicultural purposes. Half of this work was carried out in the Soviet Union (Heikurainen 1983). During this same period, silviculture developed rapidly in Quebec. Nevertheless, the first forest-drainage tests were conducted only recently. At present, 4000 to 5000 ha are drained each year. A drainage system is often established after clearcutting on mineral sites. This work is done to keep the soil productive and to make the site easier to manage and more accessible for reforestation. Other projects are undertaken to improve the growth rate of existing stands.

In Quebec, as in the rest of Canada, few studies have dealt with the growth rate of wooded peatlands after drainage (Hillman 1987). All silvicultural treatments carried out in Quebec's public forests – **including drainage** – are monitored for tree growth response. Dozens of sample plots are therefore set up each year in the regions in which drainage work is carried out, to assess the effect of drainage on the growth of wooded peatlands.

The findings presented herein are taken from a drainage system established in 1983 and remeasured in 1988, after 5 full years of growth.

SITE AND METHOD

The project was carried out in the Beauséjour forest, approximately 25 km southwest of Quebec City. Villeneuve (1948) describes the climate of the region as "temperate-continental". There are 1,230 mm of rainfall annually and the mean annual temperature is 9°C. The number of degree-days above the 5.0°C threshold is 1625. According to Grandtner (1960), who bases his claim on floristic similarities between the wooded peatlands here and those of the Abitibi region, the climate of the Beauséjour peatlands is harsher than the general climate. The Beauséjour forest is located on a plateau at an altitude of 100 m. The invasion of the Champlain Sea left clayey deposits in the depressions that were favorable to peat accumulation. This clay is covered locally with sands that have shifted, and other deposits such as schist debris from Sillery.

The soil of the peatland consists of a moderately decomposed, wood-rich organic deposit between 50 and 100 cm deep. The bulk density of the peat at a depth of 30 cm is 0.15 g/cm^3. At that same depth, the hydraulic conductivity measured with a steady-head permeameter is 0.43 m/day. Hydraulic-conductivity tests conducted according to the auger-hole method (Van Beers 1970) yield values between 0.005 and 0.021 m/day where the water table is between 35 and 50 cm deep.

The vegetation type belongs to the *Sphagnum* and *Carex* peatland (Grandtner 1960). It is characterized by an abundance of herbaceous plants typical of oligotrophic peatlands. According to Schneider (1985), this peatland, which is classified as tall-sedge/eastern larch (*Larix laricina*), can react favorably to drainage.

In 1983, a drainage system was developed in an area regenerated with larch. The network consists of six parallel ditches 120 m long, which discharge into a road ditch (Fig. 1). When the project began, the age of the stand (measured at breast height) was about 20 years.

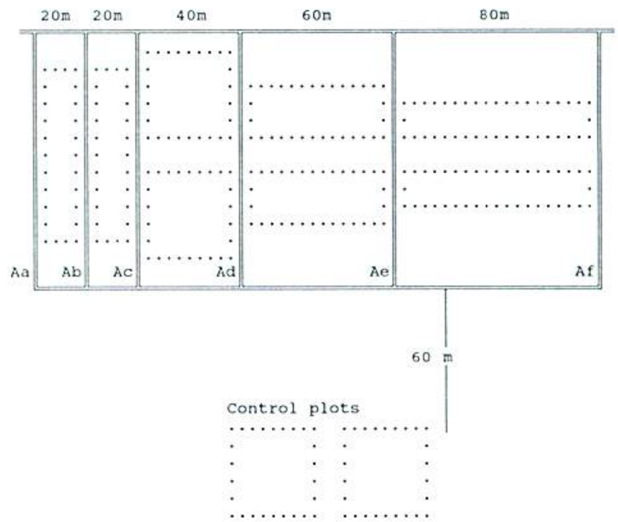

Figure 1. Drainage network and location of the sample plots.

Because of lateral drainage from the center of the peatland, the ditches were linked on the upslope side by a protection ditch. The ditches were 20, 40, 60, and 80 m apart (Fig. 1). Two sample plots were set up in each space between the ditches, and in a control area located outside the zone of influence of the ditches. Work was carried out with a 69-kW hydraulic excavator equipped with a parabolic bucket. The ditches were approximately 90 cm deep and the excavated material was deposited in discontinuous piles so as to keep blockage of surface runoff to a minimum.

Each sample plot measured 0.12 ha and covered the whole strip. The dimensions of the plots were as follows:

Ditch spacing (m)	Plot dimensions (m)
20	17 x 70.7
40	37 x 32.4
60	57 x 21.1
80	77 x 15.6
Control	34.6 x 34.6

In each plot, all trees ≥ 9 cm DBH were grouped into 2-cm DBH classes. Those from 1 to 9 cm were measured in a 0.01-ha circular plot located in the center of the main plot. Approximately 36 trees were selected in each plot. Height and DBH values were measured in 1983 and in 1988, after 5 full years of growth.

RESULTS

The trees that were damaged during the observation period were excluded from the present analysis. The trees from the two plots in each spacing have been regrouped for the analysis, which was based on 340 trees (Table 1).

Table 1. Measurements taken before and 5 years after the drainage project. Means and standard deviations (in parentheses)

Spacing treatment	Diameter (cm) 1983	Diameter (cm) 1988	Periodic increment (cm)	Increase (%)	Height (m) 1983	Height (m) 1988	Periodic increment (m)	Increase (%)
Control	3.8	4.4	0.56	14.8%	3.9	4.2	0.38	9.9%
n=72	(0.18)	(0.19)			(0.12)	(0.14)		
80 m	5.3	7.2	1.9	35.6%	4.5	6.1	1.6	35.5%
n=66	(0.21)	(0.31)			(0.13)	(0.21)		
60 m	4.3	6.5	2.2	50.4%	4	6	2	49.4%
n=69	(0.20)	(0.28)			(0.13)	(0.21)		
40 m	4.1	7.1	3	72.8%	3.7	6.3	2.5	67.8%
n=61	(0.18)	(0.24)			(0.10)	(0.13)		
20 m	4.5	8.2	3.7	84.0%	4.1	6.7	2.6	63.6%
n=72	(0.21)	(0.26)			(0.14)	(0.15)		

The trees within the 80-m plot in the southeastern part of the drainage area were generally larger when drainage began. The organic deposit is probably not as deep here because there is a sandy hill nearby, and the edaphic conditions are probably better for tree growth. Nonetheless, there were higher growth rates for narrower ditch spacings (Fig. 2 and 3).

The variations in both diameter and height within each group were greater after 5 years of growth than at the time of drainage. This phenomenon was particularly obvious in the 60-m and 80-m plots. The trees reacted differently, depending on their distance from the drainage ditches. The data have therefore been regrouped by distance classes (determined according to distance from the closest ditch) without the plots in which the trees were found being taken into account (Table 2).

The averages obtained for the groupings according to distance classes of 24, 30 and 37 m are not very precise since the sample size was small. All these trees were in the 60-m and 80-m plots. Nevertheless, the growth measures were related to distance from the ditch (Fig. 4 and 5).

CONCLUSION

Although the period studied was only 5 years, the results showed a relationship between intensity of drainage and growth rate (diameter and height). Trees that were more than 20 m from a ditch responded less well but still showed superior growth in comparison with those in the control.

The averages obtained for the groupings according to distance classes of 24, 30 and 37 m are not very precise since the sample size was small. All these trees were in the 60-m and 80-m plots. Nevertheless, the growth measures were related to distance from the ditch (Fig. 4 and 5).

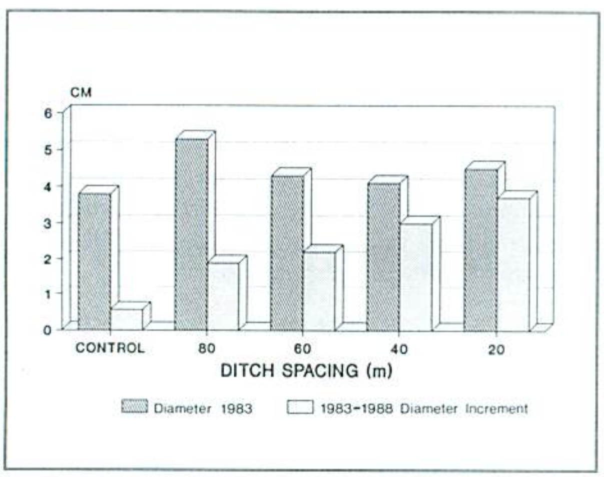

Figure 2. Diameter of trees before drainage was undertaken, and growth during the next five years.

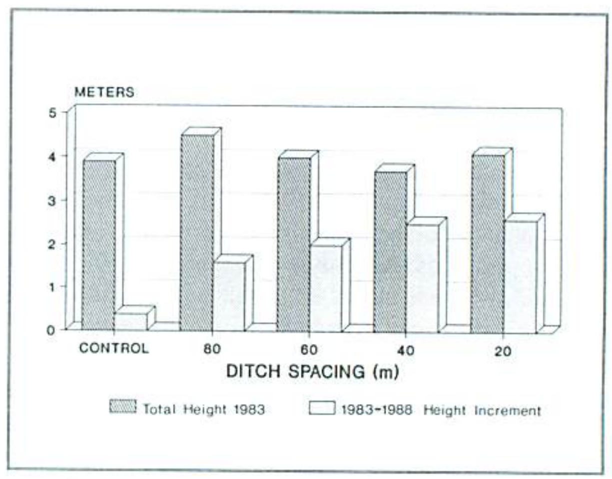

Figure 3. Height of trees before drainage was undertaken, and growth during the next 5 years.

Table 2. Measurements before drainage began and 5 years later, related to distance (midpoint) from the ditch. Means and standard deviations (in parentheses)

Spacing treatment	Diameter (cm) 1983	Diameter (cm) 1988	Periodic increment (cm)	Increase (%)	Height (m) 1983	Height (m) 1988	Periodic increment (m)	Increase (%)
Control	3.8	4.4	0.56	14.8%	3.9	4.2	0.38	9.9%
n=72	(0.18)	(0.19)			(0.12)	(0.14)		
37 m	4.6	6.1	1.49	32.6%	4	5.2	1.23	31.0%
n=12	(0.43)	(0.56)			(0.26)	(0.46)		
30 m	4.9	6.4	1.42	28.8%	4.2	5.6	1.34	31.8%
n=16		(0.61)			(0.18)	(0.47)		
24 m	4.6	6.3	1.64	35.3%	4	5.4	1.37	34.3%
n=20	(0.41)	(0.50)			(0.27)	(0.35)		
17 m	4.4	6.5	2.11	47.7%	4.14	6.1	1.94	46.9%
n=51	(0.24)	(0.27)			(0.16)	(0.21)		
10 m	4.6	7.5	2.9	63.6%	4.1	6.5	2.44	59.5%
n=74	(0.19)	(0.25)			(0.12)	(0.15)		
5 m	4.6	8.1	3.58	78.7%	4.1	6.6	2.53	61.6%
n=95	(0.19)	(0.24)			(0.11)	(0.14)		

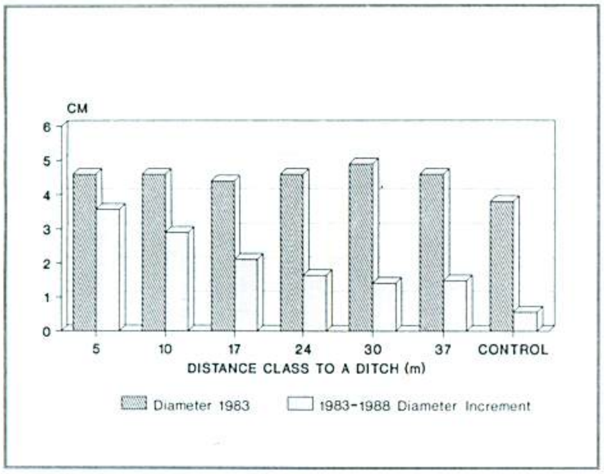

Figure 4. Diameter of trees before drainage began and growth during the next 5 years, related to distance (midpoint) from the ditch.

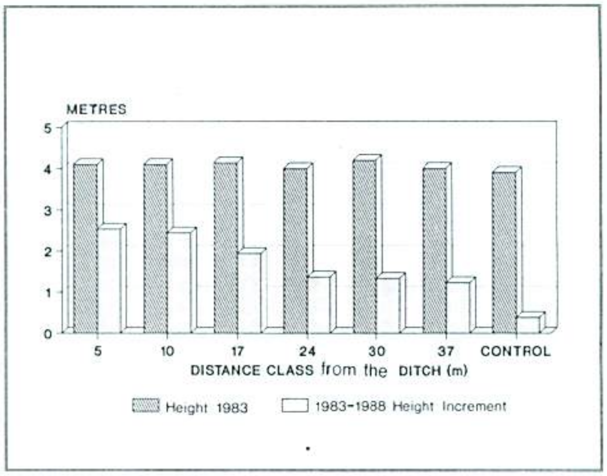

Figure 5. Height of trees before drainage began and growth during the next five years, related to distance (midpoint) from the ditch.

If this trend continues over the years, the forest will develop multiple "stories" in the wider strips (60 m and 80 m), and this will make silvicultural choices more difficult. Moreover, even if growth is better where there are 20-m spacings, such intensive drainage is not necessarily preferable since the cost of the work is then much higher, and much more land is used for ditches. The 40-m spacing seems to be an acceptable compromise.

Analysis of a few tree sections showed that, in the first year after drainage work, there was virtually no increase in diameter. The average annual growth rate over years 2 to 5 was therefore higher than the average for all 5 years shown in the results. The second remeasurement, planned for 1993, will provide more precise data on periodic growth.

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EFFECTS OF PRESCRIPTION FOREST DRAINAGE ON TREE GROWTH AND WILDLIFE IN NORTHERN MICHIGAN

C.C. Trettin
Department of Forestry
North Carolina State University
Raleigh, North Carolina
USA

R.D. Mislak
Abitibi-Price, Inc.
Alpena, Michigan
USA

J.R. Johnson
Mead Paper Inc.
Escanaba, Michigan
USA

ABSTRACT

Prescription drainage systems have been used to improve site operability, facilitate regeneration, and increase site productivity. Two studies on tree-growth response to that drainage system are summarized. Assessment of site quality, regeneration stocking, and height growth reveals that aspen (*Populus tremuloides*) productivity on a northern Michigan site has been increased from an original site index of 11.6-17.7 m to a predicted range of 18.3-24.4 m (at 100 years). Plantation trials of jack pine (*Pinus banksiana*) and tamarack (*Larix laricina*) show that these species can be successfully regenerated by means of either bedding or disking for site preparation on a sandy Aquod site. Establishment of red pine (*Pinus resinosa*) and aspen on that site after site preparation was not adequate. A third study is summarized in which species richness was used as an index to evaluate the potential effects of a pattern ditch system and subsequent stand management on wildlife. Total species richness was predicted to increase after drainage, harvesting, and stand establishment. Managing for specific habitats is essential to sustain species richness.

RÉSUMÉ

Des systèmes de drainage topographique ont été utilisés pour améliorer la capacité d'une station, faciliter la régénération et accroître la productivité de la station. Deux études sur la croissance des arbres après l'aménagement d'un tel système de drainage sont résumées ci-après. Dans une station du nord du Michigan, la productivité du peuplier faux-tremble (*Populus tremuloides*) a augmenté, passant d'un indice de qualité de station originel de 11,6-17,7 m à des valeurs prédites variant entre 18,3 et 24,4 m. Les plantations comparatives établies sur une station sableuse Aquod préparée par billonnage ou scarifiage ont montré que le pin gris (*Pinus banksiana*) et le mélèze laricin (*Larix laricina*) avaient un taux de survie et de croissance supérieur au pin rouge (*Pinus resinosa*) et au peuplier faux-tremble. Une troisième étude s'est servie de la diversité des espèces comme indice pour évaluer les effets potentiels d'un réseau de fossés et de l'aménagement ultérieur des peuplements sur la faune. Il avait été prédit que la diversité générale des espèces augmenterait après le drainage, l'exploitation et l'implantation du peuplement. Il est essentiel de pratiquer une gestion axée sur des habitats particuliers pour conserver la diversité des espèces.

INTRODUCTION

Forest drainage systems are used to ameliorate poor soil drainage conditions and improve site productivity. A pattern ditch system is the most common drainage technique used in peatland forestry. Productivity response to the pattern system has been extensively documented (Heikurainen 1964, Terry and Hughes 1975, Heikurainen and Laine 1985, Allen and Campbell 1988, Hånell 1988). Prescription drainage systems are applied to accentuate the natural drainage patterns of the landscape (Terry and Hughes 1978). They are effective in ameliorating high water table conditions (Trettin et al. 1990); however, no studies have been reported on tree growth response to prescription drainage systems. The effects of forest drainage systems on hydrology (Starr and Päivänen 1986, Gregory 1988) and water quality (Askew and Williams 1986, Williams and Askew 1988) have been documented but those on wildlife have not been reported.

Our research on operational prescription drainage focused on hydrologic and tree-growth responses after drainage. Subsequent to our initial operational trials, it was apparent that wildlife considerations needed to be included in the overall silvicultural prescriptions in intensively managed lowlands. Accordingly, we broadened the focus to include an assessment of the effects of drainage on wildlife. The purpose of this paper is to present results from three studies, two that evaluate tree-growth response after prescription drainage, and one that assesses the potential effects of drainage on wildlife. The first productivity study deals with aspen (*Populus* spp.) regeneration and growth; the second summarizes results from a plantation and site-preparation trial. The wildlife study was conducted as part of a baseline assessment of the effects of drainage. Information presented here is summarized from the project report by Premo and Premo[1].

METHODS

Aspen Regeneration and Growth

The aspen regeneration and growth study was conducted in Cheboygan and Presque Isle counties, in the northeastern part of the Lower Peninsula of Michigan. The climate is characterized by a mean annual air temperature of 6.7°C, and a mean annual precipitation of 708 mm. An operational prescription drainage system was installed on a 12,000-ha tract owned by Abitibi-Price, Inc. Approximately 80 km of prescription ditch were used to drain 6250 ha of lowland forest types within the tract. Drainage of the tract began in 1975 and was completed in 1988. Prior to drainage the stands in the study areas were composed of poor-quality, over-mature aspen, balsam poplar (*Populus balsamifera*), and red maple (*Acer rubrum*). The shrub vegetation was primarily tag alder (*Alnus rugosa*). Harvesting followed drainage by 1 to 3 years; conventional shortwood harvests were conducted throughout the year except during high-water periods in the spring. The soils within the tract are dominated by Aquods and Aquepts; they are characterized by a sandy solum underlain by lacustrine sediments, and a histic epipedon is common. Specifics of the site properties and drainage systems are described by Trettin et al. (1982).

Total stocking, percentage of aspen composition, and height growth were measured on 12 transects that were distributed among five watersheds within the tract. Each transect was perpendicular to a drainage ditch; sample plots were located at 20-, 80-, 140-, 200-, 300- and 400-m intervals or until the upland was reached. Each plot consisted of three subplots. Each subplot was 0.5 m wide, and had a variable length to obtain a minimum of 40 stems per subplot; the minimum subplot length was 10 m. There was a 2-m spacing between subplots. Data recorded on each subplot consisted of tree species and diameter at 30.5 cm above the ground surface on every live stem. Total height of every fifth stem and age of three dominant/codominant stems were also recorded on each subplot.

Four of the sampled watersheds had adjoining uncut, original stands. Twelve aspen trees were selected from these watersheds for stem analysis. Each tree was felled, total height was measured, and disks were removed at 30.5 cm, 1.3 m, and every additional 1.2 m up the stem; total age was determined for each disk. Height-age curves were developed for each tree according to Prodan's (1968) height-growth model:

Equation 1 $$Y = a\, t^{b}\, e^{-ct}$$

where: Y = total height (m); t = age; a,b,c = constants.

Annual height increment was computed according to the first derivative of Equation 1, on an individual tree basis. Each regression model was significant (P = .05) and had a correlation coefficient of more than 0.89.

Site Preparation and Plantation Trials

This study was conducted in the Upper Peninsula of Michigan. The site is characterized by a Typic haplaquod soil that is sandy throughout the solum. The forest floor

[1] Premo, D.B. and Premo, B.J. 1986. Water management on poorly drained soils as a silvicultural practice: predicted positive and negative impacts on wildlife of the Annheim study site, Houghton Co., MI. Mich. Tech. Univ., Sch. of For. and Wood Prod., Houghton, Mich. Unpubl. Rep. 40 p.

is composed primarily of *Sphagnum* spp. The preharvest vegetation consisted of black spruce (*Picea mariana*), jack pine (*Pinus banksiana*) and tamarack (*Larix laricina*). A prescription drainage system was installed on the site in July, 1984. A description of the site and drainage system is provided by Trettin et al. (1990).

Survival and growth of jack pine, red pine (*Pinus resinosa*), tamarack and aspen were evaluated on sites that had undergone three site-preparation treatments after drainage and harvesting: disking, bedding, and trenching. The TTS disk trencher was pulled with a JD 740 740 skidder, and the bedding plow and forestry disk were pulled with a D-7 Caterpillar tractor. The regeneration study was installed according to a replicated, complete block design on a 12.5-ha clearcut. The clearcut was prepared mechanically in November, 1985. Containerized seedlings were planted in May, 1986 in 10-m x 10-m tree plots, with a spacing of 2 m x 3 m. Survival was evaluated in August, 1986 and dead trees were replaced. Survival of each plot was subsequently measured in July, 1987 and July, 1989; total height (cm) of each live seedling was also measured in July, 1989.

Effects on Wildlife Populations

A study was conducted by Premo and Premo[1] in the Upper Peninsula of Michigan to evaluate the potential effects of drainage on wildlife. The soil on the study site was characterized as a Typic borosaprist "basic". The forest overstory vegetation was composed primarily of tamarack. The forest management plan that was evaluated included the installation of a pattern ditch system, followed by harvesting and regeneration. The potential effects of drainage on wildlife were considered on the basis of species richness for the vertebrate classes of Aves, Mammalia, Reptilia, and Amphibia. The measure of species richness was developed on the basis of regional vertebrate species lists, season of occurrence for the species, species habitat requirements for feeding and breeding, and special status (whether the species was threatened, endangered, rare, game, fur, or an indicator). The assembled species data base provided a basis for predicting change in the vertebrate populations in response to habitat conditions created by drainage and stand management. Four successional stages after drainage and harvesting were considered: I. shrub-sampling open stage, II. young coniferous stage, III. mature coniferous stage, and IV. old coniferous stage. Analyses were also conducted for the existing stand conditions. Lists of species that were expected to be found in the four vertebrate classes were compiled for each successional stage. Species were considered part of the community if they fed and/or bred there. Selected species lists and habitat assessments are presented here. More detailed lists and assessments are provided by Premo and Premo[1].

It should be noted that this wildlife study was conducted as a prelude to field studies that were intended to document wildlife population responses to drainage. Neither the drainage project nor the follow-up wildlife studies were implemented. However, the approach taken by Premo and Premo[1] is unique with respect to the assessment of drainage practices, and it affords an important perspective on wildlife population movements that are affected by forest management practices, including drainage.

RESULTS

Aspen Regeneration

Analysis of stocking and total height data within the sampled transects showed that two of the 12 transects were not uniform throughout their lengths, as a result of stand-age differences within the transect. Accordingly, overall transect means are reported only for those transects that were uniform, and means for the dominant age class were used for the two transects that showed significant within-transect variability.

In all transects, aspen constitutes 49% of the live stems, with red maple and red-osier dogwood (*Cornus stolonifera*) comprising 19% each; other minor components include balsam fir (*Abies balsamea*) (6%), tag alder (3%), and white ash (*Fraxinus americana*) (1%). The regeneration stocking level necessary to achieve full stocking for a site index 20 (m) site, at age 3 with 20% mortality, is approximately 27,000 stems ha^{-1} (Perala 1977). Figure 1 shows that nine of the sample transects (based on age 3) had adequate stem counts to achieve full stocking. Transects 9 and 11 were also adequately stocked according to the measurement age (ibid.). Transect 6 was the only transect that was not adequately stocked according to Perala's nomogram (ibid.). It should be noted that the 20% mortality figure was not based on actual measurements, but was used as a conservative estimator. Lower mortality rates would reduce the number of stems required to achieve full stocking at maturity.

Site parameters reported to affect aspen productivity include: depth to water table, moisture regime, surface soil texture, and topography (Stoeckeler 1960; Graham et al. 1963). On the basis of these parameters, the predicted site index for aspen could be expected to range from 18.3 to 24.4 m at 100 years (Table 1). Previous studies (Trettin et al. 1982) on this site showed that the water table was lowered by the drainage ditch, and this effectively improved the moisture regime.

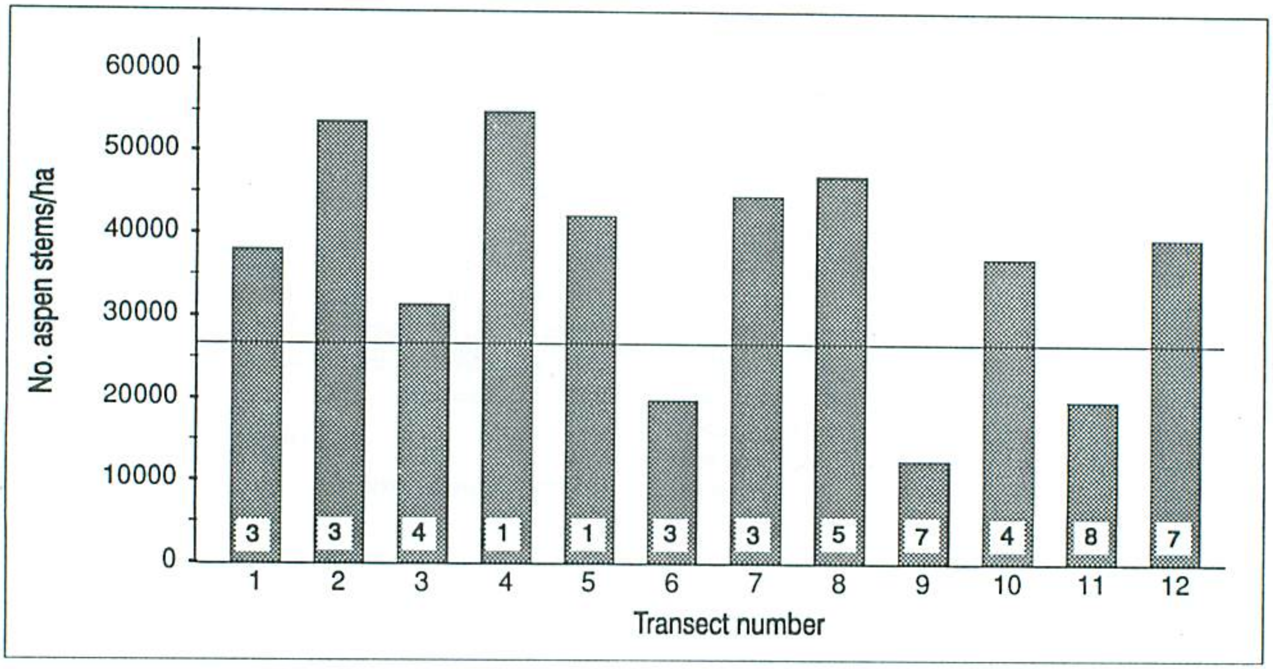

Figure 1. Average stocking of aspen stems presented by transect. Embedded number indicates stand age. Line at 27,000 stems ha^{-1} represents suggested level required for full stocking on the basis of site class 20 m, age 3, and 20% mortality, after Perala (1977).

Table 1. Predicted site index (m at 100 years) based on site-quality parameters after drainage

Predicted site index	Parameters	Reference
19.8 – 24.4	soil moisture surface-texture	Stoeckeler (1960)
18.3 – 24.4	water table	Graham (1963)

Comparison of height development of the regenerated stems with that of the original stems provided a more direct approach than site parameters. Data from four transects (Fig. 2) show that the increase in total height after drainage, at the measurement age, ranged from approximately 15% to 160% more than in the original stand. Annual height increment provided another perspective on growth, and an indication of the pattern of future stem elongation. Comparison of three-year height increment for transect 10 demonstrated a large increase in comparison with the original stand (Fig. 3). Future growth cannot be predicted accurately from these data. However, increased early growth should result in increased height throughout stand development. An example of this is provided by measured regeneration from transect 12, which was 12 years old at the time of sampling. In comparison with published site index curves, height development of the regenerated trees is equivalent to site index 24 m (Fig. 4).

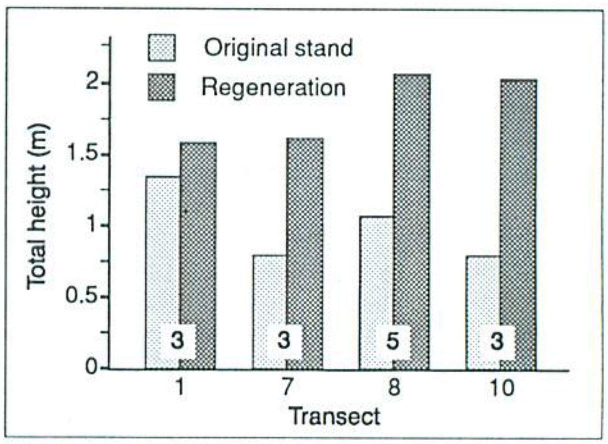

Figure 2. Average total height development of regenerated aspen stems after drainage in comparison with height development of trees from the original stand before drainage. Embedded numbers indicate age of comparison.

Site Preparation – Regeneration Trials

Survival of jack pine, red pine, tamarack, and aspen after 4 years and after different site-preparation treatments is presented in Figure 5. Jack pine had the best overall performance after each of the site-preparation treatments. The survival of tamarack was nearly equivalent to that of jack pine except for the bedding treatment.

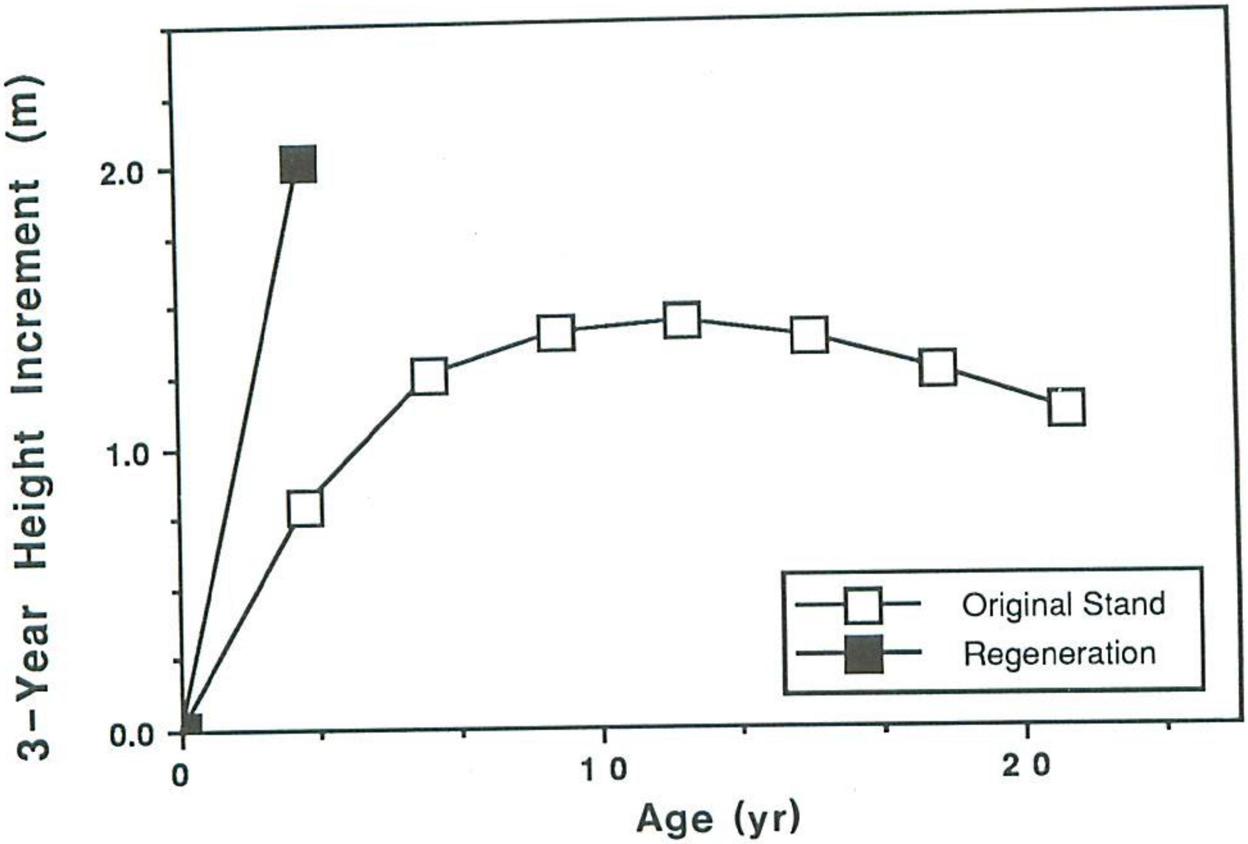

Figure 3. Three-year height increment curves for original aspen stems and regenerated aspen.

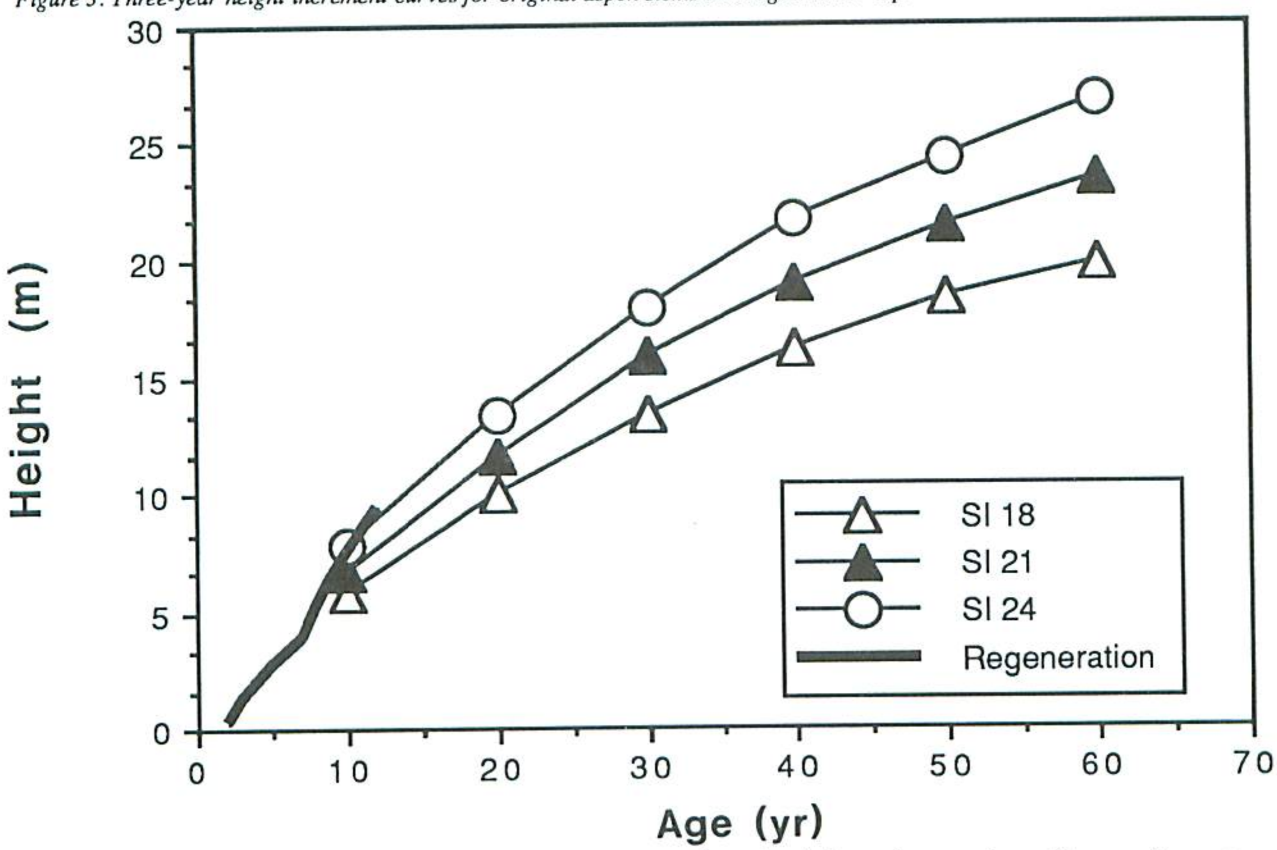

Figure 4. Mean height-age development of 12-year-old aspen regeneration, after drainage, in comparison with aspen site curves (Lundgren and Dolid 1970).

In general, survival on the beds is thought to be reduced as a result of seedlings being planted in loose organic clumps within the beds. The poor survival of red pine and tamarack is also reflected in the low average height development of those species (Fig. 6). Jack pine exhibited the best height growth after all treatments; tamarack was next. Height development was poorer on the bed plots than after other treatments.

Wildlife Population Response to Drainage

There are, potentially, 90 species in the existing study area. After drainage, harvesting and stand establishment, the total number of species is predicted to increase to 121. A subsequent decline in total population numbers occurs during the pole-size phase of stand development, and is followed by a slight increase in species richness in

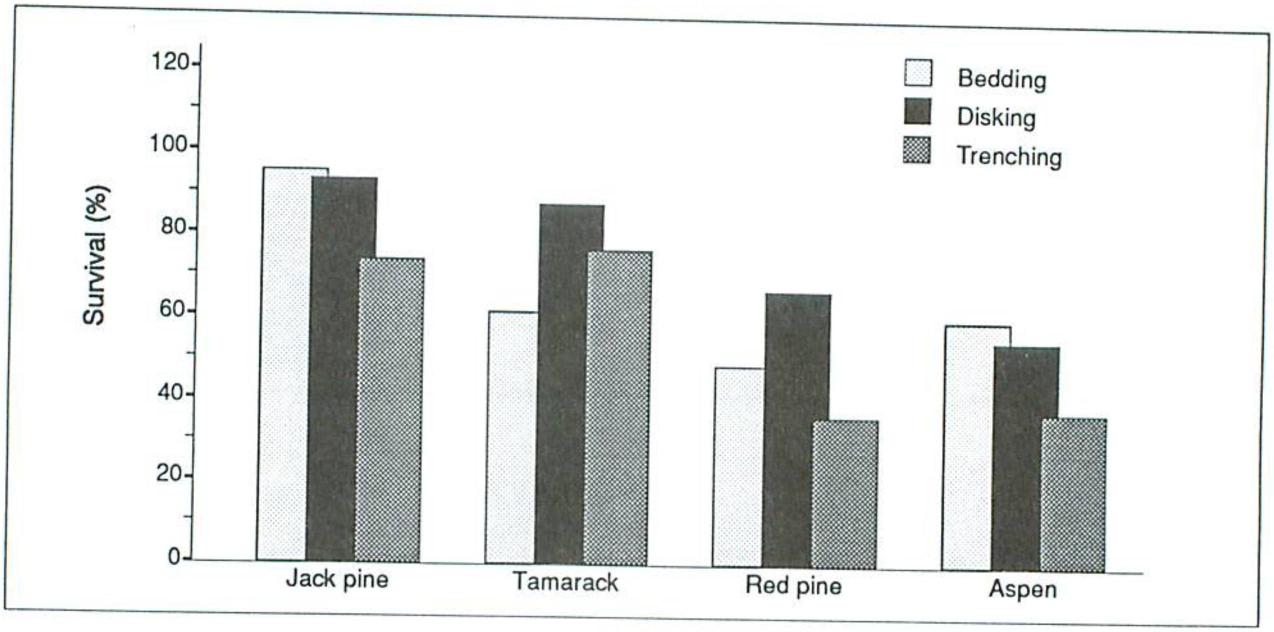

Figure 5. Average survival of planted jack pine, tamarack, red pine, and aspen after 4 years, by site-preparation treatment.

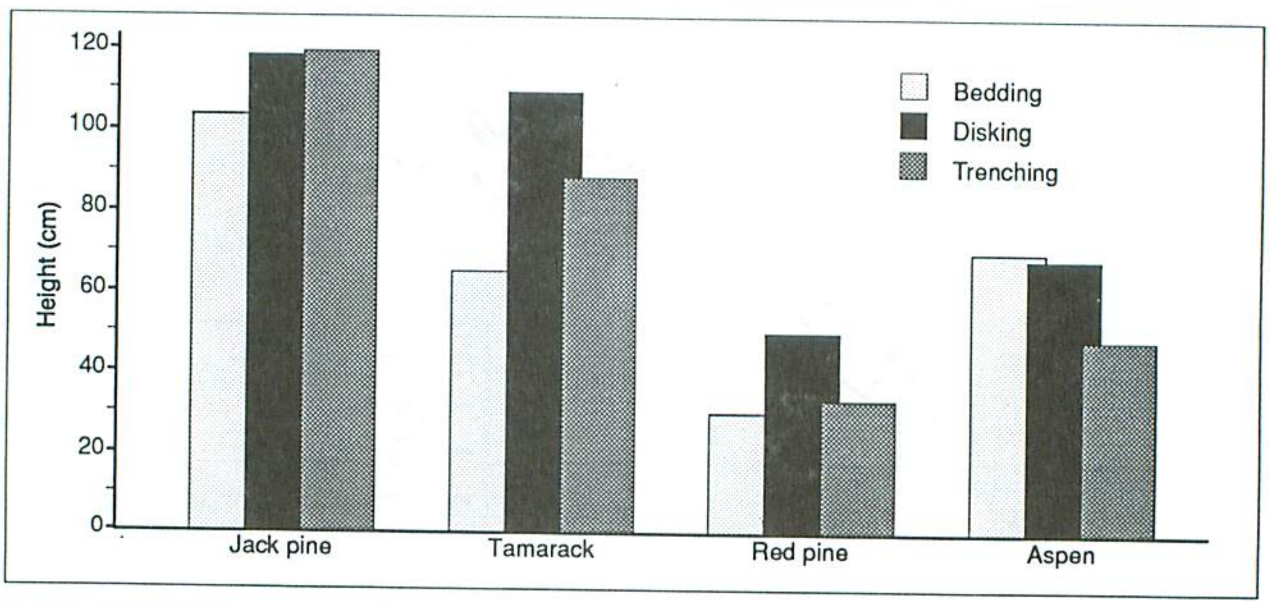

Figure 6. Average total height growth of planted jack pine, tamarack, red pine, and aspen after 4 years, by site-preparation treatment.

in the mature and old-growth phases of stand development (Fig. 7). It is predicted that 16 species will be dispossessed from the existing stand as a result of intensive management activities.

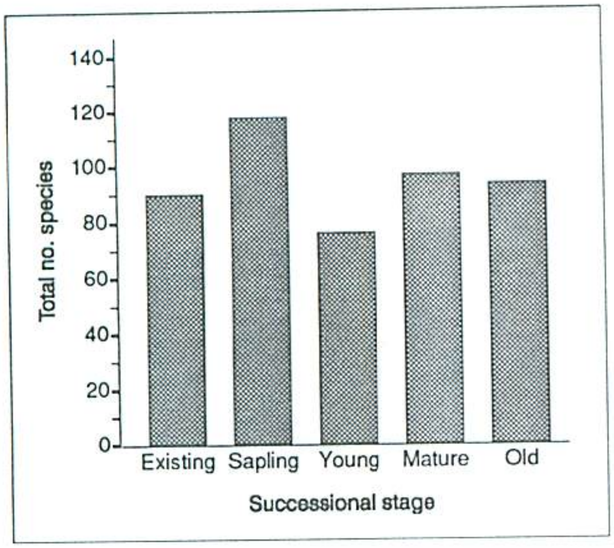

Figure 7. Predicted species richness in the existing stand and four successional stages after drainage and regeneration.

Changes in specific habitats are largely responsible for species fluctuations during stand development (Fig. 8). There was an increase in species numbers in the harvested, drained stand in comparison with the original, undrained forests because of an increase in edge habitats. Subsequent reductions in edge, snag, and log habitat result in reduced species richness in the pole-size phase. The increase in species richness in the mature stand is largely a result of increased snag and log habitat. The importance of snag and log habitat to species richness is exemplified by excluding that habitat from the assessment and determining total population sizes. Figure 9 demonstrates that individual elimination of snags or logs reduces total species numbers and the combined elimination results in population reductions ranging from 30% to 50%. Water habitat is also important in sustaining species richness; Figure 10 presents a summary of the potential number of species that are specific to ponds, or that frequent either pond or stream habitats.

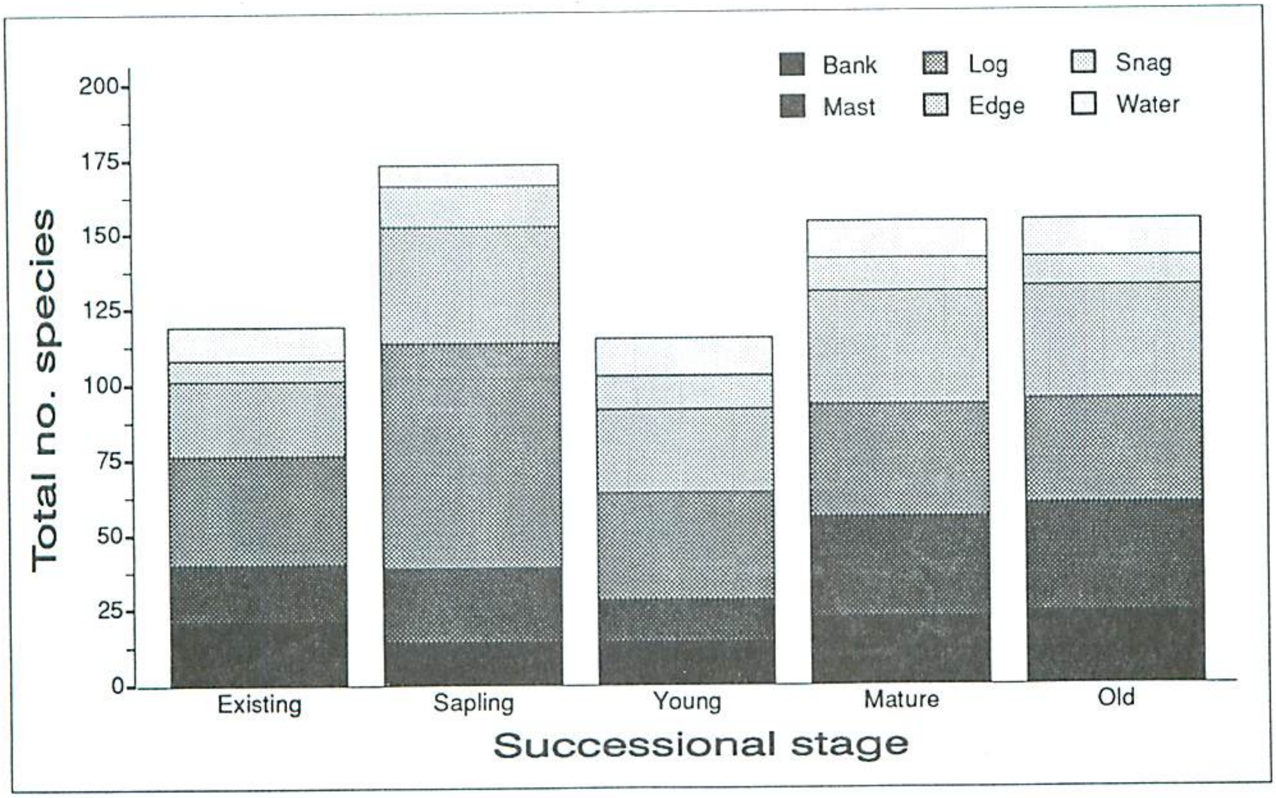

Figure 8. Potential number of species requiring special habitat; "water" includes ponds or streams; "snag" includes dead or dying trees; "edge" indicates an ecotone habitat; "log" includes decaying stems on the ground; "mast" includes pine seed or other mast fruit; "bank" is associated with bare ground on slopes. Totals exceed those on the species list because of the multiple habitat requirements of several species.

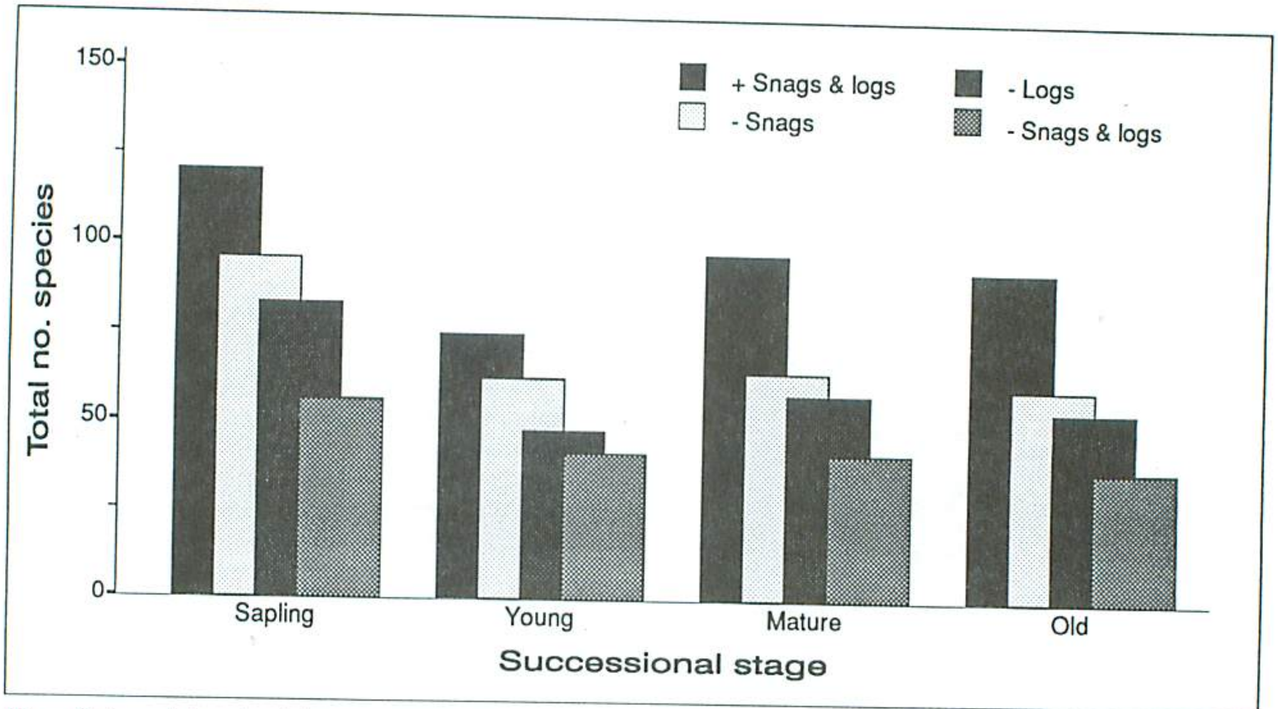

Figure 9. Potential species richness in successional communities after drainage and regeneration, when snags and logs are present, individually absent, and entirely absent.

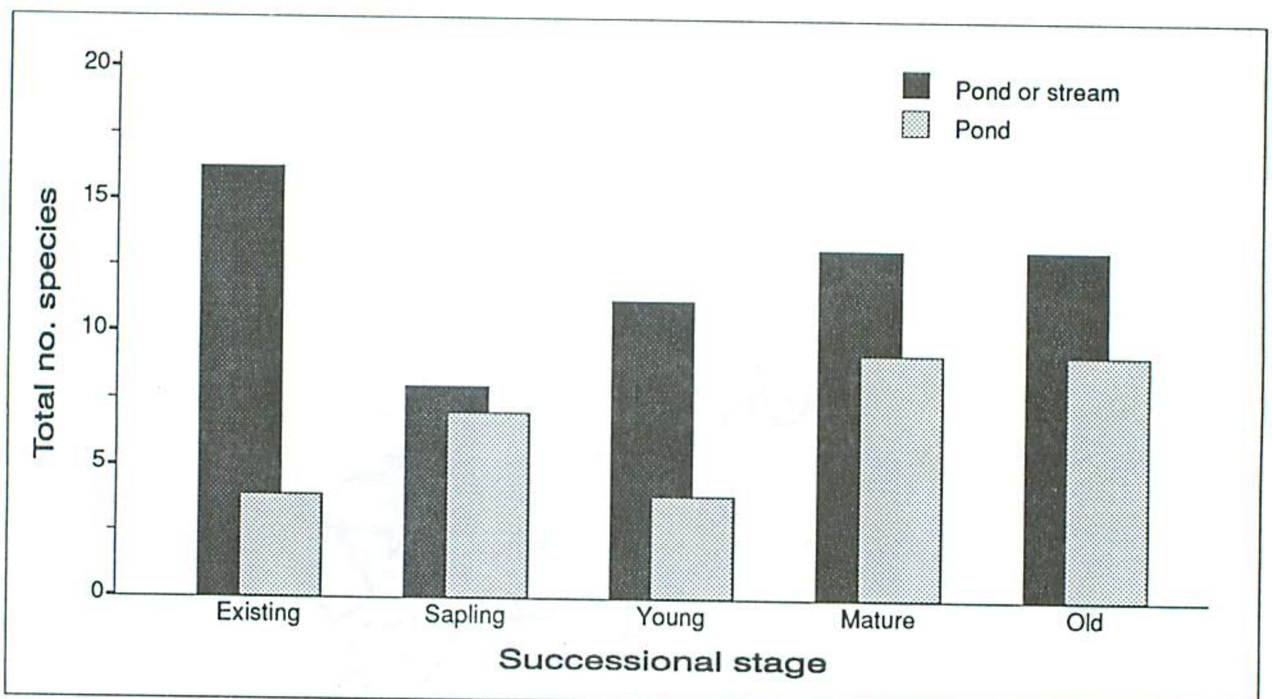

Figure 10. Potential species richness in successional communities after drainage and regeneration specific to ponds, or ponds and streams.

DISCUSSION

Tree-growth Response

The site-quality approach is an indirect method of assessing potential productivity response. The predicted increase in productivity is attributable to the increase in water-table depth and improved moisture regimes. Although growth response may not be predicted accurately from these site factors, they are recognized as being important for aspen productivity (Stoeckeler 1960, Graham et al. 1963, Brinkman and Roe 1975). Popovich

(1982) reported that bottomland sites with high fertility and good moisture conditions were the best sites for poplar cultivation. With the amelioration of the high water table it is expected that the level of extractable bases in the soils on the Abitibi study site (Trettin et al. 1982) will increase and will contribute to growth increase. Regeneration stocking and site-quality parameters are important for achieving productive aspen stands (Perala 1977). Stocking measurements on the Abitibi tract (Fig. 1) demonstrate that levels are sufficient to achieve commercially productive stands (ibid.). The measured stocking levels are reflective of stands with high site quality and productivity potential (Ek and Brodie 1975, Perala 1977).

Comparison of current growth increment with growth on adjoining stands, which developed in poor drainage conditions, provides direct evidence of the change in productivity associated with drainage. For each of the sampled sites that had both regenerated and mature stands, height growth of the regenerated stands increased. Although future height growth cannot be predicted accurately from the limited observations reported here, the initial pattern of height accumulation suggests overall increases in comparison with trees in the original stand. The analysis of the single site with 12-year-old regeneration demonstrates that the pattern of height accumulation is equivalent to a site class of 24 m (Fig. 4). Although the overall interpretation of growth response to prescription drainage is hindered by a lack of experimental controls, the combined evidence of improved site-quality factors and stocking levels suggests improvements in site class in comparison with what was measured for the original stand before drainage and harvest. Direct observation of current height accumulation supports that evidence.

The regeneration trial after drainage, harvesting, and site preparation demonstrates that jack pine and tamarack are suited to the acid, infertile haplaquod soil and that the response is generally good regardless of site-preparation treatment. Lower survival after the trenching treatment is attributable to temporary inundation of the seedlings subsequent to snowmelt. The planting microsites for both the disk and the bed treatments were higher than those for the trench treatment, and this reduced the effect of spring flooding.

Effects on Wildlife

The increase in species richness after drainage and harvesting is a response to the habitat created by the silvicultural prescriptions. Clearly, edge habitat is responsible for the predicted population increase after harvesting. Subsequent changes in stand structure during stand maturation are accompanied by changes in species richness. Specific habitats are essential to sustain species richness (Fig. 8). The important implication of these findings is that habitat niches are the result of the silvicultural prescriptions. For example, leaving snags and logs on the site is essential to sustain species richness (Fig. 9). Similarly, creation of drainage ditches and sedimentation ponds can be expected to provide important water habitat. Although the predictions by Premo and Premo[1] are based on recognized habitat and species ranges, it is evident that species richness can be sustained in association with drainage if special habitat objectives are included as part of the silvicultural prescription. Drainage does dispossess individual species requiring specific wetland habitat, and overall richness is increased as a result of the enhanced stand and habitat conditions. This initial assessment by Premo and Premo[1] suggests that there is considerable opportunity for sustaining wildlife values of the wetland in association with intensive management practices.

SUMMARY

Prescription drainage has improved site quality for the growth of aspen, primarily by ameliorating the soil moisture regime. Measures of stocking and height growth provide further evidence that the site class has been increased from a range of 11.6-17.7 m to a predicted range of 18.3-24.4 m. Direct measures of height growth from a single 12-year-old stand yielded a site class of 24 m after drainage. Plantation trials on an Entic haplaquod in which trenching, bedding, and disking were employed demonstrated that both jack pine and tamarack are well suited to the site and regeneration treatments, whereas red pine and aspen exhibit poor survival and growth.

Wildlife species richness can be influenced by both drainage and stand management practices through the achievement of special habitats. There is a potential increase in species richness of 32% in the shrub sapling stage after drainage, harvesting, and regeneration; at stand maturity the overall increase in species richness was estimated to be 8%. Providing special habitats is essential to sustaining wildlife diversity; especially important are water, snags, logs, and edge. Drainage and intensive stand management will result in the dispossession of select wetland species, but will enhance overall species diversity.

The information presented here is based on operational drainage studies and should be followed by studies to quantify long-term stand and habitat development. These initial findings, however, demonstrate important improvements in site potential after prescription drain-

age. Sustaining wildlife values is often an important objective in managing lowland types, and these pilot studies demonstrate opportunities for managers to enhance wildlife values through water-management practices.

ACKNOWLEDGMENTS

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AFFORESTATION OF OPEN PEATLANDS

E. Sundström
Department of Silviculture
Faculty of Forestry
Swedish University of Agricultural Sciences
Umeå, Sweden

ABSTRACT

Nonproductive open peatland covers one tenth of Sweden (4.9 million ha). About 30% of this land is suitable for afforestation, if it is properly treated. A large part of the nonproductive open peatland in Sweden has a comparatively high production capacity. The project described in this paper is focused on developing site-specific methods of forest establishment both on open bogs and on abandoned agricultural peatland.

In Sweden 200,000 ha of peatland have been used for agriculture. Approximately half of this land has been abandoned, and in the near future this figure will probably increase. Many earlier afforestation efforts have failed because of frost, competing vegetation, poor drainage or field mice.

If these problems can be dealt with, this type of land should be well suited to forest production. An experiment with different afforestation methods, including different tree species, has therefore been initiated.

In the 1960s and 1970s some afforestation experiments, dealing with ditching and fertilization, were started on nonproductive open peatlands. Five experimental areas were located throughout the country. The objectives of the experiment were to determine optimal ditch spacing and the right mixture and quantity of fertilizers. Some results of a first inventory of these experiments are presented.

RÉSUMÉ

Le dixième des terres de la Suède (4,9 millions d'hectares) sont des tourbières ouvertes non productives dont environ 30 % pourraient être boisées grâce à des interventions adéquates. Un pourcentage important de ces terres a une capacité de production relativement élevée. Nous tentons donc de mettre au point des méthodes adaptées aux stations en vue de l'établissement de forêts dans des marais ouverts et sur des terres agricoles abandonnées situées sur des tourbières.

En Suède, 200,000 hectares de tourbières ont été utilisés à des fins agricoles. De nos jours, près de la moitié de cette superficie est abandonnée, proportion qui devrait augmenter au cours des années à venir. Bon nombre des tentatives antérieures de boisement ont échoué en raison du gel, de la compétition végétale, d'un drainage insuffisant ou de l'activité des rats des champs (campagnols). Si l'on réussit à régler ces problèmes, ces terres pourront se prêter à un aménagement forestier. On a donc entrepris une expérience avec différentes méthodes de boisement, y compris l'utilisation de différentes essences d'arbres.

Pendant les années 60 et 70, certaines expériences de boisement, comprenant l'aménagement de fossés et la fertilisation, ont été entreprises dans des tourbières ouvertes non productives. Cinq secteurs expérimentaux étaient situés dans une vaste gamme de stations. Les objectifs consistaient à déterminer l'écartement optimal des fossés et les doses et les types d'engrais appropriés. Un premier bilan de ces expériences a été dressé et le présent rapport expose certains résultats.

INTRODUCTION

In the early 1980s, the government of Sweden accepted a plan for future forest research in which silviculture on wetlands was given high priority. One result of that plan was the initiation of a research program in 1985 entitled "Forest production and silviculture on wetlands". This program consists of seven separate research projects, one of which is "Afforestation of open peatlands". The purpose of this project is to develop site-specific methods of forest establishment and forest production both on open bogs and on abandoned agricultural peatland.

The total land area of Sweden is about 41 million ha, of which 57% is forest land. Forest land is defined as land with forest productivity exceeding 1 $m^3ha^{-1}yr^{-1}$ calculated as mean production over a rotation period of 100 years. Bogs, fens, mires and other treeless, peat-covered land cover 4.9 million ha or 12% of the total land area. This land, which will be referred to henceforth as mire, is by the previous definition nonproductive in terms of forestry, mainly because it is nutrient-poor and the water table is too high.

About one quarter (28%) of the total peatland area in Sweden consists of productive forest land and the remaining 72% is mire. Because of climate conditions, most of the mire is found in the north, whereas in the south productive forest land dominates.

Not all of the mire area is treeless. Either trees or seedlings grow on 50% of it, but tree productivity is less than 1 $m^3ha^{-1}yr^{-1}$. Climate also affects site-class distribution on mires. More than half of the mire area consists of nutrient-poor sites characterized by low sedge and marsh Andromeda-cranberry. Sites dominated by low sedge constitute 48% of the mire area. Tall sedge is found on 23% of the area, while the very rich sites with tall herbs constitutes about 2% (Fig. 1).

Although Sweden has the potential for increased forest production, very little is done to utilize this potential. Drainage of mires for agricultural purposes began in the the mid-nineteenth century and reached a peak in the 1930s. Mires have been drained for afforestation on a very small scale, mostly at the beginning of the present century.

Today, as the demand for pulpwood increases, afforestation of peatlands may be a means of satisfying that demand. Two current experiments with afforestation, one on abandoned agricultural land and the other on mires, are discussed in this paper.

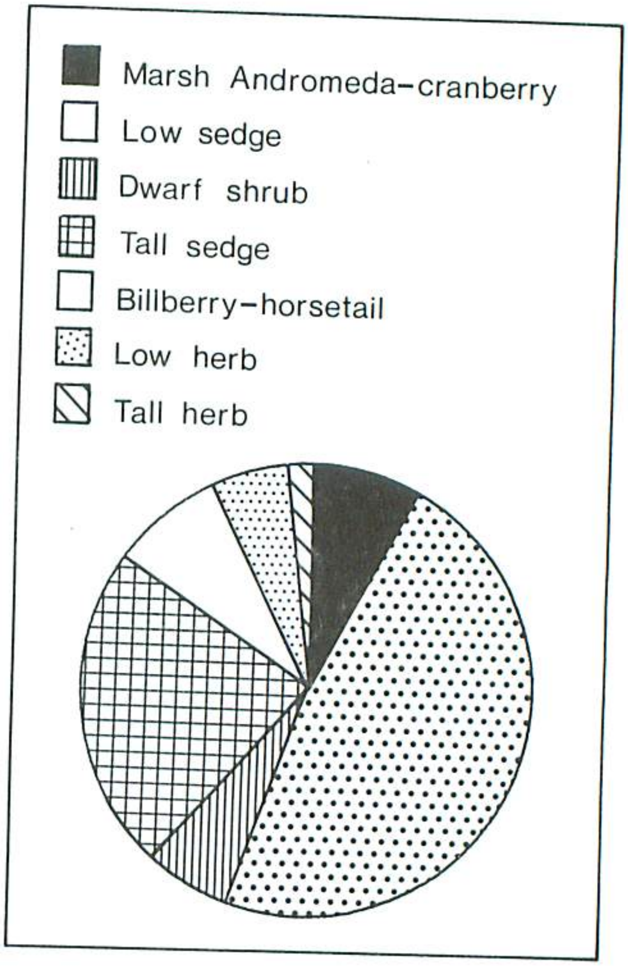

Figure 1. Vegetation types in mires (open bogs, fens and marshes) in Sweden. Types are arranged in order from poor to rich (top to bottom).

AFFORESTATION OF ABANDONED AGRICULTURAL PEATLAND

As the population of Sweden increased at the end of the last century, there was a growing demand for more land to cultivate. It is estimated that, at the most, 200,000 ha of open peatland were converted to agricultural land. This was done mostly in southern Sweden, where the population was densest and conditions for growing were best. About half of this area (mostly in the north) is abandoned today, and the trend continues. This type of land has a comparatively high capacity for forest production, but after many years it is still treeless. There are many reasons for this but some of the major problems are competing vegetation, frost, disturbed nutrient balance, poor drainage, field mice and other herbivores such as moose and roe-deer.

Nine experimental areas were established in 1987 for the purpose of managing these areas and developing practical afforestation methods (Fig. 2). The areas are located in the northern, central and southern portions of the country, and the experimental design is similar in all of them.

The abandoned agricultural peatland considered here, including the control areas, had been drained by ditching. In the experiment, two soil-preparation techniques (Fig. 2), furrowing by plow and mounding, were used to achieve better aeration, higher soil temperature, faster mineralization and reduced competition from other vegetation. There is also less risk of frost damage to seedlings planted on ridges or mounds, because of the higher minimum temperature and faster warming of the soil in spring.

Two thirds of the seedlings were fertilized with 50 g PK 7-13 each (% by weight) at time of planting (Fig. 2). Fertilization at the outset, especially with potassium, has a positive effect on survival and increases height growth. Mechanical weed control was carried out on two of three plots (Fig. 2). Herbicides were not used because they have negative effects on seedlings when used on organic soils.

Four different species, black spruce (*Picea mariana)*, Norway spruce (*Picea abies*, two sizes), lodgepole pine (*Pinus contorta*) and birch (*Betula pendula*) were planted in the spring of 1988 (Fig. 2). In southern Sweden no lodgepole pine was planted, while in central Sweden no birch was planted. Minimum temperatures and depths to water table were measured regularly.

Preliminary Results

It is our intention to follow these experiments for 3 to 4 years, taking inventory twice a year (every spring and autumn). Results of the first inventory in September 1988 show that competing vegetation has caused the death of many seedlings, especially in the north. On plots with no site preparation, 95% of the birch and 80% of the black spruce and small Norway spruce have not survived. For mounded plots comparable figures were 35%, 25% and 22%. For lodgepole pine and large Norway spruce the results were much better.

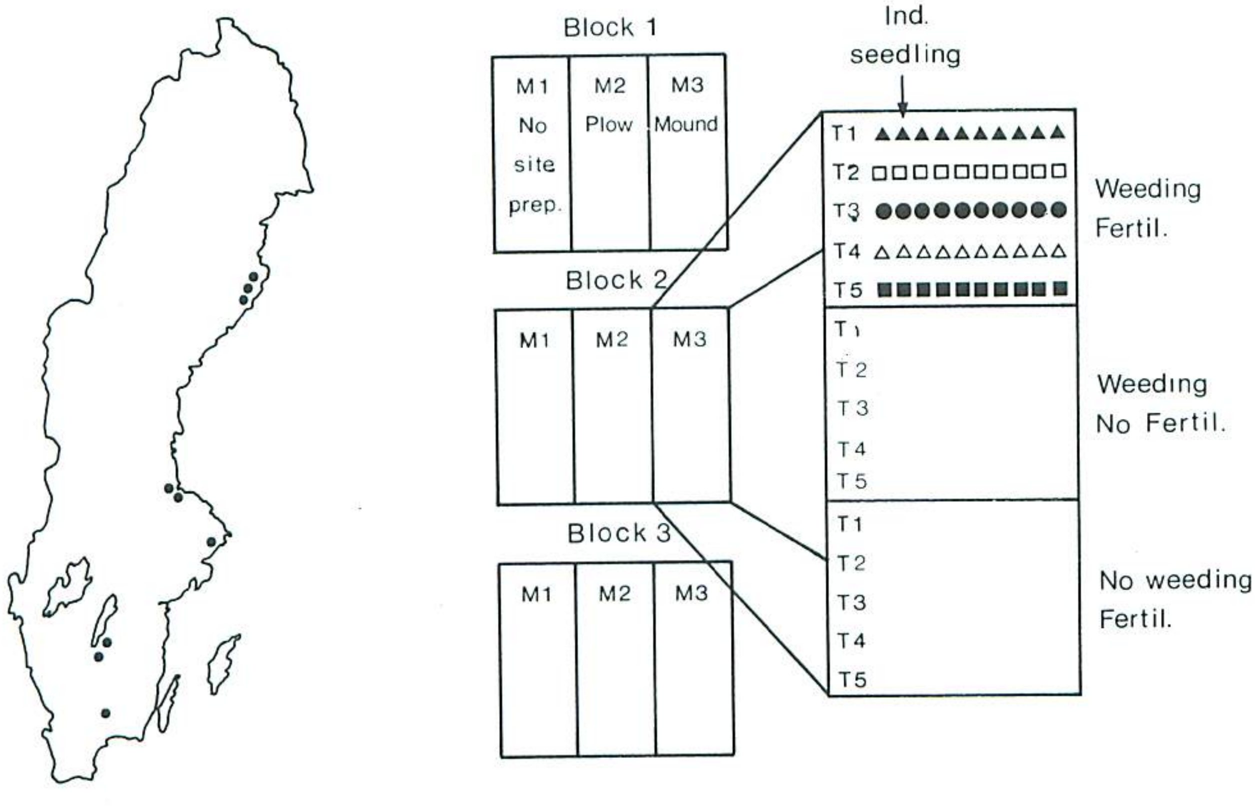

Figure 2. Experimental areas (9) and design for afforestation of abandoned agricultural peatland. Species planted were black spruce, Norway spruce (two sizes), lodgepole pine and birch.

On mounded areas only 1% of large Norway spruce and 6% of lodgepole pine were dead; on plots with no site preparation the figures were 20 and 35%, respectively.

In central Sweden there were some problems with late summer frost, especially among black spruce. Large Norway spruce grew better on unprepared plots than on mounded ones. Some of the mounds may have been too large and consequently didn't hold enough water for the big seedlings. In the south, roe-deer caused severe damage during the first season. In one area 95% of the seedlings were browsed, regardless of tree species. The seedlings used were rooted in containers. Local experience indicates that container seedlings are much more attractive to moose and roe-deer than are bare-root seedlings. Birch have done very poorly in the south. Minimum temperature and groundwater measurements indicate that it is 2-3°C warmer 20 cm above mounds than above unprepared surfaces (Fig. 3). This difference in minimum temperature can be very important to the seedling in relation to frost damage.

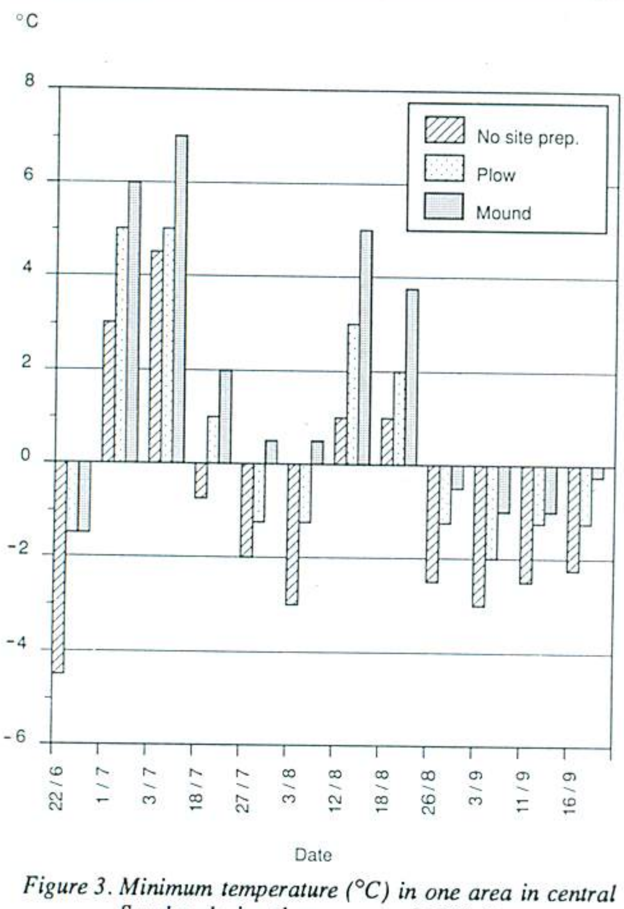

Figure 3. Minimum temperature (°C) in one area in central Sweden during the summer of 1988. Temperatures are for 20 cm above mounded, plowed and unprepared surfaces.

In addition to the normal ditching done for all these agricultural peatlands, site preparation has a minor impact on the water table. On most mounded plots the depth to water table was greater than it was on unprepared sites. The depth to water table was measured between the mounds, so the mounding itself may have had the effect of lowering the water table. There were no clear differences between the furrowed areas and the unprepared sites. It is hoped that observations over the next three years will yield information that can be used in developing practical guidelines for forest owners in Sweden who want to regenerate their abandoned agricultural peatlands.

AFFORESTATION OF NONPRODUCTIVE OPEN PEATLAND (MIRE)

Conditions for afforestation and forest production on treeless nonproductive peatland were studied in five experimental areas that were established in 1971. The areas are situated from the west coast in the south to 50 km north of the Arctic Circle (Fig. 4). The altitude varies between 100 and 325 m and the peat layer is more than 1 m deep in all areas. Low sedge and marsh Andromeda-cranberry site types, which are both relatively infertile, dominate in all the areas.

One of the main purposes of the experiments was to study variation in forest production on peatland owing to climate. The identical experimental design was used in each area. Three questions were posed at the outset: (1) Is there an optimal ditch spacing? (2) Which fertilizers are needed on these sites and in what amounts? (3) Which tree species are the most suitable in each region?

Four ditch spacings (7.5, 15, 30 and 60 m) were systematically combined with four different doses of fertilizers; there was also an unfertilized control. The fertilizers used were P from basic slag[1], K from potassium chloride and N from urea in the following doses:

1. control = no fertilizer
2. NP2K2 = nitrogen 120 kg/ha phosphorus 40 kg/ha potassium 80 kg/ha
3. P2K2 = phosphorus 40 kg/ha potassium 80 kg/ha
4. P2K4 = phosphorus 40 kg/ha potassium 160 kg/ha
5. P4K4 = phosphorus 80 kg/ha potassium 160 kg/ha

[1] Basic slag is also known as Thomas phosphate. This waste product from iron mills supplies P in a slow-release form.

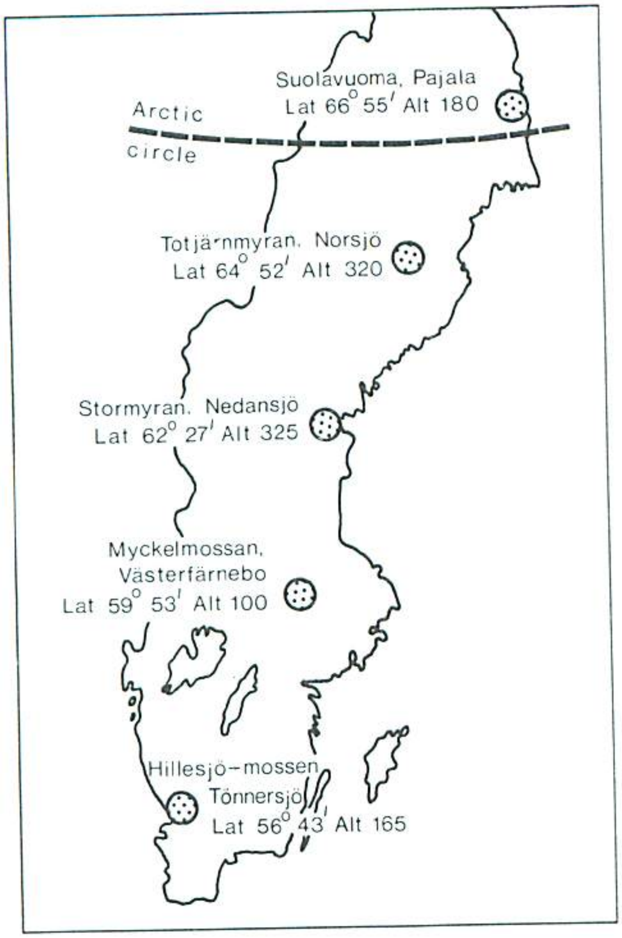

Figure 4. Afforestation of nonproductive open peatland (mire) in Sweden. Experimental areas.

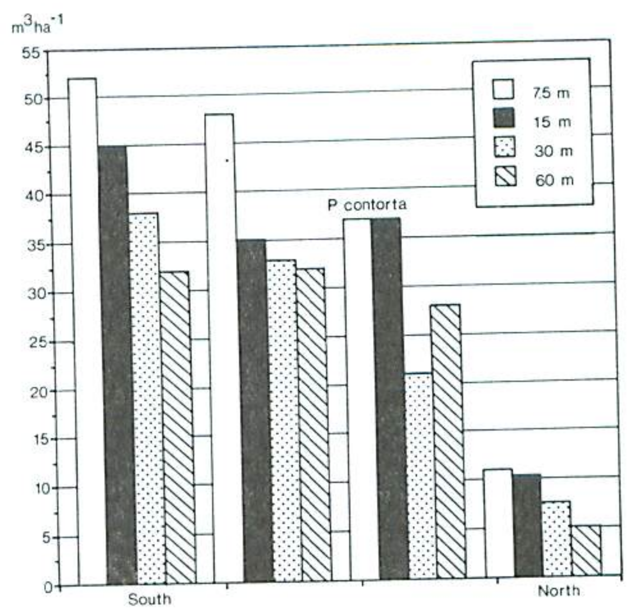

Figure 5. The effect of ditch spacing and climate on standing volume in four experimental areas in Sweden. The results refer to Scots pine, except for one area planted with lodgepole pine. The averages include the values for fertilized and unfertilized plots.

The year after draining, seedlings were planted and fertilized. The fertilizers were applied in two different ways, spot and broadcast. Scots pine (*Pinus silvestris*) and birch were planted in all areas. In the northern and southern areas Norway spruce was added; elsewhere, lodgepole pine was used instead of Norway spruce. Half of the seedlings were planted in a 30- x 30-cm piece of inverted peat, the remainder in unmodified natural peat. The seedlings were planted at a spacing of 2 x 2 m.

Preliminary Results

Since we are interested in forest production over an entire rotation period, we plan to follow these experiments for a long time. In 1988, the 18-year-old stands were inventoried. Height, diameter and different kinds of damage were registered. Nutrient conditions in needles and chemical contents of runoff water were analyzed.

Volume per hectare was calculated and, as expected, tree growth was much better in the south than in the north (Fig. 5). Today, the total standing volume per hectare for Scots pine is four times greater in the south than in the north. This is an average of all stands; neither ditch spacing nor fertilization has been taken into consideration. Decreasing the distance between ditches from 60 to 7.5 m increases volume production by about 150%. The basal area in control plots for the two rows of trees nearest the ditch was three times higher than for those rows between the ditches. In fertilized plots this difference was not as great — about 1.5 times higher than for the rows between the ditches. (The most northerly area was not included, as data were unavailable at time of writing.)

Fertilization evoked a much higher growth response than did drainage alone (Fig. 6). Volume production was 6-10 times higher in fertilized plots than in the control. This holds true for the southern and central parts of the country, while in the north, growth response to fertilization was minimal.

The differences in volume resulting from different combinations and quantities of fertilizer are small, but it seems that doubling the dose of P (P4K4) has given the best response, at least in the south. This was supported by the nutrient analysis of the needles which, however, indicated a current shortage of K. In the near future potassium must be added to prevent a decline in growth.

The volume values refer to Scots pine, with one exception. That is in central Sweden, in Stormyran, where lodgepole pine was much superior to Scots pine. Here the volume values for lodgepole pine were four times higher

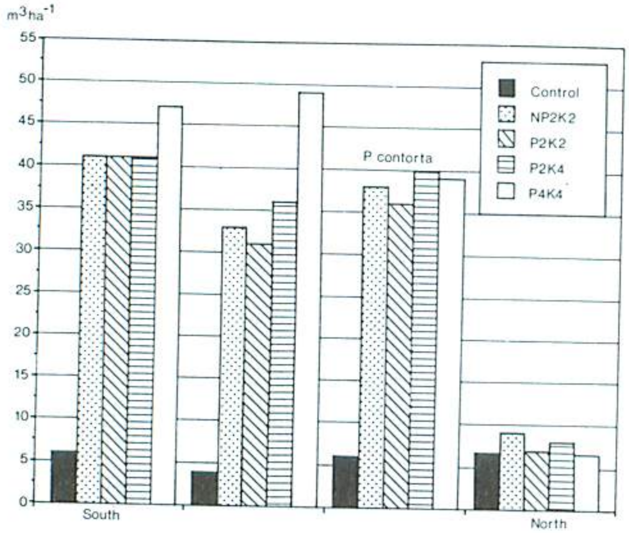

Figure 6. The effect of fertilization and climate on volume growth in four experimental areas in Sweden. The results refer to Scots pine, except for one area planted with lodgepole pine.

The decline in the length of the leading shoots may therefore be due to cooler conditions in the last few years. In the control plots, where no fertilizer is added, there seems to have been a slow decline over the last eight years; this may indicate that the drainage system is becoming less effective.

Soil Preparation

The seedlings that were planted in inverted peat had a better survival rate than did those on unprepared plots, and the volume was 30% higher on plots with inverted peat (Fig. 8). Mean height and diameter were correspondingly greater. Soil preparation seems to affect local drainage by ensuring better aeration and mineralization, since differences in growth are greatest at a ditch spacing of 60 m. On control plots (drained, but not fertilized) there was no difference in growth among seedlings planted on plots that underwent different soil preparation.

than those for Scots pine, partly, perhaps, because of a very successful provenance of lodgepole pine and partly because Scots pine has suffered from severe browsing by moose. Elsewhere, there were no large differences between species except in the most northerly area, Suoluvuoma, where Norway spruce, after a slow start because of frost problems, is now growing better than Scots pine. Also, many naturally regenerated birch (*Betula pubescens*) have become established in this area. Planted birch (*Betula verrucosa*) have been unsuccessful in all areas, and almost 100% of the seedlings have died.

Height

In the south, mean height of stands on fertilized plots was comparable to a site index for Scots pine of 24 m (at 100 yr) on mineral soils. For control plots the mean height was comparable to a site index for Scots pine of 14 m (at 100 yr) on mineral soils.

The growth increment of the leading shoots increased steadily until 1984, but declined thereafter (Fig. 7). It is too early to state whether this decline indicates that drainage and/or fertilization are not as effective as they had been. The length of the leadingshoots is very much influenced by temperature in August and September of the previous year. The deviation from the previous year's normal temperature is included in Figure 7.

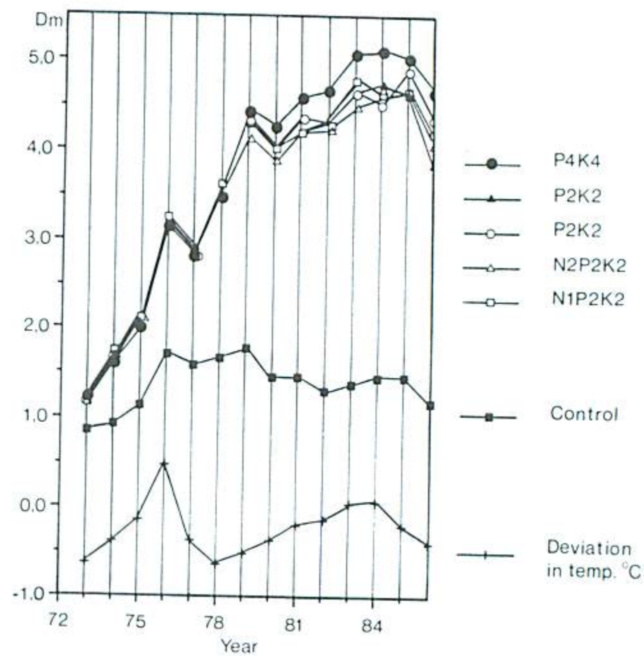

Figure 7. The length of the leading shoots in different years and for different fertilizers, as a mean value for all ditch spacings. The deviation of the previous year's mean temperature in August and September from a 30-year mean value is included (e.g., the deviation shown for 1986 is actually for the preceding year, 1985).

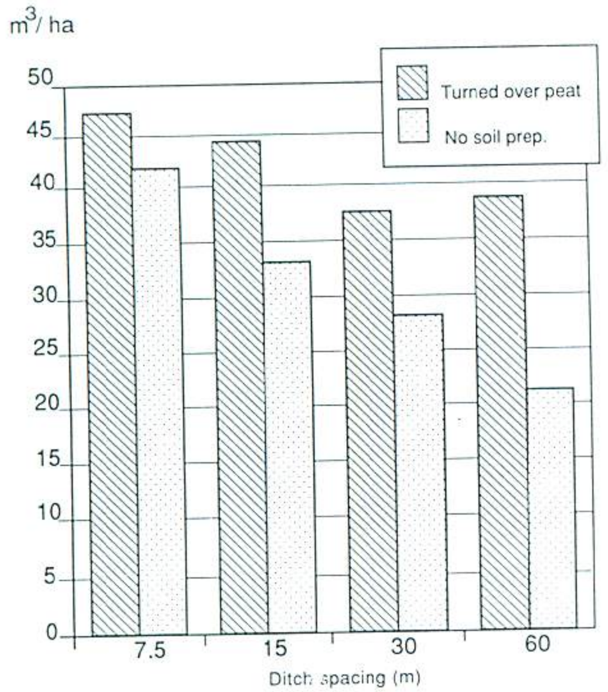

Figure 8. The effect of soil preparation and ditch spacing on volume growth. Means include both fertilized and unfertilized plots.

Damage

Many different types of damage have occurred, some specific to peatlands, others on both mineral soils and peat. As peat is not the best rooting substrate, basal sweep and windthrown trees are common. Lodgepole pine, especially, with its superficial root system, has a high proportion of basal sweep, up to 50% in some areas. This also occurs with Scots pine, but not as commonly as with lodgepole pine. On the other hand, Scots pine has been browsed severely by moose, and this has resulted in high proportions of spike knots and forks. In the north, 80% of Scots pine has been destroyed by moose. Browsing is not a typical peatland problem, however. Peatlands are often very susceptible to frost because they are in low-lying areas. Frost has been particularly hard on Norway spruce seedlings in the north, but many of these seedlings have reached a height at which they are less exposed to frost.

CONCLUSIONS

The two experiments discussed above have not yet been fully analyzed, but at this time we may draw some tentative conclusions.

The recently established experiment on afforestation of abandoned agricultural peatland shows that some type of soil preparation is necessary. The survival rate has so far been highest on mounded plots, especially for lodgepole pine and large Norway spruce seedlings. Competition from other vegetation, which seems to be the major problem, is less intense on mounded sites. There is also less risk of frost-damaged seedlings on mounds because the minimum temperature on top of the mounds is higher than that on an unprepared surface. However, if the mounds are too large they may not hold enough water for large seedlings. Birch, black spruce and small Norway spruce seedlings have had high mortality rates. Black spruce was expected to be very frost hardy, but this did not, in fact, happen. Browsing, especially by roe-deer, has been severe in some areas. In one area 95% of the seedlings were browsed, regardless of species.

The second experiment, established in 1971, deals with afforestation of nonproductive open peatland. The best conditions for forest production were found in the southern and central portions of the country. Volume production for Scots pine is four times higher in the south than in the north. Afforestation of nutrient-poor sites requires fertilization in addition to drainage. On plots treated with the highest doses of P and K, volume production was 6 to 10 times higher than on unfertilized plots. Results of needle analyses suggested that there may soon be a shortage of K. Adding N has had no effect on growth. Fertilization has led to significant improvements in site index, from 14 to 24 m (at 100 yr). Optimal ditch spacing was not determined, but the closer the spacing the better the growth. It is too early to say if growth has reached a maximum, or if ditch cleaning and refertilization are necessary. Soil preparation still has a positive effect on growth after 18 years.

The main problems observed in afforestation of open peatland are caused by wind, snow, frost and mammalian herbivores, primarily moose. One way to handle these problems is to choose the right tree species, but different species have different problems. Basal sweep, which is caused by wind and snow, is a common phenomenon in lodgepole pine. For Norway spruce, frost is the main problem in some regions, and Scots pine seems to be very attractive to moose.

Section IV
Peat Environments and Ecology

SUBSTRATE ENVIRONMENTS ON DRAINED AND UNDRAINED PEATLANDS, WALLY CREEK EXPERIMENTAL DRAINAGE AREA, COCHRANE, ONTARIO

R.L. Rothwell
Department Of Forest Science
University Of Alberta
Edmonton, Alberta
Canada

ABSTRACT

It was hypothesized that substrate environments vary with water table depth in drained areas. Soil temperature and water content were sampled in a variety of drained and undrained forest cover types. Results supported the hypothesis. Drained sites were 1 to 2°C warmer than undrained areas at depths of 0 to 60 cm. Temperatures at ditch edges averaged 2°C higher than those at midpoint locations between ditches. Water content in the surface 0 to 30 cm on a drained cutover was 8-9% greater than on an undrained cutover. The largest differences in water content occurred at depths of 20 to 30 cm, which coincided with water table depth on the undrained site. No significant differences were detected in water content between ditch edges and midpoint locations within the drained cutover.

RÉSUMÉ

On a posé comme hypothèse que les milieux du substratum varient selon la hauteur de la nappe phréatique dans les secteurs assainis. La température du sol et la teneur en eau ont été échantillonnées dans divers types forestiers drainés et non drainés. Les résultats corroborent notre hypothèse. Les stations assainies étaient de 1 à 2°C plus chaudes que les stations non drainées à des profondeurs de 0 à 60 cm. La température en bordure des fossés était en moyenne 2°C plus élevée que celle à mi-chemin entre deux fossés. La teneur en eau était de 8 à 9% plus élevée dans les 30 cm superficiels des parterres de coupe rase drainés que dans ceux non drainés. Les plus fortes différences de teneur en eau se retrouvaient à des profondeurs de 20 à 30 cm qui correspondaient à la hauteur de la nappe phréatique dans la station non drainée. Aucune différence significative de la teneur en eau n'a été décelée en bordure des fossés et à mi-chemin entre les fossés dans le parterre de coupe rase assaini.

INTRODUCTION

Peatland drainage is being considered as a means of improving tree growth and site productivity. In Canada, about 118 million ha of peatlands have been identified, most of which may be suitable for some kind of drainage (Tarnocai 1984). The lowering of the water table removes excess water and changes the physical properties of surface peats. Increased tree growth after drainage is attributed to improved substrate environments that result from decreased water content and increased aeration and substrate temperatures (Kaunisto and Päivänen 1985).

Drainage is a process that is usually achieved by means of open ditches that intercept shallow groundwater flow, collect it and carry it away from a site. The water table is not lowered uniformly, but follows a mounding pattern (Boelter 1965), with maximum depth at ditch edges and minimum depth at the midpoints between ditches. Lieffers and Rothwell (1987) observed differences of 5 to 40 cm in water table levels between ditch edges and midpoints in a drained fen. In view of these observations and the potential for capillary water movement in peat (Paavilainen and Virrankoski 1967), substrates in drained areas should vary with water table depth. Substrate environments in drained areas should be more extreme and more variable than those in undrained areas. Substrate water content should increase and soil temperature should decrease with distance from ditch edges (Fig. 1). The greatest increases in tree growth should be close to the ditches (Päivänen and Wells 1978).

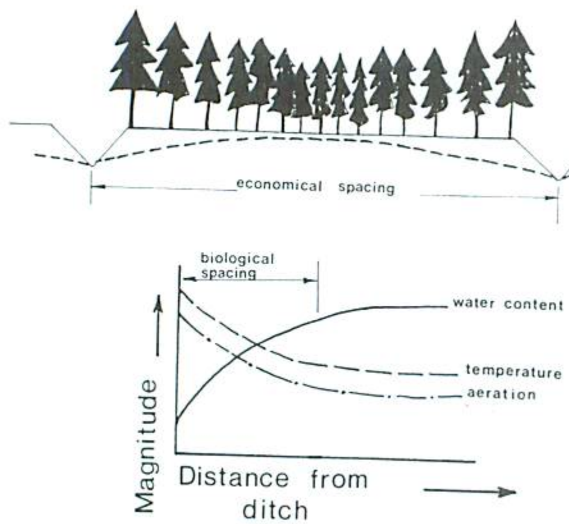

Figure 1. Biological ditch spacing is defined as the distance from the edge of the ditch at which changes in substrate parameters cease.

The effects of drainage on substrate environments and tree growth are determined largely by ditch spacing. The magnitude of water table reduction and substrate changes, for a given peat type, is greater with a narrow than with a wide ditch spacing. Ditch spacing is described by Päivänen and Wells (1978) as biologically optimal if it yields the best tree growth. Biological spacing can be further defined as the distance from ditch edges at which changes in substrate parameters cease or result in the equivalent of undrained conditions (Fig. 1). Biological spacing will vary from site to site, as it is affected by climate, slope and peat type and depth. Biological spacing will always be narrower than economical spacing, which yields the highest rate of interest in return for investments in drainage (Päivänen and Wells 1978). Management objectives for drainage should be to reduce the difference between biological and economic spacings as much as possible.

OBJECTIVES

The objectives of this study were to assess the effects of peatland drainage on substrate temperature and substrate water content, and to assess the variability of temperature and substrate water content in a drained peatland. The hypotheses tested were as follows: 1) substrate temperature is greater on drained peatlands than on undrained peatlands, 2) substrate water content is less on drained peatlands than on undrained peatlands, 3) substrate temperatures on drained peatlands are higher at ditch edges than at the midpoint between ditches, and 4) substrate water content on drained peatlands is less at ditch edges than at the midpoint between ditches.

METHODS

Study Site Description

The study was conducted in the Wally Creek Experimental Drainage Area, which is located in northern Ontario, Canada, 25 km east of the town of Cochrane. The approximate latitude and longitude of the site are 48° 52′ N and 80° 49′ W, respectively. The area is part of the Clay Belt Forest Section of the Boreal Forest of northern Ontario. The dominant tree species is black spruce (*Picea mariana*), which averages 10-15 m in height. The most common forest site type is Operational Group 11 (OG-11) (Jones et al. 1983), which is characterized by a closed canopy of black spruce with a shrub layer of Labrador tea (*Ledum groenlandicum*), blueberry (*Vaccinium myrtilloides*) and leatherleaf (*Chamaedaphne calyculata*).

The soils are organic, 40 to 160 cm thick, and overlie impermeable clay. Common moss species include *Sphagnum nemoreum*, *S. fuscum*, *S. magellanicum*, *S. girgensohnii*, *Pleurozium schreberi*, *Ptilium crista-castrensis*, and *Dicranum polysetum*.

The topography of the area is flat, with low runoff because of the deep surficial organic soil and impermeable clay soil at depth. The climate is characterized by cold winters and warm, moist summers. The mean annual temperature at Cochrane is between 0 and 1°C. Annual precipitation is between 685 and 715 mm, and is evenly distributed throughout the year.

Approximately 500 ha were drained by the Ontario Ministry of Natural Resources in 1984. Ditch spacings were 30 to 40 m on sparsely treed sites, 60 m on waterlogged mineral soil and 40 to 50 m on densely treed black spruce bog. Ditches were 1 m deep and 1.4 m wide.

Substrate Sampling

Substrates on drained and undrained peatlands were described in terms of temperature and water content. Temperatures were measured with a temperature probe containing five copper-constantan thermocouples threaded through a stainless tube to holes in which they were embedded in epoxy. The thermocouples were spaced to measure temperatures at depths of 10, 20, 30, 45 and 60 cm below the ground surface. The temperature probe was inserted in the ground and left for 5 to 10 minutes for thermocouples to equilibrate with the surrounding substrate temperature, and then voltages were read by means of an ice-point reference junction and multimeter with a resolution of 0.01 mV.

Substrate temperatures were measured at ditch edge and at midpoint locations between ditches along transects in a range of different forest cover types. Transects in most cases consisted of 10 sample points, with three replications at each point. Transects in undrained areas were established with the same spacing and number of points as in the drained areas. Sampling was done in 2- to 3-day periods, 13-17 June 1986 and 30 June-2 July 1986. Sampling on successive days was done at the same time each day to minimize confounding as a result of diurnal temperature variations. The different cover types sampled were as follows: undrained, uncut black spruce bog; drained, uncut black spruce bog; drained, cutover black spruce bog; undrained, cutover black spruce bog; and drained, uncut black spruce/tamarack (*Larix laricina*) fen.

The presence and frequency of frost were sampled by means of "walking transects", each of which consisted of 100 points. For each sample point an iron rod was inserted in the ground. In drained areas, half of the points were located along a drainage ditch and the remainder were located randomly between the ditches.

Substrate moisture content was sampled only on the drained and undrained cutover black spruce sites. The forested sites could not be sampled because of frost at depths of 25 to 30 cm. Samples were taken at ditch edge and midpoint locations to a depth of 30 cm with a sampler that was 15 cm in diameter and had a bandsaw blade attached to the lower edge. The sampler was inserted in the ground by rotating and pushing to obtain samples in 10-cm increments (volumes of 1767.2 cm^3). The sampler worked fairly well, but compression of the upper 0 to 10 cm was evident at all sample points, especially in the undrained area. Three replications were carried out at each sample point. Seven sample points were established in the drained area and four in the undrained.

Peat samples were bagged and sealed in plastic bags and transported to Forestry Canada, Ontario Region in Sault Ste. Marie, Ontario for analysis. Water contents were obtained by weighing the samples and oven-drying them. Water contents were expressed on a volumetric basis (i.e., g cm^{-3}).

Data Analysis

Differences in substrate environments among different forest cover types were compared by analysis of variance and Kruskal-Wallis' nonparametric 'one-way analysis of variance' with the SPSS/PC+ statistical package. A nonparametric test was used for substrate water content data because samples were not balanced between strata and could not be successfully transformed for normality or homogeneity of variances.

RESULTS AND DISCUSSION

Substrate Temperatures

Sampling was done from 14 to 17 June, on 30 June and on 1 July, 1986. Temperature profiles at all sites showed thermal stratification, with a warm surface layer and cold temperatures at depth (Fig. 2). Temperatures on the first sample date in the upper 0 to 20 cm varied from 6 to 14°C, while those at 20 to 60 cm varied from 2 to 9°C. By the second sample date warming was evident, with temperatures in the upper 0 to 20 cm 2 to 3°C higher while those at depth were still low, showing an increase of only 1 to 1.5°C from the earlier sample date.

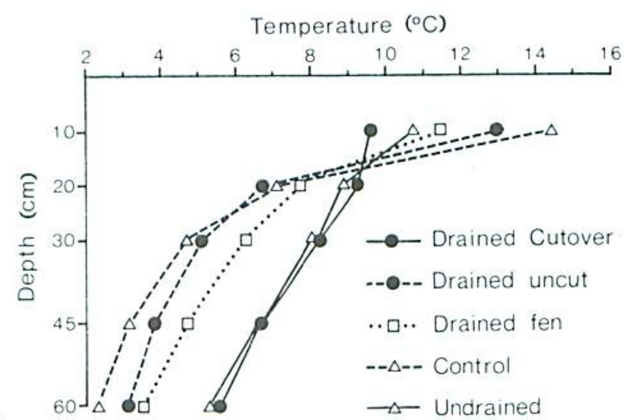

Figure 2. Soil temperature profiles for drained and undrained substrates, Wally Creek Experimental Drainage Area, 30 June 1986.

Drained vs Undrained

Soil temperatures were generally higher on the drained sites than on the undrained, uncut control site. The highest temperatures and greatest differences were observed on both the drained and the undrained cutovers (Table 1). Average soil temperatures for a depth of 0 to 60 cm on the drained and undrained cutovers were 7.94 and 7.86°C in comparison with 6.35 and 6.34°C on the drained fen and the undrained, uncut control. The drained, uncut black spruce was intermediate, with an average temperature of 6.73°C.

Table 1. Mean temperatures (°C) at a depth of 0 to 60 cm for drained and undrained substrates, Wally Creek Experimental Drainage Area, Cochrane, Ontario, Canada, 30 June 1986

Substrate	Mean[a]	SD	n
Drained cutover	7.94a	2.25	60
Undrained cutover	7.86a	2.04	60
Drained uncut	6.73ab	3.71	60
Drained fen	6.35b	4.02	60
Undrained uncut	6.34b	4.63	60

[a] Means with different letters are significantly different at the $p < 0.0$ level.

Examination of the results indicated that forest cutting and increased solar radiation were as important as drainage in causing higher substrate temperatures. Both the drained and the undrained cutovers were the warmest sites. The extra energy that reached the ground as a result of canopy removal made for extra warming, and probably contributed to the fact that there were no temperature differences between the drained and undrained cutovers. The lack of temperature differences between these areas can also be explained by the time of sampling. Lieffers and Rothwell (1987) observed earlier warming of undrained peat substrates in an Alberta fen; however, after early May, mean temperatures at depths of 10 and 30 cm on the drained site exceeded those on the undrained site. Temperatures on the drained site eventually increased because of its smaller heat capacity and thermal conductivity.

The method of sampling, which was intended primarily to test for differences between ditch and midpoint environments, may have affected the results as well. Drained and undrained conditions should be compared throughout the growing season so as to include both spatial and temporal variability. Sampling at ditch and midpoint locations represents the extremes, which may or may not equal average conditions. Furthermore, these observations are to some degree confounded by differences that occurred because sampling was done on successive days for 2- or 3-day periods.

Ditch vs Midpoints

Soil temperatures at ditch edges were found to be significantly higher than those at midpoint locations (Table 2). Air temperatures at ditch edges were 2°C higher than those at midpoints (Fig. 3). The greatest differences were on the drained cutover, where temperatures at depths of 0 to 60 cm ranged from 11.56 to 4.7°C at ditch edges and from 10.6 to 4.1°C at midpoint locations. Temperatures at depths of 0 to 60 cm in the drained, uncut black spruce varied from 10.33 to 2.91°C at ditch edges and from 9.6 to 2.4°C at midpoints. No significant differences were detected between ditch edges and midpoints in the fen.

Table 2. Mean temperatures (0°C) at depths of 0 to 60 cm for ditch edge and midpoint substrates, Wally Creek Experimental Drainage Area, Cochrane, Ontario, Canada, 30 June 1986

	Ditch		Midpoint	
Substrate	Mean	SD	Mean	SD
Drained cutover[a]	8.86	1.59	6.86	1.97
Drained uncut[a]	7.51	3.99	5.18	3.76
Drained fen	6.84	3.64	6.61	3.85

[a] Ditch and midpoint means significantly different at the $p = 0.05$ level.

The higher temperatures at ditch edges were attributed to greater exposure to solar radiation and reduced substrate water content at ditch edges. The lower temperatures at midpoint locations were attributed to shading, higher water content and the presence of frost. The low temperatures in the fen and the lack of difference in temperatures between ditch and midpoints were surprising. Higher temperatures were expected because of the open and thin forest canopy in the fen. The lower temperatures may be explained by better surface insulation because of thicker, fluffier surface moss layers in the fen than in the black spruce types. Sampling may also be confounded by the distribution of frost along ditch edges. Frost was four to five times more frequent on north-facing than on south-facing ditch edges in the fen. This was not a problem in the black spruce types because ditches were oriented north-south or were shaded by vegetation.

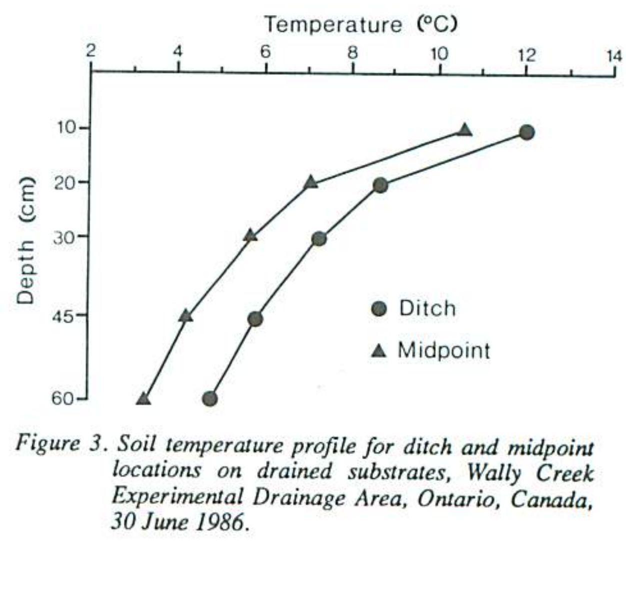

Figure 3. Soil temperature profile for ditch and midpoint locations on drained substrates, Wally Creek Experimental Drainage Area, Ontario, Canada, 30 June 1986.

Substrate Water Contents

Substrate water contents were 8-9% higher on the undrained cutover than on the drained cutover (Table 3). Average water content for the surface 0 to 30 cm on the undrained cutover was 0.398 g cm^{-3} in comparison with 0.315 g cm^{-3} on the drained site. The largest difference in water content was 14-15% at depths of 20 to 30 cm, which coincided with water table depths of 20 to 26 cm on the undrained cutover. Water table depth in the drained area varied from 80 to 50 cm between ditch edges and midpoints.

Substrate water contents at the ditch edges were consistently lower than those at the midpoint locations (Table 3). Average water content at depths of 0 to 30 cm at ditch edges was 0.299 g cm^{-3} in comparison with 0.336 g cm^{-3} at the midpoint locations. The differences between ditch edges and midpoints were similar at all depths, and ranged from 0.13 to 0.17 and from 0.46 to 0.49 at depths of 0 to 20 cm and 20 to 30 cm, respectively. However, no statistically significant difference was detected in substrate water content between ditch and midpoint locations within the drained cutover.

The absence of significant differences in substrate water contents on the drained site was attributed to the time of year and frequency of precipitation. Sampling was done in spring and early summer when peat substrates were still moist from snowmelt and temperatures were still cool. Furthermore, precipitation occurred every 4-5 days during the study, and this kept surface peats wet or moist. The effects of drainage should become more apparent later in the season when temperatures and evaporative demands are higher.

Another factor contributing to these results was sampling variability. Coefficients of variation ranged from 30 to 60%. To sample for differences of 5 to 10% in water content with the variability encountered in this study, sample volumes two to three times larger than those taken would be needed. Additional information on water table depths and peat water-retention characteristics would facilitate interpretation of these data.

CONCLUSIONS

Substrate temperatures for depths of 0 to 60 cm were 1 to 2°C higher on the drained sites than on the undrained, uncut control. Increased temperatures were ostensibly a result of the removal of excess water and resultant changes in thermal properties of the drained peat. Comparison of drained and undrained cutovers indicated that removal of the forest canopy can be equally effective in increasing substrate temperatures. Increased solar radiation appeared to compensate for differences in groundwater levels and water contents between drained and undrained sites.

Substrate temperatures at ditch edges averaged 2°C higher than those at midpoints between ditches for the drained cutover and uncut black spruce sites. No differences between ditch edges and midpoints were detected for the fen, possibly because of deeper, fluffier, surface moss layers and better insulation.

Substrate water contents at depths of 0 to 30 cm were 8-9% greater, by volume, on the undrained than on the drained cutover. The largest differences were at depths of 20 to 30 cm, which coincided with water-table depth in the undrained area. The differences were attributed to drainage.

However, no significant differences in substrate water content were observed between ditch and midpoint locations. Differences between these two locations averaged 2 to 3% by volume. The absence of differences was attributed to the time of year, sampling variability and frequent precipitation.

Table 3. Results (probabilities) of Kruskal-Wallis one-way analysis of variance for volumetric substrate water content (g cm^{-3}) on drained and undrained peatlands in the Wally Creek Experimental Drainage Area, Ontario, June 1986

	Drained			Undrained			
Depth (cm)	Mean	SD	n	Mean	SD	n	p
0-30	0.3150	0.193	56	0.3988	0.234	32	0.0210[a]
0-20	0.1496	0.059	28	0.1763	0.028	16	0.0200[a]
20-30	0.4807	0.129	28	0.6213	0.084	16	0.0002[a]
	Ditch edges			**Midpoints**			
Depth (cm)	Mean	SD	n	Mean	SD	n	p
0-30	0.2991	0.186	64	0.3367	0.203	48	0.4074
0-20	0.1300	0.046	32	0.1758	0.067	24	0.0803
20-30	0.4681	0.092	32	0.4975	0.160	24	0.2956

[a] Means are significantly different at $p < 0.05$.

These results support the hypothesis that substrate environments vary with water-table depth in a drained area, and are important for understanding and predicting the effects of drainage on tree growth. Tryon and Chapin (1983) and others (Heikurainen and Laine 1976, Van Cleve et al. 1983, Lieffers and Rothwell 1986) report substrate temperature and its interaction with other site parameters as critical factors in controlling forest productivity.

The results of this study should be regarded as preliminary. Sampling was done early when differences in temperature and water content were small in comparison with what might be expected later in the growing season as a result of increased temperatures and evaporation. Furthermore, detection of the effects of drainage was more involved than initially assumed. A more complete assessment should include a detailed look at the temporal and spatial variability of substrate temperature and water content throughout the growing season.

ACKNOWLEDGMENTS

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RELATION BETWEEN TREE ROOTS AND SOIL AERATION ON DRAINED PEATLANDS

H. Mannerkoski
Faculty of Forestry
University of Joensuu
Joensuu, Finland

ABSTRACT

Available studies on soil aeration and tree roots on drained peatlands are reviewed. The lowest level of living root tips is directly related to the level of the groundwater table, but the average depth of the root system, weighted by root mass or length, is affected very slowly and only slightly by a change in the groundwater table. Hence, the root systems are very superficial, mainly because of the continual fluctuation of the groundwater table, as short-lived high water table levels can restrict root growth. Because of the natural stratigraphy of the surface peat, i.e., more decomposed layers below a slightly decomposed surface, lowering the water table in this well decomposed layer does not ensure that sufficient macropores are drained for good aeration and root growth.

RÉSUMÉ

Le présent document fait le tour des données existantes provenant d'études sur l'aération du sol et les racines des arbres dans les tourbières drainées. Le niveau le plus bas qu'atteint l'extrémité des racines vivantes est à peu près celui de la nappe phréatique, et la profondeur moyenne du système racinaire pondérée par la masse ou la longueur des racines se modifie très lentement et très légèrement à la suite d'un changement de niveau de la nappe d'eau souterraine. Il s'ensuit que les systèmes racinaires sont très superficiels, surtout en raison des fluctuations continuelles de la nappe phréatique, qui, lorsqu'elle atteint des niveaux élevés, même de brève durée, peut limiter la croissance des racines. En raison de la stratification naturelle de la tourbe superficielle (c'est-à-dire que les couches plus décomposées se trouvent sous une couche superficielle légèrement décomposée), un abaissement de la nappe phréatique dans la couche bien décomposée ne vide pas suffisamment de macropores pour permettre une bonne aération et assurer une croissance adéquate des racines.

INTRODUCTION

On natural peatlands the growth of trees is often very poor, for at least two reasons. The most important is the wetness of the soil. The groundwater can be very near or even on the soil surface (e.g., Lähde 1969). In such cases, the surface peat is almost saturated or totally saturated with water and there is practically no available pore space in the peat for soil aeration (e.g., Päivänen 1973, Mannerkoski 1985). Oxygen diffusion in water is sufficient only for the roots that extend a few centimetres into the saturated layer. The roots of our most important tree species, Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), do not grow on anoxic media like many wetland species that have aerenchyma (e.g., Coutts and Armstrong 1976). In many peatlands the poor nutrient status of the soil can also limit growth.

Excess water can be drained quite easily by digging ditches. Theoretically, it is possible to regulate water conditions in peat so that they are optimum for tree growth. In practice, the irregular fluctuations of the groundwater table, and moisture conditions in the rooting zone, make such regulation very difficult. However, after drainage, more pore space is free of water for aeration (cf. Paavilainen 1967), and the roots of trees can grow more deeply into the peat (e.g., Heikurainen 1955, Paavilainen 1966a, Boggie 1972). The improved oxygen status of the surface peat permits better root growth and water and nutrient absorption by the roots (e.g., Glinski and Stepniewski 1985).

The purpose of this paper is to review and evaluate the effects of drainage on root systems, root growth of trees, and conditions of soil aeration in peatlands as reported in European (especially Finnish) studies.

MATERIAL SOIL AERATION

A measure of soil aeration can be obtained by calculating the air-filled pore space, i.e., subtracting the volume wetness of soil from total porosity. Paavilainen (1967) did this in a study of Scots pine roots on plots surrounded by ditches with different adjusted water levels (10, 30, and 50 cm from the peat surface). Aeration in peat can be described by using silver rods to measure the aerobic limit. Lähde (1969) used these rods and root-penetration measurements, both on natural peatlands of three different site types and on their old drainage areas, at different distances from the ditches.

With platinum microelectrodes, short-lived changes in soil aeration can be monitored by measuring the diffusion flux of oxygen and the oxygen diffusion rate (ODR) (Glinski and Stepniewski 1985, Mannerkoski 1985). Mannerkoski (1985) studied the effects of water-table fluctuation on aeration in the soil and the growth of Scots pine and birch (*Betula pendula*) seedlings on a peat substrate in the greenhouse. The pots were filled with milled and fertilized *Sphagnum* peat pressed almost to its natural bulk density. Water-table regimes consisting of depths of 10, 25, 50, 10 ± 10, 25 ± 10, 50 ± 10, 25 ± 20 and 50 ± 20 cm were established, and the length of the fluctuation cycle was 14 days.

In the United Kingdom, Boggie (1972, 1977) measured soil aeration (air volume, redox potential, and aerobic limit) and tree roots in a blanket bog area on five plots surrounded by ditches, in which the water was artificially maintained at certain levels. The plots were planted with lodgepole pine (*Pinus contorta* var. *latifolia*) transplants and some plots were fertilized (NPK).

TREE ROOTS

Because the roots of trees growing on drained peatlands are usually studied from small soil samples, the thickest parts of the root systems are left out; in such studies no information can be obtained about the form of the root systems of individual trees. The first extensive study of tree roots on drained peatlands was made by Heikurainen (1955), whose sample plots were located on 12 low-shrub pine bogs drained 20-40 years before. On seven plots the depth of the groundwater table was measured, and one undrained area was used for reference. Paavilainen (1966a) studied the roots of Scots pine in several experimental fields with different strip widths and sample plots surrounded by ditches that had different adjusted levels of water. In addition, he studied the roots of Norway spruce and birch (*Betula pubescens*) on a 50-year-old drainage area of a *Vaccinium myrtillus*-spruce swamp site (Paavilainen 1966b).

Ford and Deans (1977) studied the root development of Sitka spruce (*Picea sitchensis*) in the United Kingdom on an extremely humid, southern boreal climatic type (annual rainfall about 1800 mm) on blanket peat 10 years after planting. Boggie (1972, 1977) examined the roots of lodgepole pine. Coutts and Philipson (1978a,b) conducted special root-growth studies with lodgepole pine and Sitka spruce in a greenhouse.

Kaunisto (1972) studied the effect of soil preparation and fertilization on the root development of Scots pine and Norway spruce seedlings in greenhouse pot experiments. He adjusted the water table in the growing medium to constant levels (10, 29, 47 and 60 cm). Mannerkoski (1985) examined the roots of Scots pine and birch seedlings at the end of his experiments.

RESULTS

Soil Aeration

On natural peatlands the soil is well aerated only in the very shallow surface layer. For most of the year, especially on open peatlands, the soil is anaerobic from the surface downwards (Lähde 1969). The groundwater table in peatlands can be lowered by drainage, which always improves aeration in peat. This can be seen in the lower aerobic limit (Lähde 1969, Boggie 1972, Mannerkoski 1985) and in the increased volume of air-filled pores (Paavilainen 1967, Boggie 1977), oxygen concentration in soil air (Boggie 1977), or oxygen diffusion rate (Mannerkoski 1985) in soil surface peat. After ditches are dug, the nearer the layer to the water table (Paavilainen 1967), or the higher the bulk density of peat (Fig. 1 and Päivänen 1973), the less the volume of air in the peat .

In practical forest drainage operations the groundwater table (expressed as the average for the growing season) in the humid climate of Finland can be lowered to a depth of about 20 to 30 cm in the mid-strip between ditches (e.g., Heikurainen 1955, 1980). The yearly fluctuation of the water table is great (e.g., Lähde 1969,

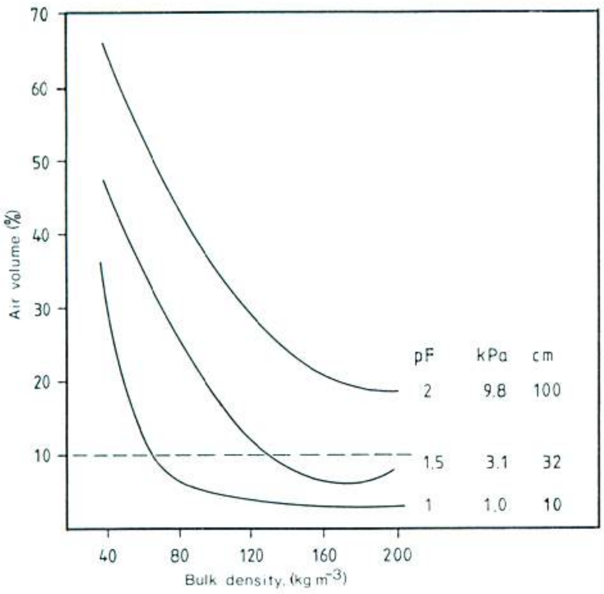

Figure 1. Volume of air-filled pores in relation to bulk density at different water-potential levels in Sphagnum *peat (drawn from the results of Päivänen 1973).*

Heikurainen 1980, Mannerkoski 1985), and it is followed by fluctuating aeration conditions. This can be seen in the depth of the aerobic limit, although this change may be delayed by several days (Lähde 1969). This delaying effect has also been found in the ODR measurements of Mannerkoski (1985), and is partly caused by hysteresis (Fig. 2). The rainwater that flows down to the groundwater also transfers dissolved oxygen, though usually not in very significant amounts (cf. Glinski and Stepniewski 1985).

For most of the growing season good aeration can be obtained only in a relatively shallow surface layer of peat. An air volume of 10%, usually considered the minimum for satisfactory root growth (e.g., Päivänen 1973), will be found at a depth of 10-15 cm when the groundwater table is 25 cm deep, and at a depth of 15-20 cm when the groundwater table is 58 cm deep (Paavilainen 1967). Important in this context is the degree of decomposition of the peat, which is related to bulk density. The higher the bulk density, the smaller the free-pore volume for aeration at a certain distance from the groundwater table (Fig. 1). In the natural stratigraphy of peat the slightly decomposed surface layers lie on top of the more decomposed lower layers.

Roots and their Relation to Aeration

On natural peatlands the root systems of trees like Scots pine and Norway spruce are very superficial. Lähde (1969) found living root tips only to a depth of 10-20 cm. The effect of drainage can be seen as an

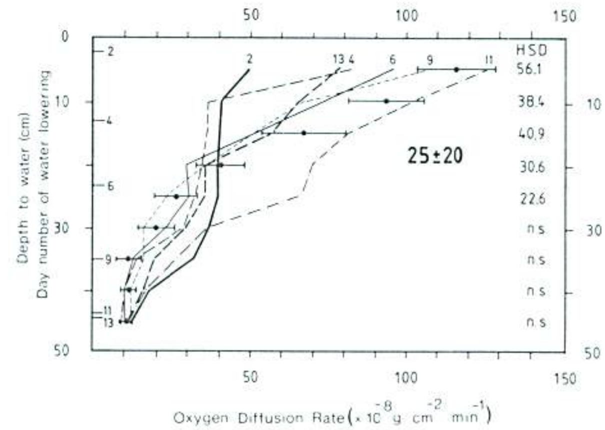

Figure 2. Mean depth profiles for the oxygen diffusion rate measured in water-table treatment 25 ± 20 cm at different times during the lowering of the water table (lines marked with numbers of days after day one when the water table was highest and then was allowed to drop), and in the constant 25-cm treatment with 95% confidence limits (⊢⊣). The mean depth of the water table on corresponding days is marked on the left ordinate. On the right the test value (HSD) for Tukey's range test (5% risk level) is given, if any significant differences occur between D.D.R. values in the depth layer in question (n.s. = no significant differences).

increase in both the vertical reach of living root tips and the quantity of roots. Most tree roots are thin; 70-95% (Paavilainen 1966a), or 85% on average (Heikurainen 1955), of the total length of Scots pine roots are under 1 mm in diameter. In drained peatlands the root systems are very superficial, too; usually over 90% of the roots can be found in the top 10 cm, and the quantity of roots growing into the deeper layers can be increased by very effective drainage (Fig. 3).

Living root tips of Scots pine can be found under the water table, if it is not more than 20-30 cm from the surface of the peat. This can be explained by the fact that Scots pine roots are poor conductors of oxygen (Coutts and Armstrong 1976), and that the distance from the free atmosphere to the water table is short. If the water table is deeper, the vertical reach of the root tips varies; in Scots pine and Norway spruce it is usually 5-20 cm above the water table (Fig. 4, Paavilainen 1966a,b; Lähde 1969, Mannerkoski 1985). The root tips will follow the largest macropores to those depths. The root tips of lodgepole pine can always grow 10-25 cm below the water table (Boggie 1972), because the roots can conduct oxygen quite well (Coutts and Armstrong 1976, Coutts and Philipson 1978b). The deeper the groundwater table, the deeper the living root tips can be found. In experiments concerned with regulation of the ditch water table, in

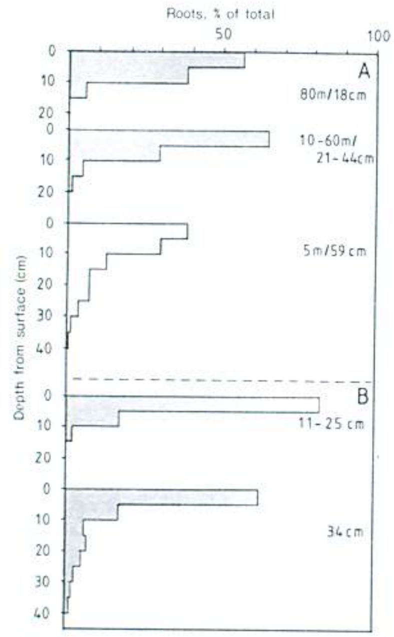

Figure 3. Depth profiles of (A) Scots pine roots (length of all roots in 4 x 5 x 5 cm^3 samples) on cotton grass pine bog with different strip-width treatments (strip-width/average depth of groundwater table) (Paavilainen 1966a), and (B) lodgepole pine roots (dry mass of all roots found in 15 x 15 x 5 m^3 samples midway between the trees) on blanket peat with different average water table levels (Boggie 1972).

In field conditions the weighted (by length of roots) average depth of roots is very low (3-6 cm) (Fig. 5, Heikurainen 1955; Paavilainen 1966a,b). The average depth is affected slightly by depth to water table, except in experiments on regulation of the ditch water table (Paavilainen 1966a,b). In greenhouse experiments with seedlings the relation between root depth and depth to water table is much clearer, especially if the water table has not fluctuated (Mannerkoski 1985). In the field, the laterally growing root tips of young trees are better able than the horizontal roots of old trees to follow the lowering of the groundwater table. In the greenhouse, fluctuation of the water table appeared to restrict root growth to the surface layers (Fig. 6 and Mannerkoski 1985). In the field, continuous fluctuation of the groundwater table can be one reason for the superficial root systems found on drained peatlands.

CONCLUSIONS

Numerous studies of tree roots on drained peatlands indicate that the rooting layer is very thin and cannot be made much deeper by practical drainage operations. This is because of aeration conditions in the peat, which are the result of peat stratigraphy, fluctuation of the groundwater table, and the presence of mineral nutrients available to plants in the superficial soil layers. Although the general outlines seem clear, there are many areas drained long before the start of the experiment, there was no evidence of this effect (Paavilainen 1966a,b) because the lateral roots were no longer able to grow more deeply. In greenhouse experiments, mixing of fertilizers in the peat soil increased the vertical reach of tree roots (Kaunisto 1972).

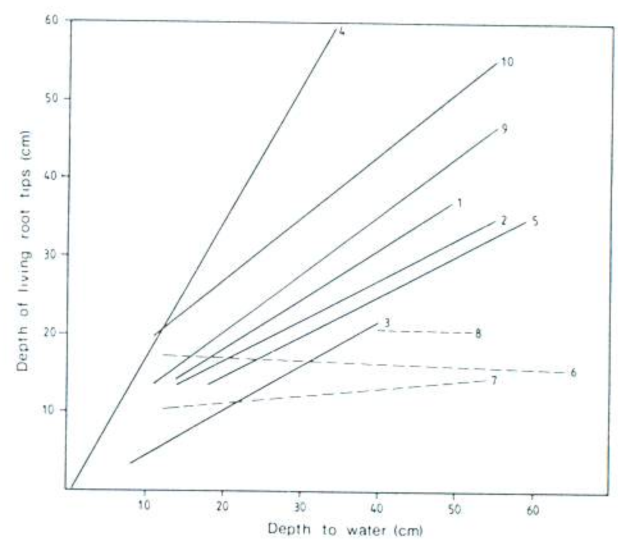

Figure 4. Vertical reach of the living root tips of some tree species in relation to depth of the groundwater table under different growing conditions: 1 = Scots pine, low-shrub pine bog, 2 = Norway spruce, Vaccinium myrtillus*-spruce swamp, 3 = Scots pine, small-sedge* S. papillosum *bog (Lähde 1969), 4 = lodgepole pine, blanket bog (Boggie 1972), 5 = Scots pine, cotton grass pine bog, 6 = Scots pine, low-shrubby cotton grass pine bog, 7 = Scots pine, herb-rich sedge birch-pine swamp, 8 = Scots pine, low-shrubby cotton grass pine bog (Paavilainen 1966a), 9 = Scots pine, and 10 = birch seedlings in greenhouse (Mannerkoski 1985). Conditions 4, 6, and 7 are from experiments on regulation of the level of ditch water, 5 and 8 are from strip-width experiments, and 6 and 8 from bogs that were drained long before the start of the experiment.*

In some studies of rooting depth, a 'weighted average depth' has been calculated, usually on the basis of length, but sometimes on the basis of the root dry mass (e.g., Boggie 1972, Mannerkoski 1985, see Fig. 5). Equation (1) gives the formula for calculating weighted average depth:

$$D = \frac{S}{i}(D_i \times R_i) / \frac{S}{i} R_i \quad (1)$$

where D_i = the average depth of the layer i, and R_i the amount (length, mass) of roots in the layer i.

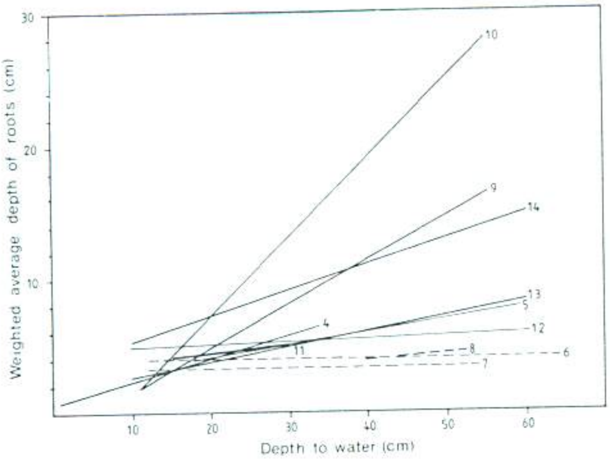

Figure 5. The weighted (by length of all roots) average depth of the roots of some tree species in relation to depth of groundwater table under different growing conditions: 1 to 10, see Fig. 4, 11 = Scots pine, low-shrub pine bog (Heikurainen 1955), 12 = Scots pine seedlings in greenhouse, planted in a natural peat block, 13 = the same but peat fertilized on the surface, and 14 = the same as 13, but fertilizer was mixed into the 20-cm-thick layer after grinding, milling, or cutting (Kaunisto 1972). There was no significant regression for lines 6, 7 and 8.

unknown factors. The root systems of single trees, especially trees of different ages and sizes, should be studied. In addition, the relation of root systems and soil aeration to peat stratigraphy need to be studied in the field. At present we have only a hypothesis drawn from the results of other studies. The root systems of the trees should also be monitored continuously, beginning at the time of drainage. Results referred to in this context are valid only for the tree species mentioned.

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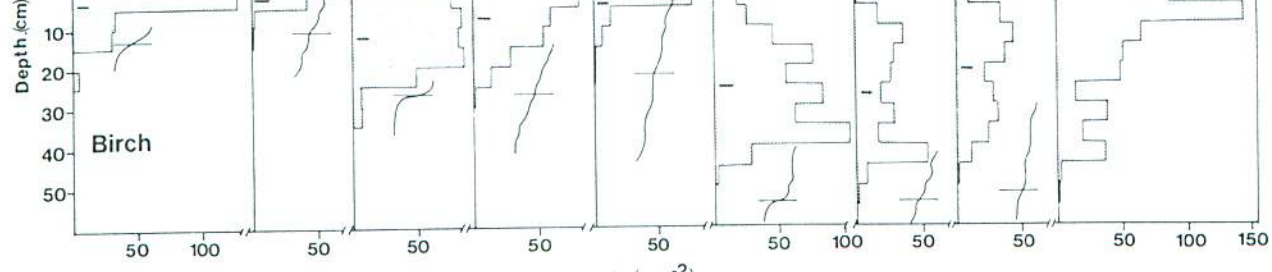

Figure 6. The weighted (by dry mass of roots) average depth of the roots has been marked with a short bar inside the shaded area, as well as a curve, showing the relative duration of the water table at different depths in the peat. The level of the horizontal line crossing it shows the measured average depth of the water table in the treatment, and its length equals the duration of the experiment (490 days). HSD is the test value for Tukey's range test between (treatments.

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DISTRIBUTION AND ABUNDANCE OF TESTATE AMOEBAE (PROTOZOA) IN THE WALLY CREEK WATERSHED, NORTHEASTERN ONTARIO

B.G. Warner
Department Of Earth Sciences And Quaternary Sciences Institute
University Of Waterloo
Waterloo, Ontario
Canada

ABSTRACT

Four Forest Ecosystem Classification (FEC) Operational Groups (OGs) are represented within the Wally Creek Watershed in northeastern Ontario. Each of the OGs contains a characteristic testate-amoebae (Protozoa) soil microfauna, with *Assulina muscorum* and *Nebela militaris* the most frequently occurring species. The testate amoebae show a rapid change in abundance in response to drainage. Species characteristic of dry microsites, such as *Nebela militaris* and *Hyalosphenia subflava*, are more abundant on drained sites than on undrained sites. Other species, such as *Nebela parvula*, are indifferent to microsite type, showing marked increases in abundance on drained sites in OG8, OG12 and OG14, but showing less of a difference within OG11.

RÉSUMÉ

Quatre groupes opérationnels (GO) de la classification des écosystèmes forestiers (CEF) sont représentés à l'intérieur du bassin hydrographique du ruisseau Wally dans le nord-est de l'Ontario. Chacun de ces GO contient une microfaune de sol à protozoaires amiboïdes à test caractéristiques, *Aussulina muscorum* et *Nebela militaris* étant les espèces les plus fréquentes. L'abondance des amibes à test change rapidement en réaction au drainage. Les espèces caractéristiques des microsites arides, comme *Nebela militaris* et *Hyalosphenia subflava*, sont plus abondantes dans les stations drainées que dans les stations non drainées. D'autres espèces comme *Nebela parvula* sont indifférentes au type de microsite, avec une augmentation marquée au niveau de l'abondance dans les stations drainées en GO8, GO12 et GO14, mais avec une moins grande différence dans GO11.

INTRODUCTION

Testate amoebae are a group of amoeboid protozoa with a discrete shell enclosing the cytoplasm. The shell is composed of layers of organic material secreted by the amoebae, siliceous or calcareous plates fitted together, and mineral grains, fungal hyphae, or diatom frustules incorporated during shell formation. These characteristics render the shell taxonomically diagnostic at the species level.

Testate amoebae are universal in distribution. They are found in fresh water, forest-floor litter, damp soil, and mossy habitats, especially with *Sphagnum*, and constitute a major component of the microfauna in bogs.

There are probably about 40 species of testate amoebae in the peatlands of Ontario. Many species are restricted to specialized ecological niches. For example, *Sphagnum fuscum* hummocks may contain a fauna quite different from that found in *S. magellanicum* at the base of the hummock, or that found in *S. pulchrum* submerged in pools. From what little we know about the North American fauna, we conclude that there seems to be a close relationship between site moisture regime on the one hand, and distribution and character of protozoan communities in *Sphagnum* on the other.

Both the narrow ecological requirements of the animals and their abundance indicate great potential for the use of testate amoebae as indicators of hydrological conditions in peatlands. The shells are resistant to decay and may be preserved for thousands of years. Consequently, hydrological changes in bogs, natural or man-induced, can be traced over longer periods than is often possible by means of continuous field observations.

This project was initiated as a test of the use of testate amoebae in characterizing various peatland site types represented in and around the Wally Creek Watershed, and in indicating environmental changes that result from drainage for peatland forestry. This paper gives some preliminary results, which suggest that the various Forest Ecosystem Classification (FEC) sites represented within the Wally Creek Watershed contain a characteristic testate-amoebae fauna that has responded rapidly to drainage of the peatland. Testate amoebae have the potential to be powerful indicators of forest peatland site-type classifications and monitors of both short- and long-term environmental changes that result from forest harvesting and drainage.

Figure 1. View of OG14 in the Wally Creek Watershed.

Figure 2. View of OG8 in the Wally Creek Watershed.

STUDY SITE

In all, 14 FEC Operational Groups (OGs) are identified in the Clay Belt region of Ontario on the basis of forest vegetation and soil characteristics (Jones et al. 1983). Four of these OGs are characteristic of lowlands in the region and are represented in the Wally Creek Watershed (Fig. 1 and 2): OG8, Feathermoss-*Sphagnum*; OG11, *Ledum*; OG12, *Alnus*-herb poor; and OG14 *Chamaedaphne*. Detailed descriptions of vegetation and soil characteristics are given in Jones et al. (ibid.). Numerous permanent growth plots have been established and described in terms of vegetation, peat profiles, and forest conditions (e.g., Rosen 1986, Jeglum 1990).

A large portion of the experimental area has been drained in both cleared and forested parts of the bog, with ditch spacings ranging from 15 to 75 m (Fig. 3). A series of control plots has been established in undrained parts of the watershed and in nearby natural peatlands, including bogs and fens, outside the main Wally Creek experimental area.

Figure 3. Drained area in the Wally Creek Watershed.

METHODS

Information on vegetation composition and cover, and on various chemical, hydrological, physical and temperature characteristics of the peat soil, has been collected from each plot. Subsamples of the surface 10 cm of the peat have been examined for testate amoebae. The ecological data are important for determining the distribution and composition of testate-amoebae communities in the Wally Creek Watershed.

Peat samples were cut with a short core-box sampler similar to that described in Cutler and Malcolm (1979). In all, 500 samples were collected for testate-amoebae analyses. The present paper provides the results of analyses of 115 samples, 84 of which proved to contain testate amoebae. They are representative of the four FEC OGs in the study area, on drained test sites, and on natural *Sphagnum fuscum* treed bog and *Carex oligosperma* poor treed fen plots adjacent to the main experimental area.

Subsamples of peat, each 3 cm^3, were taken out of larger samples from the box sampler for analyses of testate amoebae. Each sample was inoculated with a known quantity of *Lycopodium clavatum* spores (90,000 to 100,000 spores) at the outset of processing. Laboratory processing of peat samples, and counting, identification, and calculation of numbers of shells, follow the procedures of Tolonen (1986) and Warner (1987, 1988).

RESULTS

In all, 26 species or species groups were encountered in the samples from the Wally Creek Watershed (Fig. 4). The number of species per sample ranged from 3 to 21 ($\bar{\chi}$ = 14.3; s = 3.8). *Assulina muscorum* was the most characteristic component of the fauna, occurring in 95.3% of the samples. *Nebela militaris* shows the next most frequent occurrence in 91% of the samples. In order of decreasing frequency of occurrence, *Corythion dubium*, *Centropyxis arcelloides*-type, *Trinema lineare*, *Hyalosphenia ovalis*, *Euglypha tuberculata*-type, and *Nebela parvula* were found.

The total number of shells estimated per cm^3 varied from 55 to 16,697 ($\bar{\chi}$ = 3,046). Figure 5 illustrates the abundance of key species in relation to the study sites and OG classifications.

Figure 4. Selected testate amoebae found in the Wally Creek Watershed. (a) Assulina muscorum, *(b)* Amphitrema flavum, *(c)* Trinema lineare, *(d)* Hyalosphenia papilio, *(e)* H. subflava, *and (f)* H. elegans. *Scale bars equal 20 µm.*

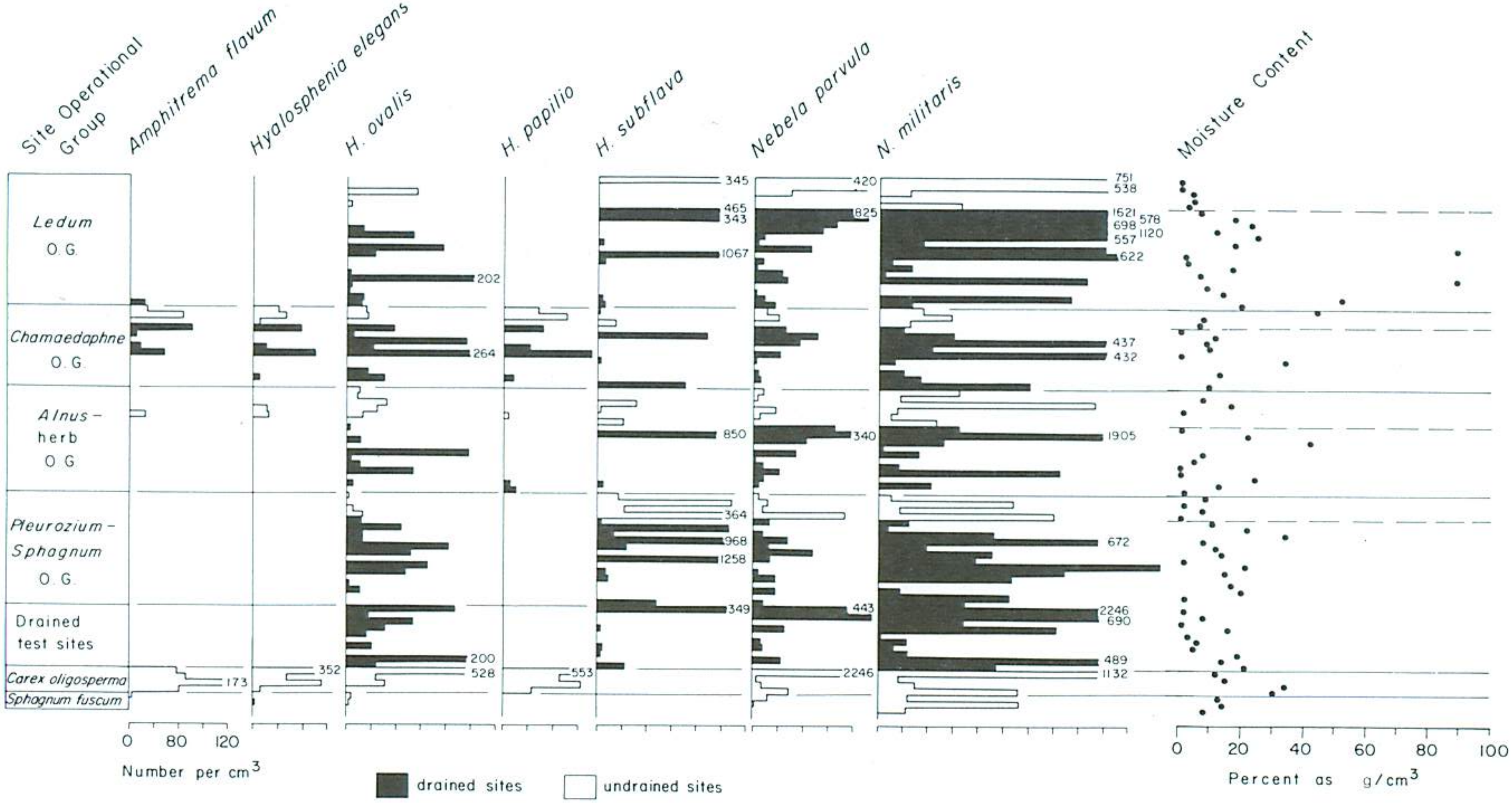

Figure 5. Graphic representation of the relative abundance of selected testate amoebae in the Wally Creek Watershed on drained and undrained sites. The soil moisture content of microsites at the time of sampling is also shown.

Hyalosphenia ovalis, *H. subflava*, *Nebela parvula* and *N. militaris* are common components of most sites in all OGs. *Nebela militaris* is less frequent in OG12 and OG14. *Hyalosphenia subflava*, though present on many plots, is more common in OG8 and OG11. *Amphitrema flavum*, *Hyalosphenia papilio*, and *H. elegans* are best represented in OG14 and on the natural *Carex oligosperma* plots.

In some instances, certain species show a change in abundance between undrained and drained plots (Table 1). *Hyalosphenia ovalis*, *Nebela parvula* and *N. militaris* tend to be less abundant on undrained plots than on their drained counterparts, especially in OG12 and OG14. *Hyalosphenia ovalis* appears in markedly lower numbers on the undrained than on the drained plots in OG8. The same seems to apply to *Nebela militaris* in OG14. *Nebela parvula* is common at Wally Creek, but its abundance is not affected by specific vegetational habitats. However, there are marked differences in its abundance on drained and undrained plots within any single OG type (Table 1).

DISCUSSION

The main features to note in these preliminary data are that plots within the various OGs and other site types contain characteristic faunas, particularly OG14, the *Carex oligosperma* and *Sphagnum fuscum* types, and that the abundance of various species within certain OGs differs on drained and undrained plots. More detailed analyses and statistical treatments of the data are needed to confirm or refine these observations. This work is in progress.

The representatives of the fauna of specific vegetational communities, soil types, and OGs also require further analysis. Inspection of the preliminary data in Figure 5 indicates that species characteristic of wet bog sites in Ontario (Warner 1987, 1988, 1989), such as *Amphitrema flavum*, *Hyalosphenia elegans* and *H. papilio*, also occur on the wettest sites in the Wally Creek Watershed. Similarly, *Hyalosphenia subflava* and *Nebela militaris* are best represented on drier sites.

Table 1. Comparison of abundance (number per cm^3) of selected testate amoebae on drained and undrained sites. Mean values are given. Note the abundance of *Nebela militaris* and *Hyalosphenia subflava* on drained sites (typical of dry microsites).

FEC OG	*Hyalosphenia ovalis*	*Hyalosphenia subflava*	*Nebela militaris*	*Nebela parvula*
OG-8				
drained	165.9	83.4	459.1	749.2
undrained	27.7	106.0	307.5	366.8
OG-11				
drained	137.0	192.0	990.0	533.9
undrained	152.0	559.3	963.8	–
OG-12				
drained	136.2	263.7	828.9	1098.0
undrained	64.8	26.5	256.5	85.7
OG-14				
drained	240.0	102.7	413.7	271.0
undrained	80.0	74.5	200.7	41.5
drained ditching	221.2	321.3	1062.6	212.2
Carex fen	140.0	207.0	950.0	–
Sphagnum fuscum	16.0	–	62.0	–

Though only preliminary, this study confirms that there is a wide range of different habitat requirements for certain testate amoebae. These observations further strengthen the possibility of identifying environmental-indicator species and of using testate amoebae both as sensors of peatland site type and soil conditions in bog environments in Ontario and as monitors of environmental impact on peatlands used for forestry purposes.

ACKNOWLEDGMENTS

This project would not have been possible without the interest and encouragement of J.K. Jeglum and V.F. Haavisto. J.K. Jeglum and S.J. Taylor kindly provided the samples and accompanying detailed ecological data base from field sites. M. Kier and J. Schneider most capably undertook laboratory preparation and analyses of the testate amoebae. I extend my thanks to all these people. Financial support in the form of a contract under the Canada-Ontario Forest Resource Development Agreement is gratefully acknowledged.

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Section V
Nutrition

USE OF NEEDLE ANALYSIS TO EVALUATE THE NUTRIENT STATUS OF PEATLAND FOREST

H. Vasander
University of Helsinki
Department of Peatland Forestry
Unioninkatu 40 B
Helsinki, Finland

T. Lindholm
Water and Environment Research Institute
Helsinki, Finland

ABSTRACT

Needle analysis is widely used in Finland in studying the need for fertilization, especially of drained peatland pine (*Pinus* spp.) stands. According to standard sampling procedures, needle samples from the youngest needles in the latest whorl are taken from 5-10 trees in the dominant tree layer during the winter dormant period. Although the correlation between nutrient concentrations in peat and needles is weak, there is a strong correlation between the need for fertilization of tree stands and nutrient concentrations in needles.

Preliminary results of a fertilization trial on a drained, raised bog in southern Finland are presented. The trial was established in 1978 to study the effects of PK and NPK fertilizers of differing solubilities on the growth of Scots pine (*Pinus sylvestris*). Needle samples were taken every winter from each of the fertilization treatments as well as from a nearby virgin bog. The following nutrients were analyzed: N, P, K, Ca, Mg, B, Cu, Mn, and Zn. Annual height and basal area growth of the tree stands were also measured. In comparison with published limit values, the concentrations of N and P were severely deficient in the drained control area as well as on the virgin bog. In contrast, concentrations of B and Cu, for example, were not deficient.

RÉSUMÉ

En Finlande, l'analyse des aiguilles est une méthode largement utilisée pour déterminer les besoins de fertilisation, notamment des pinèdes occupant des tourbières assainies. Des échantillons d'aiguilles du verticille le plus récent sont prélevés selon des méthodes normalisées sur 5 à 10 arbres de l'étage dominant pendant la période de dormance hivernale. Bien que la corrélation entre les teneurs en éléments nutritifs de la tourbe et des aiguilles soit faible, la corrélation entre le besoin de fertilisation des peuplements forestiers et les teneurs en éléments nutritifs des aiguilles est forte.

Les résultats préliminaires d'un essai de fertilisation d'une tourbière bombée assainie du sud de la Finlande sont présentés. La parcelle d'essai a été établie en 1978 afin d'étudier les effets d'apports de PK et de NPK de solubilité variée sur la croissance des pins sylvestres. Des échantillons d'aiguilles ont été prélevés chaque hiver sur des arbres soumis à chacun des traitements de fertilisation et sur des arbres d'un marais vierge avoisinant. Les éléments nutritifs suivants ont été analysés : N, P, K, Ca, Mg, B, Cu, Mn et Zn. L'accroissement annuel en hauteur et de la surface terrière des peuplements a été mesuré. Une comparaison avec les valeurs limites publiées a permis d'établir de graves carences en N et en P dans le secteur assaini ainsi que dans le marais vierge. Par ailleurs, les teneurs en B et en Cu étaient adéquates.

INTRODUCTION

The need for fertilization on peatlands can be evaluated in several ways: by site-type characterization, fertilization experiments, chemical analysis of peat or foliage, identification of visible deficiency symptoms, and remote sensing (e.g., Veijalainen 1984, Reinikainen 1988). In Finland, all these methods have been studied, and needle analysis is used for estimating the fertilization needs of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) stands.

In this paper we discuss the technique of needle analysis as it is used in Finland. We also present some preliminary results of a fertilization experiment in which needles have been analyzed and growth has been evaluated annually over a 10-year period after fertilization.

NEEDLE ANALYSIS IN FINLAND

Aaltonen (1950) was the first to apply foliar analysis in Finland. He noticed that the nutrient concentrations of needles and leaves of forest shrubs and herbs reflect, to some extent, the trophy of forest site types. Puustjärvi (1962, 1965) used pine-needle analysis in his studies to assess the fertility of mire site types and reached the important conclusion that, although the correlation between nutrient concentrations in peat and needles is weak, there is a strong correlation between the need for fertilization of tree stands and needle nutrient concentrations.

Nutrient diagnostic studies expanded in the 1960s in the Department of Peatland Forestry at the Finnish Forest Research Institute (Reinikainen 1967, Paarlahti et al. 1971). Subsequently, needle analysis of pine stands on peatlands became common practice. In practical studies, the following standard procedures were adopted:

1) sampling time was established: the winter dormant period, December-March
2) sample type was determined: current needles in the latest whorl of 5-10 trees in the dominant tree layer
3) sampling technique, sample storage and pretreatment were determined.

In addition, the following information was required:

1) site type characterization, drainage conditions, earlier fertilization
2) age of stand, proportion of tree species, growth measurement or estimate, possible nutrient deficiencies and damage.

Diagnostic limit values (Table 1) have been obtained from correlations between analytical values and growth parameters (Paarlahti et al. 1971, Veijalainen 1977). Also, the relationships between nutrients are used to reveal nutrient imbalances in tree stands (e.g., Paavilainen 1979). Recommendations for fertilizing severely and slightly deficient pine stands on peatlands are based on deficiency limits and are presented in Table 2.

In the winter of 1987-1988 a special program for forest owners called "Ilves – Forest Health Service" was organized by Viljavuuspalvelu Ltd. (Soil and Plant Analyses Company), Kemira Ltd. (Multibranch Company Manufacturing, e.g., fertilizers), Sampo (Insurance Company) and SKOP (Bank Union). The aims of this program were to interest people in their forests and familiarize them with needle analysis. Landowners collected their own needle samples and sent them to Viljavuuspalvelu Ltd. for analysis. The results of these analyses were used in making recommendations for fertilization. The price of the analysis was 180 FIM ($50 CAN) for N, P, K, Ca, Mg, and B. If additional Cu, Zn, and Mn were analyzed the price was 240 FIM ($65 CAN); it was 280 FIM ($75 CAN) if S was analyzed. In all, 1600 needle samples were analyzed, a figure that far exceeded the 20-40 samples analyzed before the program. Of the samples, 77% were from forests on mineral soil and 23% were from peatland forests. Most (77%) samples were from pine; the remainder were from spruce (*Picea* spp.) forests (Mälkönen[1]). The program will be repeated after some years, and will be aimed at combining needle and soil analyses (Dr. V. Mäntylahti, Viljavuuspalvelu Ltd., pers. comm.).

[1] Mälkönen, E. 1989. Ilves-metsänterveyspalvelu metsäntutkimuksen näkökulmesta (unpubl. ms.).

Table 1. Deficiency limit values obtained from needle analysis of peatland pine stands (Reinikainen 1988)

	Severely deficient	Slightly deficient	Hazardously low	Hazardously high
N mg/g	< 11.9	12.0 – 12.9	..	..
P mg/g	< 1.39	1.40 – 1.69	..	..
K mg/g	< 3.49	3.50 – 4.49	..	..
Mg mg/g	..	..	< 1.00	
Cu ppm	..	..	< 2.5	
B ppm	< 4.9	5.0 – 7.5	..	> 40
Mn ppm	..	..	..	> 600

Table 2. Recommendations for fertilization based on needle analysis in peatland pine stands (Reinikainen 1988)

	Need for nutrients (kg/ha, elementary values)			
	Severely deficient	Slightly deficient	Hazardously low	Hazardously high
N[a]	150	100	–	–
P	60	45	–	–
K	115	85	–	–
Mg	–	–	1	–
Cu[b]	–	–	2	–
B[c]	3	3	3	–
Mn	–	–	–	–

[a] Instead of urea, another N-fertilizer containing Mg was used.

[b] Fertilizers containing Cu were used, either CuO (10 kg/ha) or $CuSO_4$ (30 kg/ha).

[c] Fertilizers containing B were used, approx. 2 kg/ha.

CASE STUDY – FERTILIZATION EXPERIMENT ON LAAVIOSUO BOG

Study area

Laaviosuo (61°02′ N, 25°00′ E, 151 m above sea level) is an ombrotrophic raised bog complex about 60 ha in area. The bog lies on the regional limit between concentric and eccentric raised bogs. The uppermost 2 m of peatland are purely ombrotrophic (Reinikainen and Lindholm 1980, Tolonen 1987). The virgin bog supported a sparse stand of Scots pine prior to drainage (Lindholm and Vasander 1979, Vasander 1982).

The site was drained in February 1978 by means of open ditches 1 m deep with 45-m spacings. For the fertilization trial, 12 plots, each 40 x 40 m, were established in May and June of 1978. There were six treatments, including an unfertilized control, with two replicates. The fertilizers used (Table 3) were products of Kemira Ltd., some of which are used in large-scale practice and others only for test purposes. The latter types include ureaformaldehyde (trade name Nitroform), Siilinjärvi apatite, which is a hard, magmatic rock phosphate from the Siilinjärvi phosphate mine, and biotite, a mica-type mineral also from the Siilinjärvi phosphate mine.

MATERIALS AND METHODS

Samples for needle analysis were taken between 1979 and 1988, except in 1980. Needles were collected for six years on the virgin bog. The leader and basal area growth were measured on the fertilized plots (Lindholm and Vasander 1988). The nutrient contents of needles from a similar raised, undrained bog at Kaurastensuo, 400 m distant, were used for comparative purposes. Needle samples were analyzed at Viljavuuspalvelu Ltd. for N, P, K, Ca, Mg, B, Cu, Mn, and Zn.

RESULTS AND DISCUSSION

In the virgin bog and in the control area, the concentrations of N and P were severely deficient and K was slightly deficient in the virgin bog (cf. Tables 1 and 4). The values of all nutrients were higher on the fertilized than on the control plots, but in some cases were still very low for N and P on the fertilized plots (Table 4).

Table 3. Design of the fertilization trial at Laaviosuo

Abbreviation	Fertilizer	Solubility	kg/ha	Nutrients, kg/ha
0	–	–	–	–
AB	apatite	slowly	400	P 54, K 31
	biotite	slowly	570	Ca 178, Mg 66
PK	superphosphate	readily	500	P 44, K 85, S 60
	potassium chloride	readily	170	Fe 2, Mg 1, Na 2
UAB	urea	readily	215	N 100, P 54,
	apatite	slowly	400	K 31, Ca 178,
	biotite	slowly	570	Mg 66
UABM	urea	readily	215	N 100, P 54,
	apatite	slowly	400	K 31, B 1.1,
	biotite	slowly	570	Cu 12.8, Mn 5.5,
	micronutrients		100	Fe 9.8, Zn 5.5,
				Mo 1.4, Na 0.7
NFAB	nitroform	slowly	310	N 118, P 54,
	apatite	slowly	400	K 31, Ca 178,
	biotite	slowly	570	Mg 66

Table 4. Variation in needle nutrient concentrations on the various fertilization plots (A) and in the unfertilized control area (B) at Laaviosuo and at the virgin bog of Kaurastensuo (C) between 1979 and 1988.

Element	A	B	C
N (g/kg)	1.12 – 2.02	1.05 – 1.23	1.00 – 1.10
P (g/kg)	1.23 – 1.80	0.95 – 1.18	0.99 – 1.17
K (g/kg)	4.5 – 6.0	4.4 – 5.0	3.9 – 4.4
Ca (g/kg)	2.2 – 3.9	2.2 – 2.7	2.5 – 3.0
Mg (g/kg)	0.68 – 1.19	0.88 – 1.05	1.03 – 1.19
B (mg/kg)	13 – 41	19 – 33	27 – 35
Cu (mg/kg)	2.6 – 7.1	2.8 – 3.9	2.6 – 3.2
Mn (mg/kg)	200 – 750	370 – 620	390 – 620
Zn (mg/kg)	45 – 120	58 – 77	48 – 57

The N concentrations increased sharply after the treatments on the plots fertilized with urea (readily soluble), but then declined and maintained a steady level. After nitroform (slowly soluble) fertilization, the N concentrations in the needles showed no change (Fig. 1). Tree growth was steadier after slowly soluble N fertilizers were added than it was after the addition of readily soluble fertilizers (Lindholm and Vasander 1988, Martikainen[2]).

Clearly, P concentrations in needles were lower in the control area than in the fertilized areas; however, no clear trend after fertilization was evident. For many years after fertilization, K concentrations in needles were higher on the plot fertilized with readily soluble K fertilizer (Fig. 1).

The concentrations of some nutrients such as Ca varied greatly, depending on the year and the fertilization treatment, but needles from the control area showed the lowest concentrations. For some other elements, e.g., B, the lowest values were recorded on those plots to which N, P, and K were added. Needle values in the control area usually exceeded those on fertilized plots (dilution effect, e.g., Veijalainen 1977).

The relative annual basal growth peaked 3 to 4 years after fertilization and then dropped (Fig. 2). Needle nutrients did not show a similar pattern (cf. Fig. 1 and 2). In future studies, one aim will be to relate nutrient concentrations to needle mass (cf. gravimetric and volumetric peat analyses).

CONCLUSIONS

Balanced nutrition is an important factor controlling the growth and health of forests on peatlands. It is possible to obtain accurate information by using needle analysis if there are problems in the development of the forest stand or if it is necessary to assess nutrient proportions and/or possible deficiencies. As diagnostic tools, soil

[2] Martikainen, P.J. *Ed.* 1989. Effects of fertilization on forest ecosystem[s]. (unpubl. ms).

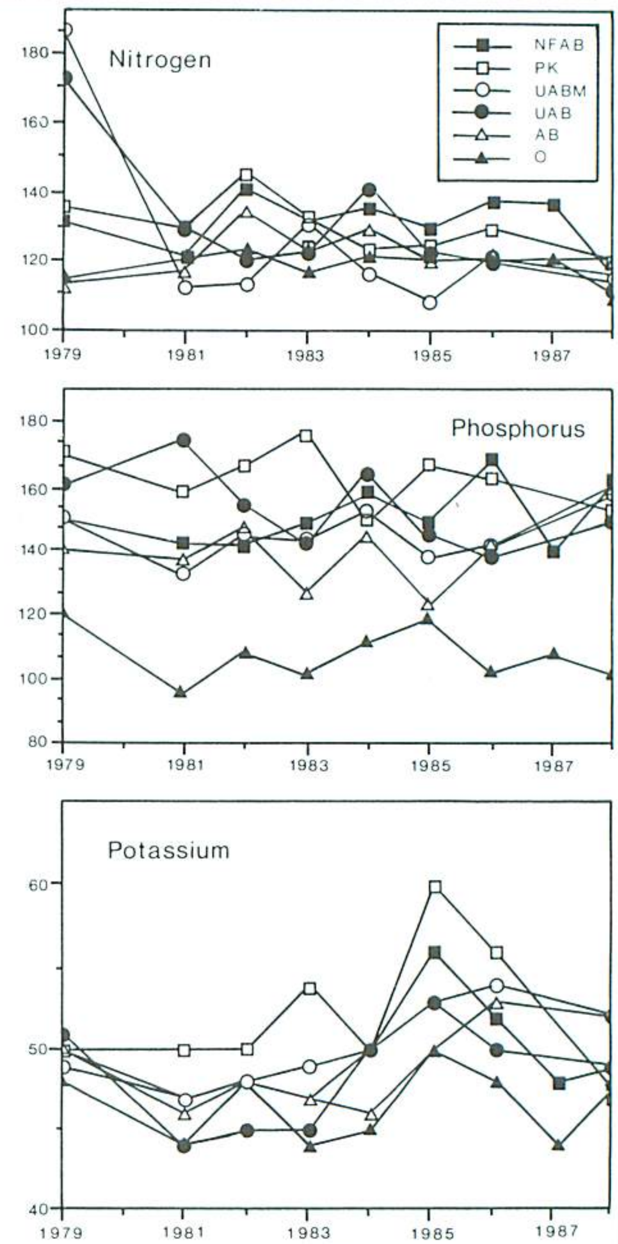

Figure 1. Concentrations, over time, of N (upper, 0.1 g/kg), P (middle, 0.01 g/kg), and K (lower, 0.1 g/kg) in needles after different fertilization treatments. See Table 3 for abbreviations of fertilizers.

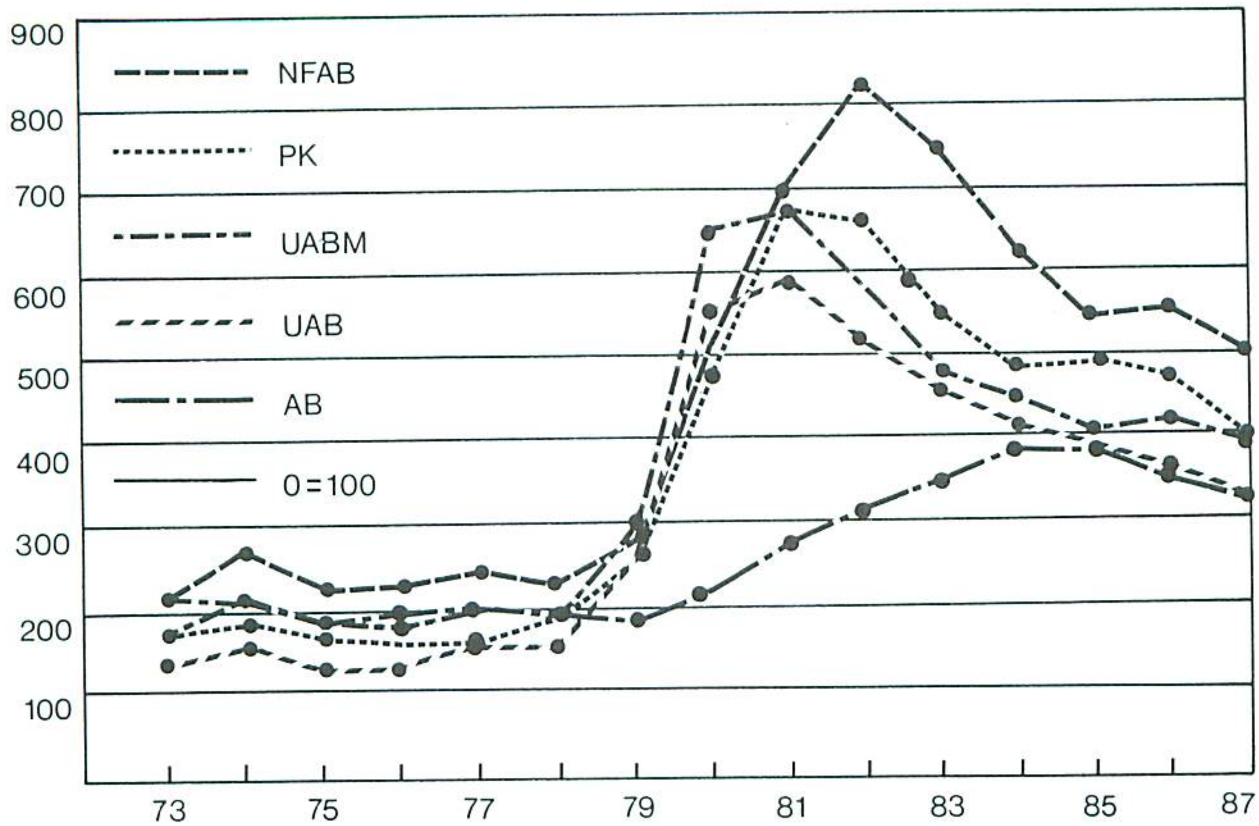

Figure 2. Relative annual basal area growth of pine trees after various fertilization treatments compared with basal area growth in unfertilized control areas (= 100). See Table 3 for abbreviations of fertilizers. (Lindholm and Vasander 1988)

analysis and deficiency symptoms are not as versatile as needle analysis (Table 5).

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Table 5. Evaluation of methods of analyzing the need for fertilization of peatland forest stands (Veijalainen 1984, Reinikainen 1988)

Method	Sites/use	Value of use[a]
Fertilization trial	all	3
Site type classification	drained peatlands	3
Peat analysis	forested fields	1
	harvested peatlands	1
	additional method for drained peatlands	1
Needle (leaf) analysis	pine stands (devel. classes 1-4)	2
	others	0-1
Deficiency symptoms	severe symptoms	1-2
	additional method	1
Remote sensing	large areas	?

[a] 0 = not suitable for practical use
1 = can be used only to show the deficiency of one nutrient or to give preliminary results
2 = makes it possible to provide fertilization recommendations for one or more nutrients
3 = gives a basis for fertilization recommendations

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EFFECTS OF REFERTILIZATION OF AN 18-YEAR-OLD JAPANESE LARCH (*LARIX LEPTOLEPIS*) PEATLAND PLANTATION IN WESTERN NEWFOUNDLAND, CANADA

E.D. Wells
Forestry Canada
Newfoundland and Labrador Region
St. John's, Newfoundland
Canada

ABSTRACT

In 1986, an 18-year-old peatland plantation of Japanese larch (*Larix leptolepis*) was refertilized with P, PK and NPK fertilizers. Height growth was significantly greater in the NPK-fertilized plots than in the other fertilization treatments. Diameter growth was also greater in the NPK fertilized plots in all 3 years but was significantly greater only in the second year. The overall 3-year (1986-1988) growth increments in height and diameter were also significantly greater in the NPK fertilized plots. Analyses of foliar nutrient concentrations (% dry matter) indicated uptake of N, P and K in plots fertilized with these elements. Foliar nutrient vectors indicated that N, P and K were severely deficient in the unfertilized controls. Although uptake of all three elements was high in the fertilized plots, foliar weights increased significantly only when N was applied in combination with P and K.

RÉSUMÉ

En 1986, une plantation de mélèzes du Japon (*Larix leptolepis)* de 18 ans établie sur une tourbière a de nouveau été fertilisée au P, PK et NPK. La croissance en hauteur des arbres des parcelles traitées au NPK était beaucoup plus importante que celle des autres traitements fertilisants. L'accroissement du diamètre était également supérieur dans les parcelles traitées au NPK au cours des trois années, mais seulement très supérieur au cours de la deuxième année. L'accroissement général de la hauteur et du diamètre au cours des 3 années était significativement plus élevée dans les parcelles traitées au NPK. Des analyses des teneurs en éléments nutritifs du feuillage, établies en pourcentage de matière sèche, ont révélé une absorption de N, P et K dans les parcelles fertilisées à l'aide de ces éléments. Les composantes des feuilles assurant le transport des éléments nutritifs ont révélé une grave carence en N, P et K dans les parcelles témoins non fertilisées. Bien que l'assimilation de ces 3 éléments ait été forte dans les parcelles fertilisées, le poids des feuilles n'a augmenté de façon significative que lorsque N a été appliqué en combinaison avec P et K.

INTRODUCTION

Peatland afforestation began in Newfoundland about 20 years ago with the establishment of a variety of species on six sites comprising about 50 ha of peatlands. Many of the species proved unsuccessful because of poor planting stock, poor choice of species and, in certain cases, poor site selection and inadequate drainage design (Wells 1985). Since growth of the surviving species,black spruce (*Picea mariana*), Sitka spruce (*P. sitchensis*), white spruce (*P. glauca*), lodgepole pine (*Pinus contorta*) and Japanese larch (*Larix leptolepis*), was poor after 8 to 10 years, these peatland plantations were considered unsuccessful and the projects were discontinued.

One of the peatland afforestation sites in western Newfoundland (Fig. 1), which was planted with Japanese larch in 1968, was selected to determine if nutrient deficiencies were limiting growth of the trees. Height growth during the past 8 to 10 years was extremely poor and visual observations of the foliage (c.f. Binns et al. 1980) suggested nutrient deficiencies. Analyses of foliage in the early fall of 1985 indicated levels of nitrogen (N), phosphorus (P) and potassium (K) (Table 1) well below the deficiency level determined for this species in the United Kingdom. As a result, a fertilization trial was established to: (1) determine which nutrients were limiting growth and (2) assess the duration of the effect of fertilization. The results of the first 3 years of the experiment are presented. Annual growth measurements and nutrient analyses will continue in an effort to determine the duration of the effect of the fertilization.

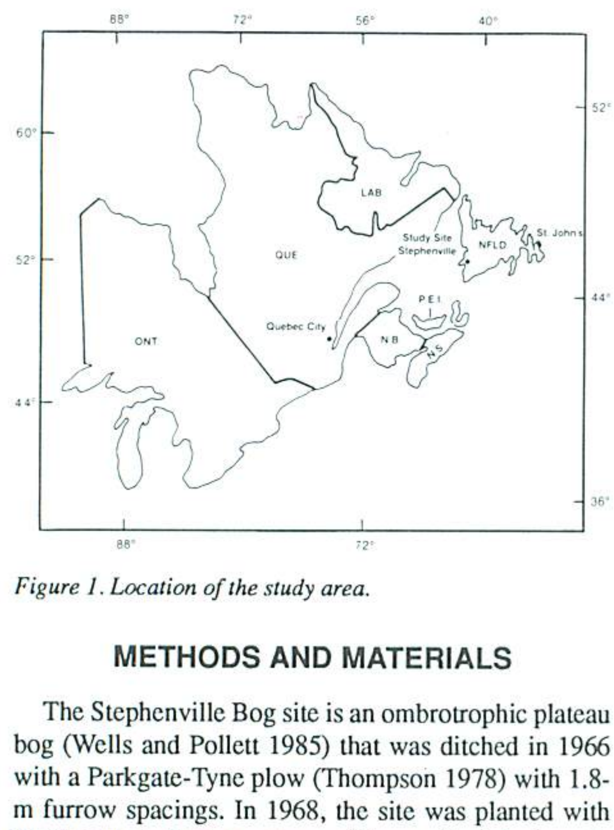


Figure 1. Location of the study area.

METHODS AND MATERIALS

The Stephenville Bog site is an ombrotrophic plateau bog (Wells and Pollett 1985) that was ditched in 1966 with a Parkgate-Tyne plow (Thompson 1978) with 1.8-m furrow spacings. In 1968, the site was planted with black spruce, Norway spruce (*Picea abies*), lodgepole pine, Japanese birch (*Betula ermanii*), and Japanese larch. A top-dressing of 57 g per tree of ground mineral rock phosphate was applied in 1968 and, in 1970, 128 g of PK fertilizer (20% P_2O_2, 20% K_2O) were similarly applied.

Table 1. Pretreatment concentrations of nutrients in the foliage of Japanese larch planted in the Stephenville Bog compared with published optimum and deficiency levels of these nutrients

Foliar nutrient	Levels in Stephenville Bog	Deficiency-optimum levels[a]
N (%)	1.03	1.80-2.50 (1)
		1.13-2.88 (2)
P (%)	0.12	0.18-0.25 (1)
		0.16-0.42 (2)
		0.40-0.50 (3)
K (%)	0.45	0.50-0.80 (1)
		0.38-1.35 (2)
Ca (%)	0.33	-
Mg (mg/g)	0.49	-
Cu (ppm)	3.03	-

[a] (1) Binns et al. 1980; (2) Leyton 1956; (3) Leyton 1957

In the early fall of 1985, foliar samples of Japanese larch were collected from the first and second lateral branches below the top and were kept cool during transport to the drying ovens, in which they were dried at 75°C for 3 to 4 days before being finely ground in a blender. Total N and P were determined with a Technicon Auto-Analyzer II after 0.5-g samples had been digested at 390°C in a mixture of 25 ml of concentrated H_2SO_4 and 10 g of catalyst (15 K_2SO_4:0.7 HgO). The solution was allowed to cool, then was diluted to 250 ml with water (Anon. 1976). Total metals (K, Ca, Mg and Cu) were determined with a Perkin-Elmer Model 2380 Atomic Absorption Spectrophotometer after 1.0 g of dried sample had been dry-ashed in a muffle furnace at 475°C. The ash was dissolved in 6N HCl, and digested with HF and 1 ml of aqua regia (3 HCl:1 HNO_3) solution (modified after Desjardins [1978]).

A randomized complete block design for the fertilization experiment (Fig. 2) was established in the early spring of 1986. Heights and diameters of all trees within the plots were measured at 1.3 m above the ground. This was followed by the establishment of P, PK, and NPK fertilization treatments, consisting of 200 kg/ha elemental N (435 kg/ha urea [46-0-0]), 60 kg/ha elemental P (280 kg/ha triple superphosphate [0-46-0]), and 100 kg/ha elemental K (200 kg/ha muriate of potash [0-0-60]). Heights and diameters were remeasured in the fall in 1986, 1987 and 1988.

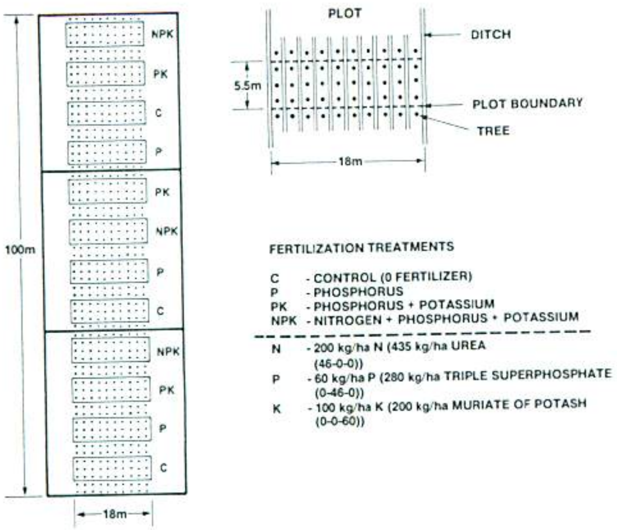
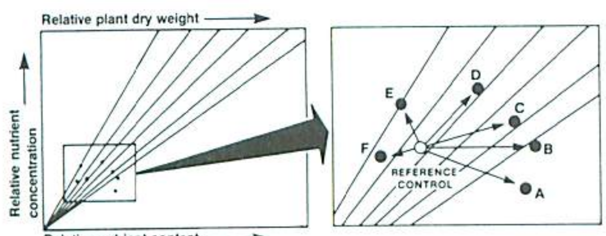


Figure 2. Experimental design of the Japanese larch fertilization experiment in Stephenville Bog (showing enlarged view of a plot).



Direction of shift	Change in relative: Plant weight	Nutrient conc.	Nutrient content	Interpretation	Possible diagnosis
A	+	-	+	Dilution	Non-limiting
B	+	0	+	Sufficiency	Non-limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury consump.	Non-toxic
E	-	++	±	Excess	Toxic
F	-	-	-	Excess	Antagonistic

Figure 3. Interpretation of directional differences (nutrient vectors) in nutrient concentration, nutrient content and dry weight of plants (from Timmer and Armstrong [1987]).

A two-way analysis of variance (Steel and Torrie 1960), and statistical comparisons of treatment means with Student-Newman-Keul's test, (Freund et al. 1986), were computed according to the following experimental model:

$$Y_{ij} = \mu + B_i + F_j + \varepsilon_{ij}$$

where:

Y_{ij} = the response of the plot in the i^{th} block under the j^{th} level of fertilization in the i^{th} block;

μ = the overall experimental mean;

B_i = the effect of the i^{th} block ($i = 1,2,3$);

F_j = the effect of the j^{th} fertilization treatment ($j = 1,2,3,4$);

ε_{ij} = the experimental error.

RESULTS

Height and Diameter Growth, and Foliar Weights

Height increments (Table 2) differed significantly ($P \leq 0.05$) among fertilization treatments for 1987 ($P = 0.0051$), for 1988 ($P = 0.0338$) and for the 3-year period from 1986 to 1988 ($P = 0.0002$). A comparison of the means of height increments (Table 2) shows control < P < PK < NPK treatments for all of these growth periods. In 1987, height growth in the NPK treatment (20.47 cm) was significantly greater than that in all other treatments. However, in 1988, height growth in both the NPK (25.71 cm) and PK (19.39 cm) treatments was significantly greater than in the P (12.88 cm) and control (8.74 cm) treatments. For the 3-year period 1986-1988, growth of trees in the NPK treatment (46.84 cm) was significantly greater than that in all other treatments, and growth in the PK treatment (21.26 cm) was significantly greater than that in the P (16.28 cm) and control (10.79 cm) treatments.

The response of diameter growth to fertilization (Table 3) appears to have been much slower than that of height growth. Significant differences ($P \leq 0.05$) in diameter increment among treatments occurred only during the 3-year growth period ($P = 0.0046$). Although annual diameter increments were generally greater in the P, PK and NPK treatments than in the control, comparison of the means (Table 3) indicated that only growth in the NPK treatment (9.17 mm) during the 3-year period was significantly greater than that in all other treatments.

Foliar weights (Table 4) differed significantly ($P \leq 0.05$) among fertilization treatments in 1987 ($P = 0.0009$), but not in 1988 ($P = 0.0680$). Although foliar weight increased with all three fertilization treatments (P, PK and NPK), the difference was significant only in the NPK treatment. Foliar growth response in the P and PK fertilization treatments also appeared to be increasing with time. In 1987, foliar weight in the NPK treatment was about three times that in the control and in the P and PK treatments; in 1988, foliar weight in the NPK treatments remained about three times greater than that in the control, but was only twice that in the P and PK treatments.

Table 2. Analysis of variance and multiple comparisons of mean height increments (cm) of Japanese larch for 1986, 1987 and 1988 and for the 3-year period from 1986 to 1988

	1986			1987		1988		1986 - 1988	
Source	DF	MS	P	MS	P	MS	P	MS	P
Blocks	2	22		272		127		502	
Fertilizer	3	91	0.1371	2959	0.0051	2373	0.0338	10775	0.0002
Error	6	33		231		413		262	
Treatment		N	Mean ± SE		Mean ± SE		Mean ± SE		Mean ± SE
Control		35	-1.02 ± 1.35		3.07 ± 1.20 b		8.74 ± 1.51 b		10.79 ± 2.04 b
P		40	-0.27 ± 0.96		3.67 ± 1.55 b		12.88 ± 1.64 ab		16.28 ± 2.43 b
PK		36	-2.95 ± 0.83		4.81 ± 1.58 b		19.39 ± 2.00 a		21.26 ± 2.31 b
NPK		45	0.65 ± 1.60		20.47 ± 3.09 a		25.71 ± 2.67 a		46.84 ± 3.94 a

Means followed by different letters are significantly different ($P \leq 0.05$, Student-Newman-Keul test).

Table 3. Analysis of variance and multiple comparisons of mean diameter increments (mm) of Japanese larch for 1986, 1987 and 1988 and for the 3-year period from 1986 to 1988

	1986			1987		1988		1986 - 1988	
Source	N	MS	P	MS	P	MS	P	MS	P
Blocks	2	28.5		6.8		2.1		60.3	
Fertilizer	3	3.3	0.2666	60.3	0.0172	28.2	0.2421	207.3	0.0051
Error	6	1.9		7.7		15.4		16.1	
Treatment		DF	Mean ± SE		Mean ± SE		Mean ± SE		Mean ± SE
Control		3	1.11 ± 0.26		1.04 ± 0.29 b		1.99 ± 0.26		4.14 ± 0.32 b
P		3	1.04 ± 0.24		1.56 ± 0.31 b		2.09 ± 0.30		4.69 ± 0.43 b
PK		3	1.53 ± 0.23		1.62 ± 0.24 b		2.67 ± 0.29		5.81 ± 0.45 b
NPK		3	1.62 ± 0.25		3.73 ± 0.38 a		3.69 ± 0.30		9.05 ± 0.60 a

Means followed by different letters are significantly different ($P \leq 0.05$, Student-Newman-Keul test).

Table 4. Analysis of variance and multiple comparison of means of foliar weights (mg/100 needles) of Japanese larch planted in the Stephenville Bog

	1987			1988		
Source	D	MS	P	DF	MS	P
Blocks	2	258		2	210	
Fertilizer	3	13051	0.0009	3	2922	0.0680
Error	2	540		4	539	
Treatment	N	Mean ± SE		N	Mean ± SE	
Control	3	91.43 ± 9.09 b		3	40.70 ± 8.49	
P	3	97.73 ± 12.31 b		3	72.80 ± 4.30	
PK	3	100.87 ± 9.09 b		3	68.90 ± 0.90	
NPK	3	228.40 ± 17.60 a		3	116.67 ± 18.72	

Means followed by different letters are significantly different ($P \leq 0.05$, Student-Newman-Keul test).

NUTRIENT STATUS

Concentrations of foliar N (Table 5) differed significantly ($P \leq 0.05$) among fertilization treatments in 1986 ($P = 0.0009$) and 1987 ($P = 0.0465$), but not in 1988 ($P = 0.3078$). A comparison of the means of foliar N concentrations (Table 5) shows that, during 1986 and 1987, N concentrations were highest in the NPK treatment and concentrations in all three fertilization treatments were significantly higher than those in the control (unfertilized) plots. The highest concentration of foliar N (2.07%) occurred in 1986 in the NPK treatment, the first growing season after fertilization; N concentrations in the NPK treatment declined to 1.68% in 1987 and 1.28% in 1988.

Table 5. Analysis of variance and multiple comparisons of means of annual concentrations of N, P and K in the foliage of Japanese larch. Means are expressed as a percentage of dry weight.

			1986		1987		1988	
NITROGEN	Source	DF	MS	P	MS	P	MS	P
	Blocks	2	0.0013		0.0098		0.0142	
	Fertilizer	3	0.4943	0.0009	0.0642	0.0465	0.0043	0.3078
	Error	[a]	0.0200		0.0130		0.0027	
	Treatment		N	Mean ± SE		Mean ± SE		Mean ± SE
	Control		3	1.19 ± 0.05 b		1.34 ± 0.05 b		1.17 ± 0.05
	P		3	1.27 ± 0.03 b		1.41 ± 0.08 ab		1.25 ± 0.05
	PK		3	1.36 ± 0.05 b		1.44 ± 0.07 ab		1.30 ± 0.04
	NPK		3	2.07 ± 0.12 a		1.68 ± 0.06 a		1.28 ± 0.05
PHOSPHORUS	Source	DF	MS	P	MS	P	MS	P
	Blocks	2	0.0324		0.0036		0.0026	
	Fertilizer	3	0.0736	0.0061	0.0672	0.0005	0.0069	0.0008
	Error	6	0.0062		0.0023		0.0003	
	Treatment		N	Mean ± SE		Mean ± SE		Mean ± SE
	Control		3	0.20 ± 0.04 b		0.21 ± 0.04 b		0.19 ± 0.01
	P		3	0.55 ± 0.10 b		0.51 ± 0.03 ab		0.28 ± 0.02
	PK		3	0.50 ± 0.05 b		0.52 ± 0.01 ab		0.29 ± 0.02
	NPK		3	0.45 ± 0.06 a		0.34 ± 0.02 a		0.29 ± 0.01
POTASSIUM	Source	DF	MS	P	MS	P	MS	P
	Blocks	2	0.0165		0.0219		0.0087	
	Fertilizer	3	0.0403	0.0108	0.1434	0.0038	0.0390	0.0255
	Error	6	0.0043		0.0100		0.0059	
	Treatment		N	Mean ± SE		Mean ± SE		Mean ± SE
	Control		3	0.51 ± 0.04 c		0.60 ± 0.04 c		0.48 ± 0.03
	P		3	0.59 ± 0.06 bc		0.71 ± 0.08 bc		0.51 ± 0.03
	PK		3	0.78 ± 0.06 a		1.11 ± 0.09 a		0.70 ± 0.05
	NPK		3	0.69 ± 0.03 ab		0.83 ± 0.04 b		0.69 ± 0.06

Means followed by different letters are significantly different ($P \leq 0.05$, Student-Newman-Keul test).

[a] Error DF for nitrogen = 6 (1986, 1987) and 5 (1988).

Concentrations of foliar P (Table 5) differed significantly ($P < 0.05$) among fertilization treatments in 1986 ($P = 0.0061$), 1987 ($P = 0.0005$) and 1988 ($P = 0.0008$). A comparison of the means (Table 5) shows an increase in concentration from approximately 0.20% in the unfertilized controls to values of 0.55, 0.50 and 0.45% in the P, PK and NPK treatments, respectively, one growing season (1986) after the application of fertilizer. Concentrations remained high in the fertilized plots during the second year (1987) after fertilization but, by the third year, had dropped to 0.28, 0.29 and 0.29% in the P, PK and NPK treatments, respectively.

Concentrations of foliar K (Table 5) also differed significantly ($P < 0.05$) among treatments in 1986 ($P = 0.0108$), 1987 ($P = 0.0038$) and 1988 ($P = 0.0255$). During the first 2 years after fertilization, concentrations of K were highest in the treatments in which that element was used (PK and NPK). The fact that concentrations in the NPK treatment were lower than those in the PK treatment may be a result of dilution of the nutrient as a result of increased foliar biomass within the NPK treatment. In 1988, concentrations of K remained highest in the PK (0.70%) and the NPK (0.69%) treatments, but were not significantly different ($P = 0.0255$) from those in the control (0.48%) or the P (0.51%) treatments.

Fertilization did not significantly ($P \leq 0.05$) affect uptake of Ca, Mg and Cu (Table 6) during either of the experimental periods. During the response period, both Mg and Cu concentrations remained relatively equal in the different treatments. Although concentrations of Ca increased from control to P to PK to NPK in 1986, this trend was reversed in 1988.

The large increase in foliar concentrations of N, P and K in the fertilization treatments, as demonstrated by the values for treatment means (Tables 5 and 6), and as illustrated graphically by foliar nutrient vectors (Fig. 4 and 5), suggests that the trees growing on this site were deficient in N, P and K. Phosphorus showed the largest relative response (major vector) of all the nutrients both in 1987 and in 1988. However, the 1987 foliar nutrient vectors (Fig. 4) indicate that, although P and K appeared to be more limiting than N, an increase in needle weight did not occur until N was added in combination with P and K.

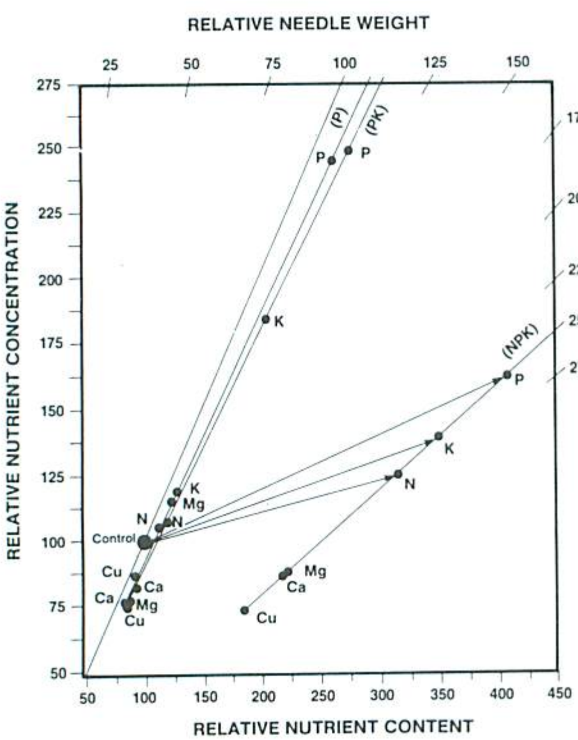


Figure 4. Relative differences in 1987 nutrient concentrations, nutrient contents and dry weight of foliage of Japanese larch fertilized with P, PK and NPK. Values for control treatment (large dot) were equalized to 100 to allow for comparisons of all nutrients on a common base.

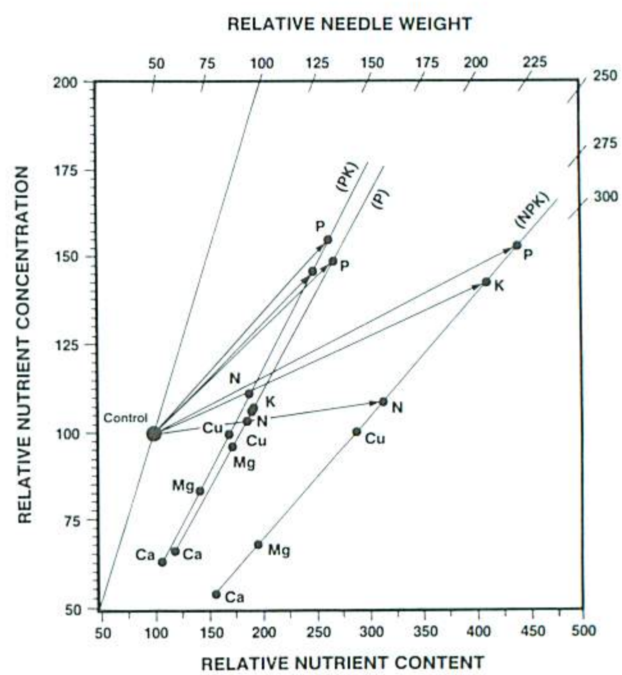


Figure 5. Relative differences in 1988 nutrient concentrations, nutrient contents and dry weight of foliage of Japanese larch fertilized with P, PK and NPK. Values for control treatment (large dot) were equalized to 100 to allow for comparisons of all nutrients on a common base.

Table 6. Analysis of variance and multiple comparisons of means of annual concentrations of Ca, Mg and Cu in the foliage of Japanese larch. Means are expressed (on a dry-weight basis) as % (Ca), mg g^{-1} (Mg) and ppm (Cu).

			1986		1987		1988	
	Source	DF	MS	P	MS	P	MS	P
CALCIUM	Blocks	2	0.0285		0.0083		0.0368	
	Fertilizer	3	0.0104	0.1369	0.0025	0.1708	0.0294	0.1933
	Error	6	0.0038		0.0011		0.0136	
	Treatment		N	Mean ± SE		Mean ± SE		Mean ± SE
	Control		3	0.29 ± 0.05		0.30 ± 0.05		0.50 ± 0.14
	P		3	0.33 ± 0.07		0.23 ± 0.02		0.33 ± 0.04
	PK		3	0.34 ± 0.05		0.25 ± 0.02		0.32 ± 0.05
	NPK		3	0.43 ± 0.06		0.26 ± 0.01		0.27 ± 0.05
MAGNESIUM	Source	DF	MS	P	MS	P	MS	P
	Blocks	2	0.0044		0.0845		0.2303	
	Fertilizer	3	0.0004	0.9222	0.0331	0.4595	0.0183	0.7023
	Error	6	0.0025		0.0336		0.0374	
	Treatment		N	Mean ± SE		Mean ± SE		Mean ± SE
	Control		3	0.48 ± 0.04		0.63 ± 0.12		0.54 ± 0.25
	P		3	0.47 ± 0.03		0.73 ± 0.19		0.52 ± 0.19
	PK		3	0.46 ± 0.02		0.49 ± 0.07		0.45 ± 0.08
	NPK		3	0.48 ± 0.06		0.54 ± 0.09		0.37 ± 0.09
COPPER	Source	DF	MS	P	MS	P	MS	P
	Blocks	2	0.0274		0.1633		3.3558	
	Fertilizer	3	6.2533	0.1497	0.3275	0.0517	0.2255	0.9593
	Error	[a]	2.0000		0.0700		2.3635	
	Treatment		N	Mean ± SE		Mean ± SE		Mean ± SE
	Control		3	5.20 ± 0.85		3.53 ± 0.09		3.98 ± 1.25
	P		3	4.35 ± 0.25		3.33 ± 0.09		4.14 ± 0.73
	PK		3	4.10 ± 0.10		2.93 ± 0.23		3.98 ± 0.50
	NPK		3	7.53 ± 0.76		2.83 ± 0.23		3.99 ± 1.50

[a] Error DF for copper = 4 (1986), 6 (1987) and 5 (1988).

Nutrient-vector analyses of Ca, Mg and Cu in 1987 (Fig. 4) showed a reduction in both concentrations and contents, but a slight corresponding increase in foliar dry weight (Table 4) in the P and PK treatments. This suggests possible antagonistic effects of fertilization on uptake of these nutrients. However, in the 1987 NPK treatment (Fig. 4) and in all the 1988 fertilization treatments (Fig. 5), nutrient concentrations decreased while foliar weights increased significantly. This suggests "false antagonism" or "dilution" of these elements as a result of increases in foliar biomass.

DISCUSSION

The establishment and growth of trees on drained peatlands are often limited by availability of N, P and/or K. There is general agreement that P is the major element required at planting time (e.g., Wright 1959, Dickson 1965, O'Carroll 1967, Carey et al. 1984). Nitrogen and K may also be required at that time, but, depending on the fertility of the site and the species planted, these elements may become limiting to growth at some later stage. For example, on nutrient-poor sites in the United Kingdom and Ireland, both lodgepole pine and Sitka spruce require PK fertilization at the time of establishment; however, Sitka spruce generally requires additional N inputs every 3 to 4 years, starting at ages 8 to 10 years and continuing until crown closure (Jack 1965; Dickson 1965, 1971; Carey et al. 1984; Taylor 1986).

The nutrient status of peatlands and the nutrient requirements of Japanese larch growing on these sites in

Newfoundland were relatively unknown at the time of planting in 1968. At that time, P was applied, and in 1970, P and K were added. Additional fertilizers were not applied until 1985, when the present experiment was established. Foliar nutrient analyses at that time indicated that concentrations of N (1.03%), P (0.12%) and K (0.45%) (Table 1) were all below the required deficiency/optimum ranges described by Binns et al. (1980) and Leyton (1956, 1957) for Japanese larch in the United Kingdom. Unfortunately, since the nutrient status of these peatland plantations was not monitored over the years, determination of when nutrients became deficient and limiting to growth is difficult.

Height and diameter growth, and increases in foliar biomass, responded positively to NPK fertilization during all three growing seasons of the study. The increased growth in the P and PK treatments in 1988, 3 years after fertilization, also suggests a possible delayed growth response to those treatments. Although foliar weights remained higher in the NPK treatments in 1988, differences among the other treatments were not significant ($P \leq 0.05$, Table 4). However, in both years, the mean needle weights (2.28 mg in 1987 and 1.16 mg in 1988, Table 4) were less than the mean needle weight (3.0 mg) identified by Binns et al. (1980) as the value below which growth of Japanese larch is characteristically poor.

In 1988, needle weights in all of the treatments were only about half those in 1987 (Table 4). One possible explanation is that a physiological response of the trees to moisture stress occurred during the 1987 growing season. During that period, the climate throughout Newfoundland, as well as most of Atlantic Canada, was characterized by record high temperatures and hours of sunshine, as well as by record low amounts of rainfall (Scholefield 1987a, b, c; Shabbar 1987). This was followed in 1988 by above-average production of flowers by most trees species and, in the case of conifers, an extremely high cone production throughout the province. As a physiological response to moisture stress in 1987, the trees possibly responded, in 1988, by allocating much of their available energy and nutrient resources to seed production rather than to vegetative production of biomass such as needles (e.g., Harper 1970, Kimmins 1987). Similar results occurred in black spruce trees on an adjacent peatland plantation, as well as in peatland plantations of black spruce and lodgepole pine in central Newfoundland (E.D. Wells, unpublished data).

Two and 3 years after refertilization of Stephenville Bog, it was clear that P and, to a lesser extent, K were growth-limiting elements: the length of the foliar nutrient vectors (Fig. 4 and 5) is an indication of significant uptake of these elements. Although the vectors for N are considerably shorter than those for K and P, evidence that N was the nutrient most limiting to tree growth was clearly demonstrated by the increases in foliar weight when N was applied in combination with P and K (NPK treatment, Table 4; Fig. 4 and 5). Additions of P and K in the absence of N resulted in very little increase in growth over that of the control. Since significant increases in concentrations of P and K occurred (in 1987) without any accompanying increase in foliar weight (Table 5), the uptake of these two elements must be considered luxury consumption in the absence of N fertilizer.

The positive growth response of Japanese larch on Stephenville Bog to the addition of N may also be attributed to the presence of added P in the NPK fertilizer. For example, in Holland, Van Goor (1953) found relationships among growth of Japanese larch, concentrations of soil P and soil N, and fertilization with these elements. Growth of larch planted on soils poor in P decreased when N fertilizer was applied. However, in a soil rich in phosphate, growth was increased by the addition of N.

The immediate effect of fertilization on tree growth, and the duration of the effect, appear to depend on the nutrient status of the site as well as the nutrient requirements of the tree (e.g., Karsisto 1974, Paavilainen and Simpanen 1975, Kaunisto 1982). The total N concentrations of surface peats similar to those of the Stephenville site are about 0.76% (Pollett 1972). This value is considerably less than the critical range of 1.10 to 1.15% defined by Kaunisto (1984), below which NPK fertilization is required to improve growth of Scots pine *(Pinus sylvestris)* on such sites in Finland. Furthermore, when total peat N is between 1.30 and 1.40%, N fertilization is not required. If the N concentrations are 1.90% or more, NPK fertilization is unnecessary and will likely cause a decline in growth.

The significant growth response to NPK fertilization and the limited growth response to P and PK fertilization on the Stephenville site is similar to results obtained in peatland afforestation studies in Finland. However, since fertilization in the spring of 1986, foliar nutrient concentrations have decreased (in 1988) almost to original levels (Table 5), and this suggests that the duration of the effect of fertilization may be shortlived. Furthermore, since foliar nutrient concentrations were not determined for the Stephenville Bog plantation until 1985, determining the duration of the effect of early fertilization (at planting time) and the time when levels of N, P and K became limiting to growth may now be possible only through analysis of growth rings.

In summary, low levels of N, P and K all appear to limit growth of Japanese larch on N-poor peatlands in Newfoundland. The low concentrations of these elements in the foliage 3 years after refertilization suggests that the effect of the fertilizers has been greatly reduced; however, further annual foliar analyses and growth measurements are recommended for determination of the duration of the effect of these fertilizers. In the future, PK (and possibly N) fertilization at planting time, followed by annual monitoring of foliar nutrient concentrations, is strongly recommended for planting on such nutrient–poor sites in Newfoundland.

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Section VI
Hydraulic Conductivity

LOW HYDRAULIC CONDUCTIVITY IN CATOTELM LIMITS EFFECTIVENESS OF DRAINAGE

J.L. Bélair
Forestry Canada
Quebec Region
Ste-Foy, Quebec
Canada

ABSTRACT

In 1985, a drainage network was established, through a federal program, on private woodlots in St-Bruno-de-Kamouraska. One of the aims of the project was to determine where the water table would stabilize after drainage. In 1986 and 1987, water-table measurements were taken in a raised bog at five distances from the main ditch. The measurements, except for short distances, revealed a non-significant drop in the water tables. A high water table, even after drainage, is likely due to the presence of a layered peat with an almost impermeable layer (catotelm) at a depth of 0.50 m.

RÉSUMÉ

Un réseau de fossés a été aménagé en 1985 dans des boisés privés de Saint-Bruno-de-Kamouraska en vertu d'un programme fédéral. Ce projet avait de nombreux objectifs, mais l'un d'eux était de déterminer si la nappe phréatique se stabiliserait après l'aménagement de fossés. Les mesures de la nappe phréatique prises en 1986 et 1987 dans une tourbière bombée à 5 distances différentes du fossé principal ont révélé des différences significatives entre 2,5 + 5 m et 10 + 20 m. Toutefois, les nappes phréatiques proches du fossé étaient toujours à moins de 30 cm de la surface, même après le drainage, probablement en raison de la présence de tourbe stratifiée comportant une couche presque imperméable (catotelme) à une profondeur d'environ 0,50 m.

INTRODUCTION

Forest drainage involves the lowering of a groundwater table that is regarded as limiting to tree growth. Highly successful forest drainage has been carried out in many parts of the world (e.g., Finland, the USSR and the United States). Although current knowledge of forest drainage under Canadian conditions is limited (Hillman 1987), private woodlot owners in Quebec would like to establish drainage as a silvicultural treatment. Many of them already have experience with drainage in agriculture, as well as knowledge of the benefits derived from drainage, and this is reflected in their annual and perennial crops.

In eastern Quebec, pilot projects were started by the federal government on private woodlots to evaluate the degree of difficulty involved in drainage. It was essential to monitor the groundwater table to determine the effects of drainage. Therefore, an experiment was established in the St-Bruno-de-Kamouraska drainage area in the fall of 1985 to enable us to determine the depth at which the groundwater table would stabilize after drainage, and to explain why it responded as it did.

BACKGROUND

In artificial drainage, hydraulic conductivity is the single most important factor to be considered (Rycroft et al. 1975a,b). Many have studied vertical (K_v) and horizontal (K_h) hydraulic conductivity for different purposes. Boelter (1965) found no significant differences between the two. There are two distinct layers in peat material, the acrotelm and the catotelm (Ivanov 1981; Ingram 1978, 1983; Chason and Siegel 1986), with very different hydraulic conductivities. The auger-hole method, for measuring hydraulic conductivity, is considered the best field method because it is more representative of the natural heterogeneity of the soil than other methods that use smaller samples (Chason and Siegel

1986). Hydraulic conductivity measured at different groundwater table heights, in a peatland near Quebec City, was shown to fall rapidly to a depth of 20 cm, and to remain stable for the next 40 cm[1]. The relation between K and depth was similar to that found by Päivänen (1973) in *Sphagnum* peat.

SITE DESCRIPTION

The site is located at St-Bruno-de-Kamouraska, 150 km from Quebec City at latitude 47°30′ N and longitude 69°43′ W.

The watershed area is 230 ha and the peatland occupies 70 ha, or 30% of the area. The length of the main ditch is 3 km and the width of the watershed is 0.8 km.

The total length of lateral ditches is 7 km. Total drainage intensity is 140 m/ha with a spacing of 120 m between the lateral ditches. The ditches were dug in August of 1985. The depth of the main ditch at the site is about 1.5 m.

The center of the peatland is occupied by a raised bog; the vegetation includes stunted black spruce (*Picea mariana*), all from layering, ericaceous plants, and *Sphagnum*. At the edge of the bog is a swamp in which black spruce grows much better and the lower vegetation is dominated by *Carex* species. This gives way gradually to swamp dominated by eastern white cedar (*Thuja occidentalis*).

The center of the bog has ± 2 m of organic material underlain by fluvial material on glacial till. The fine fluvial material forms an impermeable layer, deposited by flooding of adjacent Rivière du Loup, which has also left a natural levee. On the upper part of the watershed, there is glacial till with a fragipan at ± 50 cm. A network of sorted polygons rests on the fragipan, covered by 10 to 15 cm of organic material; these polygons continue under deeper layers of organic material for an unknown distance. The polygons are of the same kind as those found in the permafrost areas of the north, except that they are hidden beneath an organic horizon. They undoubtedly have a great influence on groundwater movement and on the shape of the water table.

MATERIAL AND METHODS

This study dealt with the raised bog area only. Water wells were established on three lines (A, B and C) (Fig. 1), starting in the main ditch, at distances of 0.0 (ditch), 2.5, 5, 10, 20 and 40 m. One line (line B) was established in the middle of two lateral ditches, and the other two were established 20 m from the lateral ditches.

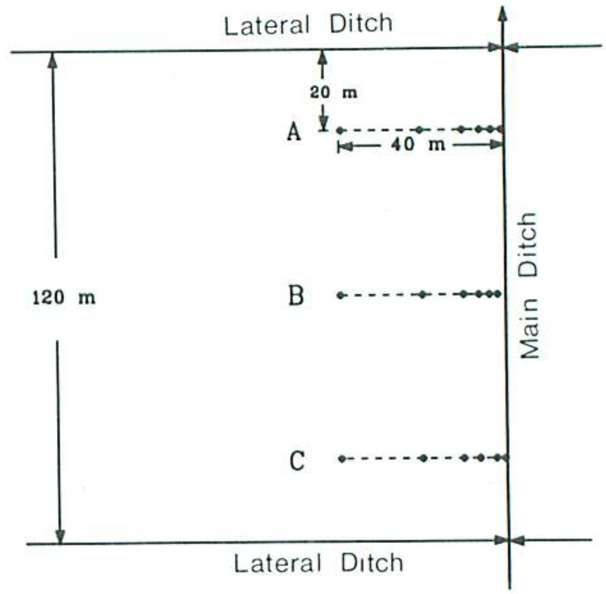

Figure 1. Experimental design with water wells (points) along survey lines A, B and C.

In 1986, 51 readings were taken between 20 May and 3 November, and in 1987, 103 readings were taken between 20 April and 30 October. Readings were taken with a homemade device in which the water surface is used as a conductor between two electrodes linked to a buzzer.

Statistical analysis was carried out with the three lines as replications and the wells as fixed effects. The 40-m distance was not retained in the analysis because lines A and C were 20 m from lateral ditches.

Hydraulic conductivity was measured according to the auger-hole method (van Beers 1958) as it is used for layered soil when the water table lies in the upper layer. This method gives K_1 and K_2 values. The readings were taken twice, except for hole number one (Table 1).

Total porosity, volumetric water content, and bulk density were measured on blocks of ± 30 cm 2^3 obtained from larger blocks of ± 30 x 20 x 20 cm cut with a chainsaw. These analyses were completed according to the methods outlined by the Canada Soil Survey Committee (McKeague 1978) for paraffin-coated samples.

[1] Belleau, P. 1988. Drainage d'une pessière noire à sphaigne et à némopanthe mucroné. Univ. Laval, Master's thesis

Table 1. Hydraulic conductivity trials field data

Hole	Digging	Reading	Temp	Shallow hole				Deep hole[a]					
				N[b]	F[c]	H[d]	Y_o[e]	N	F	H	Y_o	K_1[f]	K_2
no.	date	date	°C	cm				cm				m	d^{-1}
1	10.19.88	10.21.88	5	32	53	21	13	32	168	136	53	2.9	~0
2	10.19.88	10.21.88	5	35	64	29	11.5	35	112	77	24.5	8.6	~0
2	10.19.88	11.18.88	3	28	60	32	18	28	111	83	29	10.7	~0
3	10.19.88	10.21.88	5	25	56	31	24.2	25	111	86	44	2.3	~0
3	10.19.88	11.18.88	3	21	56	35	19	21	111	90	46	4.6	~0

[a] = Holes protected from collapsing by a 10-cm plastic drain

[b]N = water-table depth

[c]F = depth of hole

[d]H = depth of hole below water table

[e]Y_o = distance between water table and water in hole at time of first reading

[f]K_1 = hydraulic conductivity of upper layer

K_2 = hydraulic conductivity of lower layer

RESULTS AND DISCUSSION

Data taken before 15 June were not included in the analysis of the water table because, before this date, the frost was so close to the surface that the shape of the water table was affected. Under black spruce, frost has been observed until the end of July. Figure 2 shows the water-table profiles for 1986 and 1987 as the highest, lowest, and mean altitudes for the three lines.

Table 2 presents the data in terms of water-table altitude, depth, and hydraulic head for all the distances. The water table was horizontal starting at 10 m from the ditch, and the water-table depth was lowest at 40 m because the soil surface is slightly lower at this point. Although 1986 was a wetter season than 1987, the hydraulic head was very constant for distances of 10 m or more for both years. The difference in rainfall explains

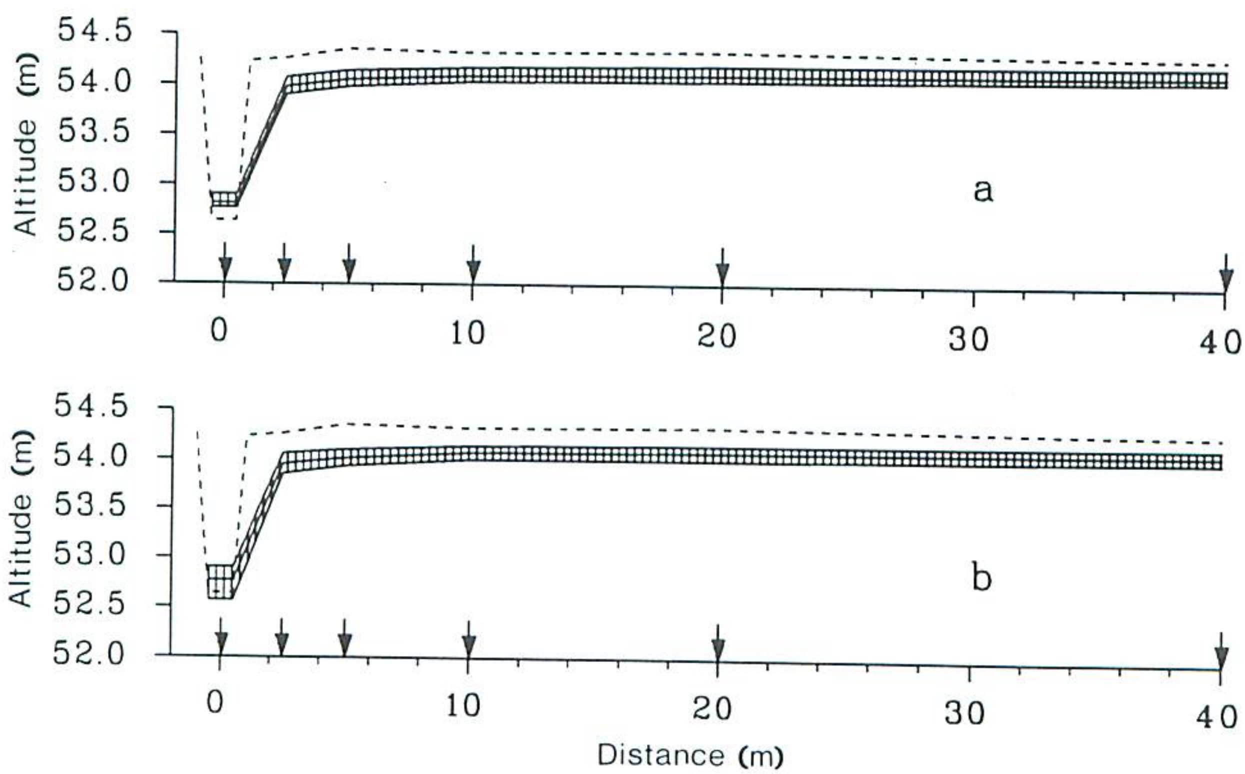

Figure 2. Soil surface (dotted line), water wells (arrows) and the highest, lowest, and mean groundwater table (shaded range) from 15 June to 30 October, 1986 (a) and 1987 (b).

Table 2. Data for the water table at the different distances after 15 June
(Each distance represents the mean of the points along three lines of water wells.)

Distance (m)	Soil-surface altitude (m)	Water-table altitude (m)		Water-table depth (m)		Hydraulic head (m)	
		1986	1987	1986	1987	1986	1987
0.0	52.64	52.81	52.78	N/A	N/A	N/A	N/A
2.5	54.26	53.98	53.95	0.28	0.31	1.17	1.17
5.0	54.35	54.05	54.01	0.30	0.34	1.24	1.23
10.0	54.32	54.09	54.07	0.23	0.25	1.28	1.29
20.0	54.33	54.10	54.08	0.23	0.25	1.29	1.30
40.0	54.27	54.10	54.08	0.17	0.19	1.29	1.30

why the water table was slightly deeper in 1987 than in 1986 for distances of 5 and 2.5 m. The difference in 1986 in the mean altitude of the groundwater table between the distances of 2.5 and 20 m was 0.12 m, with a total variation of 0.17 m at the 2.5-m distance and 0.15 m at the 20-m distance. The difference in 1987 was 0.13 m between 2.5 and 20 m, with a total variation of 0.21 m at 2.5 m, and 0.15 at 20 m.

In freshly opened soil pits and at the sides of ditches, water seeped out of the acrotelm, but not out of the catotelm, which starts about 0.50 m below the surface.

Hydraulic conductivity was measured to detect any difference between the two layers. Because the acrotelm was not very thick, it was difficult to achieve the minimum conditions required for the auger-hole method, and consequently experimental error increased. Because the surface of the peat was hummocky, the water-table depth of the deep hole had to be adjusted to the same ground surface level as the water-table depth of the shallow hole. The results are presented in Table 1. The calculated K_2 values are negative because of experimental error. The K_1 values are very high, and the K_2 values should be close to 0, an indication that the catotelm could be considered an impervious layer for drainage purposes.

On the basis of the mean altitude of the groundwater table (Table 2), the difference between the 2.5 + 5-m distances and the 10 + 20-m distances was very significant ($p < 0.01$, Table 3). The 2.5- and 5-m distances were also significantly different ($p < 0.01$). The difference between the 10- and 20-m distances was not significant (at $p = 0.05$). These findings held for both years.

A positive correlation between the von Post humification scale and bulk density has been reported (Silc and Stanek 1977). According to that correlation, a bulk density between 0.10 and 0.15 (Table 4) would indicate a von Post degree of humification between 3 and 6. The field data indicated a humification value slightly higher, about 7. On the other hand, the relation between K and the degree of decomposition has been established as negatively correlated (Päivänen 1973).

The bulk density data below 45 cm (Table 4) do not suggest a high degree of decomposition and certainly not an extremely low hydraulic conductivity. Another process must be involved. It is possible that the pores of the catotelm are obstructed by colloidal matter because, with hand-squeezing, dark water issued from the material. It was very unstable, almost turning to liquid after being disturbed. For this reason the sides of the deep

Table 3. Anova for 1986 and 1987 data for distances from the main ditch
(2.5 m [1], 5 m [2], 10 m [3] and 20 m [4])

Year	Source	df	SS	MS	F	R^2
1986	model	5	0.033	0.0066	46.28	0.97
	error	6	0.0009	0.00014		
1987	model	5	0.035	0.007	13.61	0.91
	error	6	0.038	0.00052		
Year	**Contrast**	**df**	**SS**		**F**	**P**
1986	12 vs 34	1	0.022		150.06	0.0001
	1 vs 2	1	0.008		55.08	0.0001
	3 vs 4	1	0.0004		2.88	0.1403
1987	12 vs 34	1	0.020		40.11	0.0007
	1 vs 2	1	0.012		23.39	0.0029
	3 vs 4	1	0.00015		0.29	0.6103

Table 4. Bulk density on humid basis (mean of 3 samples)

Depth (cm)	Total porosity (%)	Water (%)	Bulk density ($g\ cm^{-3}$)
0 – 10	95.07	50.48	0.07
10 – 20	94.64	70.31	0.08
20 – 30	94.22	78.57	0.08
30 – 45	96.01	91.62	0.06
45 – 60	92.57	87.41	0.10
60 – 80	90.03	84.39	0.14

holes had to be retained by a plastic drain. Another reason for the low hydraulic conductivity could be the influence of methane gas, as an inhibitor of water movement, reported by Mathur et al. (1990) in these proceedings.

CONCLUSION

On this raised bog site, study of freshly open pits and the positioning of the groundwater table over a two-year period indicated that the catotelm, which started 0.50 m below the surface, was impermeable as far as drainage was concerned. This was confirmed by hydraulic conductivity measurements for layered soils.

Evapotranspiration is a significant factor in lowering the groundwater table (Dutil et al. 1989). The maximum depth reached by the water table is explained by the combined effects of ditching and evapotranspiration. Without evapotranspiration, ditching would be less efficient in lowering the water tables than was observed in this study.

If we assume that a distance of 2.5 m from the ditch would be approximately equivalent to a spacing of 5 m, with an impermeable layer at 0.50 m, it would be useless to ditch at a lower level, unless possible changes in the physical properties of the catotelm over the long term were considered. Ditching with 5-m spacing would create a well aerated zone deep enough for growing trees, but with the high porosity of the acrotelm (Table 4) and its high water yield (Boelter 1964), overdrainage of the acrotelm must be considered.

ACKNOWLEDGMENTS

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ESTIMATION OF THE HYDRAULIC CONDUCTIVITY OF PEAT FROM BULK DENSITY AND VON POST DECOMPOSITION

A.P. Plamondon
Département des sciences forestières
Faculté de foresterie et de géodésie
Université Laval
Ste-Foy, Québec
Canada

P. Belleau
Syndicat des producteurs de bois
du Bas Saint-Laurent
Ste-Foy, Québec
Canada

ABSTRACT

This study was established to investigate the possibility of using indirect measures of bulk density and von Post decomposition scale to evaluate the hydraulic conductivity of peat by comparing values measured in the field and the laboratory. The sites were divided into two groups. Group 1 sites had shallower peat depths (1 m), higher bulk densities and lower hydraulic conductivities than Group 2 sites. The relationship between hydraulic conductivity measured in the laboratory and either bulk density or von Post decomposition rating was the same for the two groups. Hydraulic conductivity was calculated for each depth on the basis of the depth-bulk density and the bulk density-conductivity relations developed in the laboratory. For the 20- to 50-cm layer, the calculated conductivities were very close to those measured in the field. A similar procedure using the relationships between the depth-von Post scale and von Post-conductivity yielded higher conductivity values than those measured in the field. The results indicated that the approach can be recommended for comparing sites and ranking them according to their potential for drainage and for preliminary drainage planning. For hydrological studies or for modeling the effects of drainage, direct measures of hydraulic conductivity are still desirable.

RÉSUMÉ

La conductivité hydraulique est l'un des principaux facteurs permettant de déterminer les avantages que pourrait procurer le drainage d'une tourbière. La présente étude se penche sur la possibilité d'utiliser une méthode indirecte d'évaluation de la perméabilité de la tourbe en comparant les valeurs mesurées sur le terrain et en laboratoire avec celles de la profondeur de la tourbe, de la densité apparente et du degré de décomposition de la tourbe mesurée grâce à la méthode de von Post. Les stations ont été divisées en 2 groupes. La couche tourbeuse de 1 m d'épaisseur des stations du groupe 1 avait une densité apparente plus élevée et une plus faible conductivité hydraulique que la tourbe plus profonde (de plus de 1,5 m) des autres stations. La relation entre la conductivité hydraulique mesurée en laboratoire et la densité apparente ou l'indice de décomposition de von Post ne différait pas entre les 2 groupes. La conductivité hydraulique a été calculée pour chacune des profondeurs selon des relations profondeur-densité et densité-conductivité élaborées en laboratoire. Dans le cas de la couche de 20 à 50 cm, les conductivités calculées étaient très près de celles mesurées. Une méthode similaire basée sur la relation entre la profondeur et l'indice de von Post, et entre l'indice de von Post et la conductivité, a donné des valeurs plus élevées que la conductivité mesurée au champ. Les résultats étaient tels que l'approche peut être recommandée pour comparer des stations et les classer selon leur potentiel de drainage et ainsi qu'à des fins de planification préliminaire du drainage. Il est toutefois souhaitable de mesurer directement la conductivité hydraulique dans le cas d'études hydrologiques ou de modélisation des effets de l'aménagement de fossés.

INTRODUCTION

In several studies the efficiency of drainage as a means of modifying the water regime (Trottier 1986) and of improving growing conditions of forest sites (Hillman 1987) has been demonstrated. A water table of at least 30 to 40 cm under the soil surface should assure sufficient aeration to increase the growth of many tree species significantly (Päivänen 1973, Braekke 1983). The downward movement of the water table after rainfall must be sufficiently rapid to maintain good growing conditions (Toth and Gillard 1988). Evapotranspiration and drainage are responsible for the declining level of the water table.

Hydraulic conductivity is a key factor in the prediction of the potential benefits of peatland drainage. The contribution of drainage can be evaluated by mathematical models (Guyon 1978, Riedl 1984, Belleau[1]), with hydraulic conductivity as the most important parameter (Lagacé 1981). Because measurement of hydraulic conductivity is quite laborious, it could be useful to evaluate this parameter by indirect means for the conditions found in Canada. The object of this study was to relate hydraulic conductivity, measured both in the laboratory and in the field, with measures of bulk density and degree of decomposition.

[1] Belleau, P. 1988. Drainage d'une pessière noire à sphaigne et à némopanthe mucroné. Univ. Laval, Thèse de maîtrise. 82 p.

SITE AND METHOD

The study took place in 1988 on 12 forest sites (Table 1) located in the Saint Lawrence Lowlands (Fig. 1). Group 1 sites were located at Saint-Gilles de Lotbinière and Saint-Jean Chrysostome, while Group 2 sites were at Lemieux. Several of the sites had been drained previously by digging 1-m-deep ditches with 1:1 side slopes.

The average July maximum and January minimum temperatures were 24 and -17°C, respectively. Total precipitation from May to September averaged 500 mm, and the potential evapotranspiration calculated by Thornthwaite's method was 560 mm (Wilson 1971). The length of the vegetative season averaged 185 days (Dumas-Rousseau 1975).

The saturated hydraulic conductivity (K_{fld}) in m/day was measured in the field by the auger hole method (van Beers 1970). With this technique, the rate at which the water entered a cylindrical hole 10 cm in diameter was measured after removal of the water. The hole was excavated with an auger and the sides were retained with a perforated drainage pipe. Five holes were dug to a depth of 1 m at each site. Two measurements were obtained from each hole.

Table 1. Description of the study sites

Study area	Site	Drainage year	Peat type	Peat depth (m)	Forest type
Group 1 Sites					
St-Gilles	A	1987	Sphagnum (Carex)	1	*Picea mariana*
	B	Undrained	Sphagnum (Carex)	0.9	*Picea mariana*
	C	Undrained	Sphagnum	1	Open
St-Jean Chrysostome	D	1983	Sphagnum	0.9	*Larix laricina*
Group 2 Sites					
Lemieux	E	1983	Ligneous (Hypnum)	>1.5	*Picea mariana*
	F	1983	Ligneous (Carex)	>1.5	*Picea mariana* *Abies balsamea*
	G	1983	Carex	>1.5	*Picea mariana*
	H	1983	Ligneous (Carex)	>1.5	*Abies balsamea* *Thuja occidentalis*
	I	1983	Ligneous	>1.5	*Thuja occidentalis* *Abies balsamea*
	J	1983	Ligneous (Carex)	>1.5	*Abies balsamea* *Thuja occidentalis*
	K	1983	Ligneous (Carex)	>1.5	*Larix laricina* *Picea mariana*
	L	1983	Sphagnum (Carex-Hypnum)	>1.5	*Picea mariana* *Larix laricina*

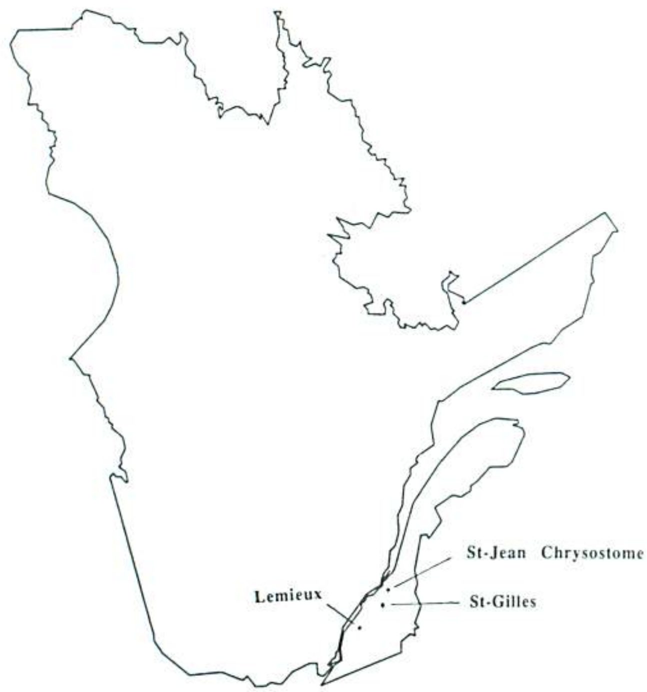

Figure 1. Location of study sites.

Two peat samples were collected horizontally at 10-, 20-, 30-, 50-, 70-, and 90-cm depths with aluminum cylinders 15 cm in length and 7.35 cm in diameter. In the undecomposed surface layer, the samples were cut manually. A constant-charge permeameter was used to measure, twice on each sample, the horizontal conductivity in the laboratory (K_{lab}). The conductivity in the horizontal direction is higher than that in the vertical, owing to the orientation of the fibers (Edil et al. 1986). The hydraulic gradients were maintained between 1.4 and 7.4. This varied, depending on the conductivity of the peat, higher gradients being used for less conductive peats to reduce the measuring times. Care was taken that the hydraulic charge was not so high that artificial channels would be created, giving artificial increases in K_{lab} (Ingram et al. 1974, Rycroft et al. 1975, Waine et al. 1985). Bulk density was obtained after the samples had been dried at 100°C for 24 hr (Table 2).

RESULTS AND DISCUSSION

Field-measured Hydraulic Conductivity

Filed-measured hydraulic conductivity (K_{fld}), expressed as a function of water-table depth (Fig. 2), was lower at Group 1 sites than at Group 2 sites, where the peat layer was deeper. The ligneous nature of the peat (Table 1) and the lower bulk density (Fig. 3) for Group 2 explain most of these differences. The variation in permeable depth beneath the holes could also account for some of the differences. The higher degree of peat decomposition for Group 2, for a given bulk density (Fig. 4), did not offset the effects of bulk density on conductivity.

Bulk Density in Relation to Depth and von Post Decomposition

Bulk density (D) decreased in both directions from a maximum value at a depth (Z) of 50 cm (Fig. 3). The Z-D relation (equations 1 and 2) was statistically significant but explained only 69% and 30% of the variation for groups 1 and 2, respectively. The coefficients of variation were, respectively, 17.7 and 35.5%.

$$D = 0.021 + 0.0065\ Z - 6.0425 \times 10^{-5}\ Z^2 \quad \text{(Group 1)} \quad (1)$$

$$D = 0.059 + 0.003\ Z - 2.906 \times 10^{-5}\ Z^2 \quad \text{(Group 2)} \quad (2)$$

The 70- to 90-cm peat layer in both groups, being derived principally from *Carex* spp., had a lower bulk density. Although the bulk density of peat generally increases with depth (Hänninen 1983, Boelter 1965), reverse trends have sometimes been reported elsewhere (Edil et al. 1986). It is expected that drainage will reduce the variations in density with depth because of accelerating decomposition (Päivänen 1973) and will increase the density of the surface layer (Edil et al. 1986).

Table 2. Average peat bulk density and hydraulic conductivity measured in the laboratory (standard deviation)

	Group 1 sites		Group 2 sites	
Depth (cm)	Hydraulic conductivity ($m\ d^{-1}$)	Bulk density ($g\ cm^{-3}$)	Hydraulic conductivity ($m\ d^{-1}$)	Bulk density ($g\ cm^{-3}$)
10	418 (290)	0.073 (0.03)	359 (282)	0.073 (0.03)
20	2.9 (3.5)	0.133 (0.04)	81 (172)	0.123 (0.03)
30	0.3 (0.3)	0.161 (0.02)	2.5 (5.1)	0.137 (0.03)
50	0.1 (0.1)	0.186 (0.03)	2.9 (5.0)	0.143 (0.02)
70	0.2 (0.3)	0.172 (0.03)	0.5 (0.4)	0.122 (0.03)
90	0.004 (0.007)	0.150 (0.01)	2.7 (7.1)	0.114 (0.02)

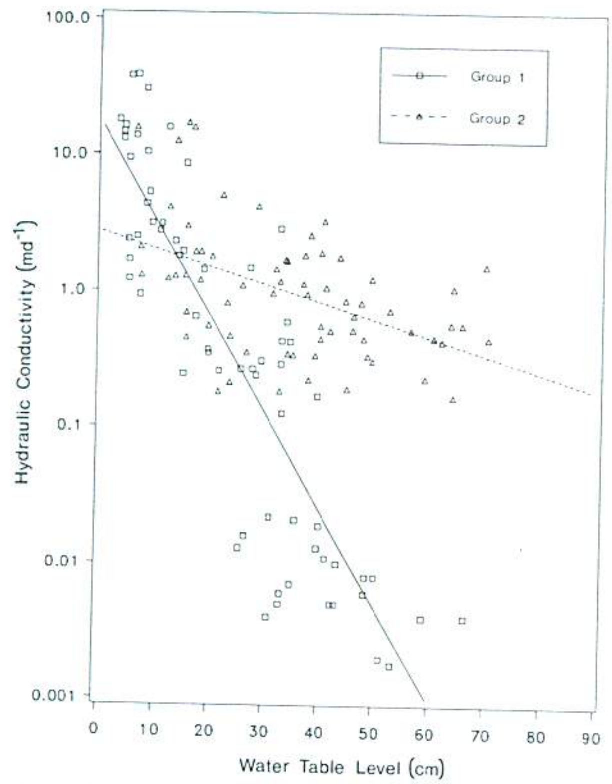

Figure 2. Field-measured hydraulic conductivity in relation to water-table depth.

The degree of decomposition of peat can be determined from its fiber content (Laine and Päivänen 1982) or through the use of the von Post decomposition scale (Rycroft et al. 1975). The latter method, though subjective, is used because it is quick and easy to apply in the field.

On our sites, there was a shallow fibric layer of peat (cf. Canada Soil Survey Committee 1978) in the top 10-20 cm. The passage between the fibric and mesic horizons was continuous. For a given bulk density, the peat was more decomposed in Group 2 sites. However, the bulk densities, averaging 0.15 g cm^{-3} and 0.12 for Group 1 and Group 2 sites, respectively, indicate a slightly lower overall degree of decomposition for Group 2.

With all the data grouped, the linear relation between bulk density and von Post rating was significant (P = 0.0001), and explained 36% of the variation. The slope was about 0.015 g cm^{-3} per von Post unit. Silc and Stanek (1977) obtained a more significant linear relation (r^2 = 0.88) and a slope of 0.02 g cm^{-3} per degree von Post when they used ligneous peat only. In the present case, when we limited our analysis to 1-6 degrees von Post, the coefficient of determination reached 0.49 and the slope was also 0.02 g cm^{-3} per degree von Post.

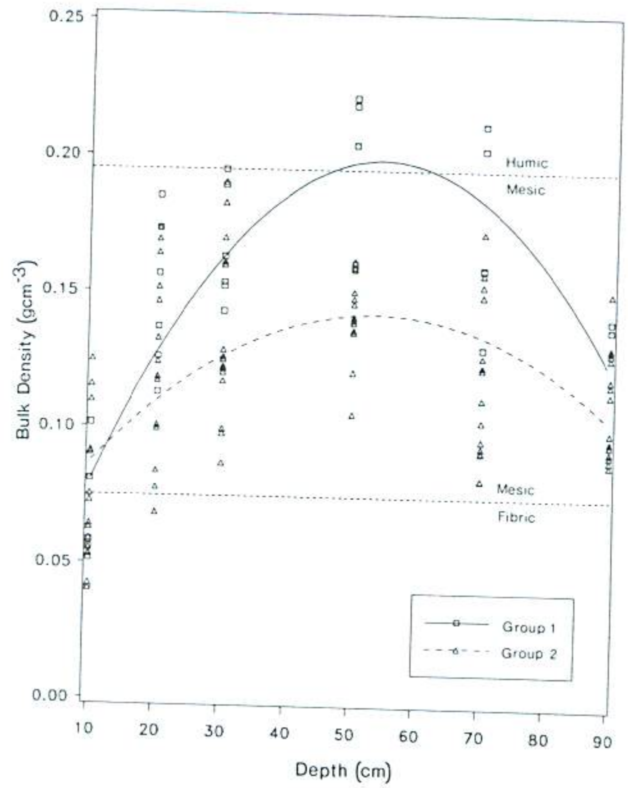

Figure 3. Peat bulk density in relation to peat depth.

Hydraulic Conductivity Measured in the Laboratory

The logarithm of saturated hydraulic conductivity measured in the laboratory (K_{lab}) was linearly related (Fig. 5, equation 3) to bulk density. When the data from all sites were pooled, the coefficient of determination reached 0.57 in spite of the great variability in peat material (Novikov et al. 1972).

$$\log(K_{lab}) = 3.595 - 28.242\,D \qquad r^2 = 0.57 \qquad (3)$$

Boelter (1969) and Päivänen (1973) obtained similar coefficients (equations 4 and 5) when they used the piezometer method to measure the conductivity of different peat layers. However, the slopes of equations 4 and 5 were about half of those calculated in this study, an indication of a slower decrease in conductivity with increased density.

$$\log(K_{lab}) = 1.348 - 16.068\,D \qquad r^2 = 0.54 \qquad (4)$$

$$\log(K_{lab}) = 0.731 - 15.224\,D \qquad r^2 = 0.51 \qquad (5)$$

The relation (Fig. 6, equation 6) between K_{lab} and the von Post degree of decomposition (VP) explains 45% of the variation. A single regression can be applied for all sites.

$$\log(K_{lab}) = 2.405 - 0.577(VP) \qquad r^2 = 0.45 \qquad (6)$$

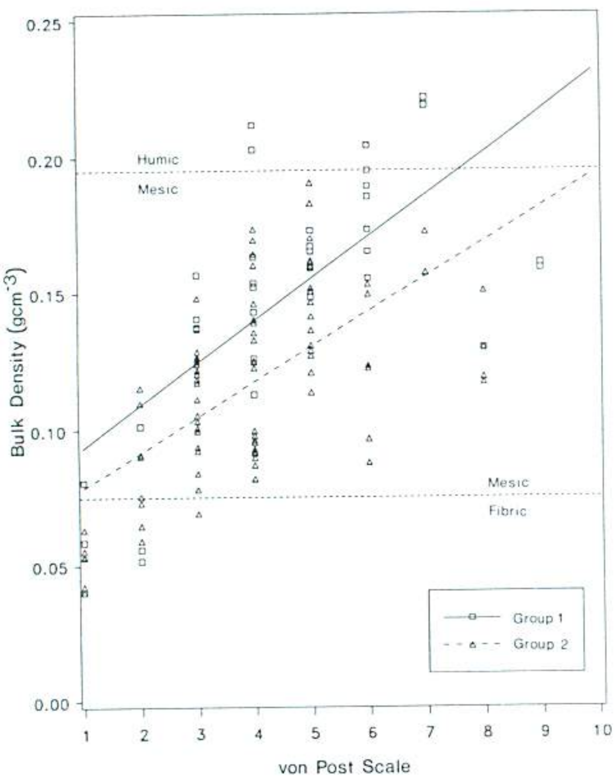

Figure 4. Peat bulk density in relation to degree of decomposition on the von Post scale.

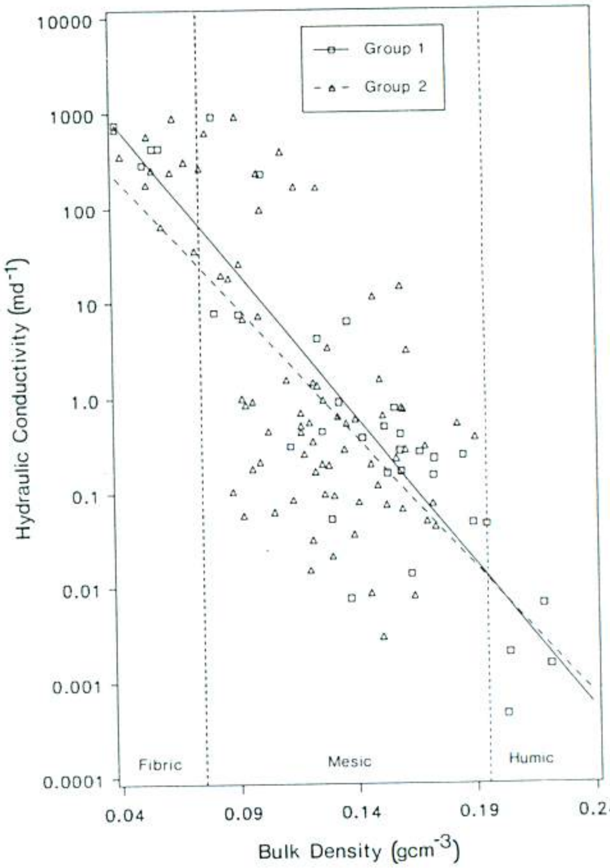

Figure 5. Hydraulic conductivity in relation to peat bulk density.

The relation between hydraulic conductivity and degree of decomposition was not as good as that with bulk density. However, the small difference between the two suggests that the degree of decomposition could be used instead of the more laborious determination of bulk density, when the object is to order the sites according to their potential response to drainage. It is important to note that the relation between hydraulic conductivity measured in the laboratory, and bulk density or von Post degree, did not differ between the two groups of sites. Therefore, this approach may be useful.

Prediction of Hydraulic Conductivity

Hydraulic conductivity was estimated for various depths from the depth-density and the density-laboratory conductivity relations. Calculated conductivities were similar to field-measured conductivities (Table 3) for the 20-, 30- and 50-cm depths.

When the same type of relation with von Post degree of decomposition was used, calculated conductivities overestimated field conductivities, especially on Group 2 sites. However, the data obtained for the 20- to 50-cm layers seemed good enough for site comparisons and preliminary planning.

Table 3. Comparison between calculated and measured hydraulic conductivities

Depth	Group 1 sites			Group 2 sites		
	Bulk density	K_{lab}	K_{fld}	Bulk density	K_{lab}	K_{fld}
(cm)	(g cm^{-3})	(cm d^{-1})	(cm d^{-1})	(g cm^{-3})	(cm d^{-1})	(cm d^{-1})
10	0.08	40	3	0.08	15	2
20	0.13	1.16	0.08	0.11	3.1	2
30	0.16	0.11	0.11	0.13	1.0	1.04
50	0.20	0.01	0.007	0.14	0.9	0.8

CONCLUSION

The relation between hydraulic conductivity measured in the laboratory and bulk density or von Post decomposition rating did not differ among sites. Therefore, these relations may be applicable over a wide range of sites within the Saint Lawrence Lowlands. We believe that it is worth pursuing the use of these indirect measures for evaluating hydraulic conductivity. Conductivity calculated from bulk density or the von Post rating provides relative values that should be sufficient

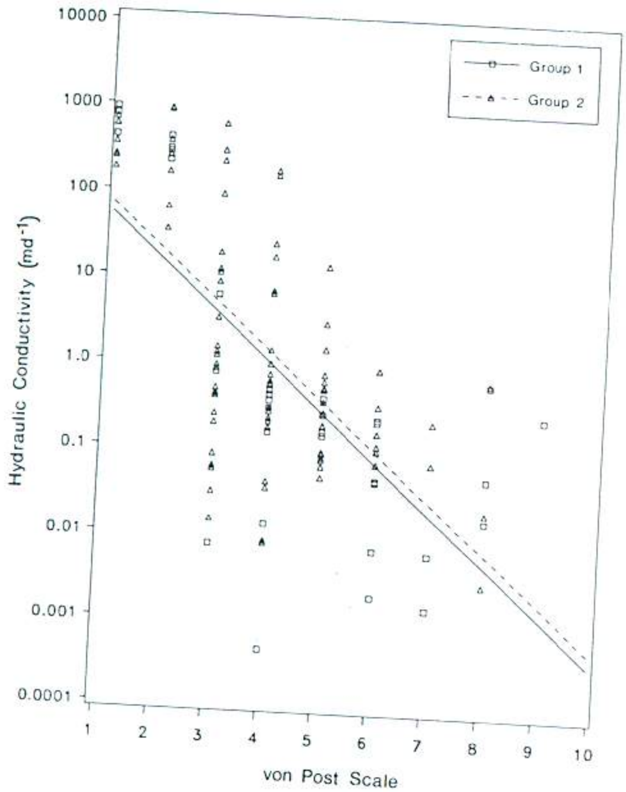

Figure 6. Hydraulic conductivity in relation to von Post degree of decomposition.

for choosing which sites should be drained, as well as the approximate ditch spacing. For studies of hydrological processes or for modeling the effects of drainage, direct measurements are still desirable.

ACKNOWLEDGMENTS

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THE ROLE OF METHANE GAS IN PEATLAND HYDROLOGY: A NEW CONCEPT

S.P. Mathur[1], A. Brown[2], H. Dinel[1], A. Buttler[3] and M. Levesque[1]

[1] Land Resource Research Centre
Agriculture Canada
Ottawa, Ontario

[2] National Research Council of Canada
Ottawa, Ontario

[3] University of Neuchatel,
Neuchatel, Switzerland

ABSTRACT

We postulate that the methane produced by bacteria in deep anaerobic layers of peats is trapped (occluded) by the peat matrix and the hydrostatic pressure of overlying water. The methane is outgassed whenever the water, supersaturated with methane or mixed with pressurized methane, is subjected to pressure, concentration or temperature gradients in auger holes or near ditches. The evolved gas bubbles block some pore spaces as a result of the Jamin effect, reduce effective pore space, and isolate some pore water from the hydraulic gradient.

RÉSUMÉ

Nous avançons l'hypothèse que le méthane produit par les bactéries dans les couches profondes de tourbe où l'oxygène fait défaut est retenu (par occlusion) dans la matrice et par la charge hydrostatique de l'eau qui recouvre la tourbe. Le méthane se dégage lorsque l'eau, sursaturée de ce gaz ou mélangée à ce gaz sous pression, est soumise à des gradients de pression, de concentration, ou de température dans les trous de tarière ou près des fossés. Les bulles de gaz qui se dégagent bloquent un certain nombre d'espaces lacunaires (effet de Jamin), réduisent les espaces lacunaires efficaces et empêchent une partie de l'eau de porosité d'être soumise au gradient hydraulique.

INTRODUCTION

The hydrological behavior of peat, especially humified peat, has been found by numerous workers to deviate severely and widely from Darcy's Law (Rycroft et al. 1975a). The anomalies have generally been attributed to "nondarcian" behavior of the humified peat layers often found at depth, and a need has been expressed for a new concept of peat hydrology. For example, unit permeability, supposedly a constant property of a porous medium, varies in the case of some peats with the thickness of the peat, the water-pressure gradient and time. Consequently, in peatlands, unlike in mineral soils, (a) drainage is sometimes better achieved by 1-m-deep ditches than by much deeper ditches; (b) the water table in up to 90% of a ditched area can be at the same level as in an undrained area after runoff; and (c) the water table between ditches generally has the shape of a bow, with water closer to the surface in the middle of a flat site.

A fundamental principle of hydrology, Darcy's Law, stipulates that the rate of flow of a homogeneous fluid through a saturated porous medium is determined by the pressure gradient, viscosity of the fluid, and the medium's unit permeability (the saturated hydraulic conductivity, K_{sat}), which is a constant property of a physically and chemically stable medium. In Darcy's Law, K_{sat} does not change with distance travelled in the medium, time or the pressure gradient. In the case of peat, however, K_{sat} has been found to change with the length of the medium traversed, with time and with the pressure gradient. In a field experiment with seepage tubes, K_{sat} of peat was found by Galvin and Hanrahan (1967) to vary with both time and pressure gradients, within relevant limits, for up to 7 months. They attributed these and other anomalies, such as the reduction in effectiveness of drains deeper than 1.1 m, to entrapped air. However, air does not occur in deep anaerobic layers. Rycroft et al. (1975a,b) observed the same deviations from Darcy's Law in their own experiments. Nonetheless, Rycroft et al. (1975b) and Dai and Sparling (1973) noted that the change in K_{sat} with time was limited mainly to 20 min in a seepage tube and in a cavity, and should therefore be ignored.

Ingram et al. (1974) and Rycroft et al. (1975b) reasoned that humified peat does not always comply with Darcy's Law because the peat, being an unstable medium that changes its porosity, does not meet the requirements of that law. This contention, however, had been found earlier by Egglesmann and Makela (1964) to be false, although, as expected, humified peats, being composed of finer particles, tend to have lower K_{sat} values than the coarser, undecomposed peat; this follows the analogy of the difference between fine clay and coarse sand. As the older and deeper layers closer to the mineral substratum within a peatland tend to be more humified, their deviation from Darcy's Law was ascribed to humification and, recently (Hemond and Goldman 1985), to stress and compression resulting from the burden of overlying peat and the weight of the operators of the measurement instruments. However, Galvin and Hanrahan (1967) had stressed earlier that compression of the deeper layers could not have been a factor in the case of a 4.06-m-deep layer of peat supersaturated with water (80% by volume), as water is incompressible. As well, it should be remembered that K_{sat} of a mineral soil, within relevant limits, does not change with depth or time. The variation of K_{sat} with time in laboratory columns of peat was suspected to be a result of plugging of some pores by microbial bodies and detritus (see Ingram et al. 1974; Rycroft et al. 1975a,b), but this could not be confirmed conclusively by attempts to sterilize the peat with Cu or formaldehyde, as these treatments could have caused other alterations as well.

Another interesting anomaly was well documented by Stewart and Lance (1983) in a study in the Pennines in England. They observed that the main role of ditches was to remove runoff from surface layers before the water went through the usual bow-shaped water table between ditches, so that, after runoff, the water table in up to 90% of the ditched area was at the same level as in the unditched area.

Faced with these baffling anomalies and other conflicting observations and explanations (e.g., Boelter 1965, Sturges 1968, Korpijaako and Radforth 1972, Päivänen 1973, Chason and Siegel 1986), George (1975) and others have expressed the need for a new concept of the peat-water system.

We believe that a series of studies by a group of Canadian scientists provides the basis for a feasible new concept of peatland hydrology. The following sections outline these studies.

Study 1 (Mathur and Levesque 1985)

All visually discernible layers in a Couteaux core (Couteaux 1962) from the surface to a depth of 20 cm in two representative areas in each of eight virgin peatlands were measured and sampled. The samples were analyzed by standard methods to characterize their state of humification (Table 1). Weighted means were calculated for each property for various depths.

The auger-hole method of van Beers (1983) was used to measure K_{sat} of three peat layers (0 to 60, 0 to 100, and 0 to 125 cm deep) separately, at 10 holes for each depth (Table 1). The water tables were within 2 to 10 cm of the surface during the measurements.

At seven of the eight peatlands, K_{sat} was found to decrease regularly with depth, although the state of humification increased with depth at only one of the eight sites (Table 1). Multiple linear regression (MLR) analysis revealed significant negative correlations ($P = 0.99$) between depth and K_{sat} and a general lack of correlation of depth or K_{sat} with properties related to the state of humification.

The geometric mean K_{sat} values of the 0 to 60 cm, 0 to 100 cm, and 0 to 125 cm deep layers at the eight sites were 5.39, 3.16 and 2.32 m d^{-1}, respectively. It can be inferred from these values that the 60 to 100 cm and 100 to 125 cm layers were nearly impervious to water, but this was not true. Nevertheless, the data could not be explained by any known concept in peatland hydrology. It was therefore proposed that methane, produced and present at lower depths in the peatlands, was subjected to pressure, concentration, temperature, and density gradients when an air-filled cavity was created for the purpose of taking the K_{sat} measurements, as would also happen near interfaces between deep water and the atmosphere in the vicinity of deep drains and ditches. The evolved gas bubbles block pore spaces as a result of the Jamin effect, which hinders water movement. Orlob and Radhakrishna (1958) showed that a 10% level of insoluble gas in a mixture with water can curtail permeability

Table 1. Properties of the three layers at the eight sites in Study 1[a]

Properties	Depth (cm)					
	0-60	0-100	0-125	0-60	0-100	0-125
		Site A (Albion, Ont.)			*Site B (Alfred, Ont.)*	
K_{sat} m d^{-1}	3.26b	2.15c	8.26a	5.33b	4.55b	5.58a
% unrubbed fiber	68.4	65.6	64.7	65.0a	55.0a	51.3b
% rubbed fiber	16.0	15.5	14.8	13.5	15.5	15.3
% 1-2 mm fraction	9.2	8.5	8.4	6.8	6.8	6.6
% 50-150 μm fraction	17.8	19.1	19.2	19.0a	21.8ab	24.8b
pyrophosphate index	27.5	23.9	21.6	46.2	35.6	29.0
% ash	16.4	18.4	21.6	4.3	3.8	4.2
pH	5.51	5.54	5.63	3.02	3.32	3.81
C:N ratio	18.4	18.3	18.2	28.6a	28.2a	27.2b
		Site C (Caledonia, Ont.)			*Site D (Mer Bleue, Ont.)*	
K_{sat} m d^{-1}	6.43a	4.27b	3.46b	11.01a	5.05b	3.01b
% unrubbed fiber	49.0	48.6	50.1	59.8a	55.0ab	51.3b
% rubbed fiber	15.0	15.3	14.9	34.2a	29.8ab	27.0b
% 1-2 mm fraction	6.7	6.8	6.3	9.0a	8.8ab	7.8b
% 50-150 μm fraction	21.0	21.6	20.8	9.4	10.4	12.3
pyrophosphate index	122.7	99.3	71.0	25.1	26.8	22.0
% ash	11.1a	10.2b	9.2c	2.3	2.7	3.4
pH	5.11	5.11	5.10	3.27	3.51	3.74
C:N ratio	22.6a	24.6ab	27.0b	39.8a	40.4b	43.7b
		Site E (Ormstown, Que.)			*Site F (St. Chrysostome, Que.)*	
K_{sat} m d^{-1}	2.55	1.5	1.84	9.40	4.52	3.14
% unrubbed fiber	56.2a	51.8ab	47.4b	61.5	61.7	61.7
% rubbed fiber	19.9	15.6	13.3	30.8	30.7	29.3
% 1-2 mm fraction	7.1a	6.3ab	5.7b	6.2	6.5	6.9
% 50-150 μm fraction	10.0a	10.5ab	11.9b	17.7	17.7	17.9
pyrophosphate index	28.1	27.0	26.5	12.1	12.1	13.6
% ash	3.0	3.0	3.2	5.3a	5.6a	6.6b
pH	2.97a	3.13ab	3.33b	4.20	4.30	4.51
C:N ratio	35.3a	34.0ab	33.1b	30.4	31.8	33.5
		Site G (St. Lambert, Que.)			*Site H (Rivière-Quelle, Que.)*	
K_{sat} m d^{-1}	5.05	2.30	0.94	1.8	1.70	1.54
% unrubbed fiber	71.2a	67.9ab	63.4b	62.2	60.3	58.1
% rubbed fiber	25.4a	25.2ab	22.0b	27.1	26.8	26.0
% 1-2 mm fraction	6.8a	6.1ab	5.1b	8.9	9.4	10.7
% 50-150 μm fraction	13.2	14.0	16.3	5.3	5.3	5.5
pyrophosphate index	26.0	35.2	39.6	19.0	17.8	16.6
% ash	1.5	1.4	1.4	2.4	2.4	2.5
pH	2.85a	2.88ab	2.92b	3.04	3.20	3.37
C:N ratio	38.4	38.7	38.5	60.9	61.7	62.0

For each property at a site, values not followed by any letter or followed by the same letter are not significantly different at $P = 0.05$ (Duncan's new multiple-range test).

[a] Source: Mathur and Levesque (1985)

of even a homogeneous sandy medium by 35%. The effect should be much greater than 35% when the medium is nonhomogeneous, like peat, and the gas is under considerable hydrostatic pressure.

This proposed role for methane in peatland hydrology resolves several anomalies recorded in the literature, where K_{sat} varied with time, depth and hydraulic head. The proposed explanation did not include a significant role for CO_2 and H_2S, also produced at depth. Because of their high solubility and ionization in water, CO_2 and H_2S equilibrate in the water layers much more than does methane.

The new hypothesis faced three main questions: (1) Is methane actually produced in the anaerobic layers of peatlands even under the prevailing cold and highly acidic conditions, since no known pure cultures of methanogenic bacteria are acidophilous or cold-loving? (2) Are lower peat layers richer in dissolved and/or gaseous methane than the surface waters of peatlands? and (3) Can it be shown that methane bubbles influence water movement near atmospheric interfaces? The following three studies were conducted in an attempt to answer these questions after a probe was designed for collecting water and gas samples from specific peatland layers.

Study 2 (Dinel et al. 1988)

Double-jacketed tubular probes of stainless steel, with the outer jacket containing an open side window and a retractable inner tube (plunger) fitted with a rubber O-ring, were built and used to sample unartefacted water and gas from layers 40 to 60 cm, 90 to 110 cm, and 125 to 145 cm beneath the surface of waterlogged peat in two basin swamps at similar sites. Samples were collected periodically for up to 2 hr, each time in evacuated gas bottles, with the O-ring on the plunger acting as a seal in the withdrawn position after time zero. The gases collected were measured by means of gas chromatography.

The quantities of methane and carbon dioxide evolved were found to increase with depth and to decrease with time. The methane, but not the carbon dioxide, evolved from deeper layers was too abundant to be dissolved in all the water that the sample probe could hold. The fact that most of the methane evolved within minutes of exposure to atmospheric pressure indicated that the gas was trapped in a pressurized state.

The results of this study showed that deep layers of the peatland water held trapped (occluded) and pressurized gaseous methane, or were supersaturated (on the basis of 1 atm) with dissolved methane, or both. The deeper layers were richer in methane than the layers closer to the surface.

Study 3 (Brown et al. 1989)

In this study, a detailed report of which is being prepared, the instrument system described above was used to detect and measure the methane present at 60-, 90- and 120-cm depths in an ombrotrophic bog. A McCauley sampler was used to obtain samples of the corresponding peat. Twelve samples of the peat were incubated in the presence of CO_2 and H_2 at 25°C. Methane was produced in all the samples despite the fact that the pH of the peat was between 3.04 and 4.63. The rate of methane production in the samples (0.80 to 5.28 nmol $g^{-1}h^{-1}$) was correlated at a 95% confidence level with the amount of methane present *in situ* in the peat layers. The results also indicated that the methane present *in situ* represented ~100 years of production at 25°C. Detectable amounts of methane were produced even when the samples were incubated at 4 or 12°C.

The data suggest that bacterial production of methane occurs in peatlands even at low temperature and high acidity, and that substantial portions of the gas produced are entrapped at depth in the peatland waters.

Study 4 (Buttler, Dinel, Levesque and Mathur, manuscript in preparation)

An instrument was designed to collect water and gas simultaneously from a specific peat layer without exposure to the atmosphere during or between the sampling periods. The results showed that even at the 45- to 60-cm layer studied, pressurized and occluded methane was present here and there as large and small bubbles; the release of this methane influenced water movement variously but significantly.

CONCLUSIONS

The results of these four studies indicated that (a) methane is produced biologically in anaerobic layers of peatlands even in acidic and cold environments; (b) unlike the CO_2, the CH_4 is present under supersaturated conditions in the subsurface waters and trapped as pressurized gas bubbles at the 45- to 60-cm depth, with increasing concentrations at deeper levels; and (c) the occluded methane influences the ability of the peat medium to transmit water so that the evolved gas bubbles at interfaces with the atmosphere near water tables, and around drains, ditches, or even temporary holes made for measurements, hinder water movement. More studies are needed to elaborate this new concept and to examine the means by which the methane can be outgassed before it reaches the ditches or drains, so as to facilitate water movement and improve drainage. The microbiology of methanogens in peatlands should also be studied.

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Section VII Environmental Impacts

INFLUENCE OF FOREST DRAINAGE ON RIVER RUNOFF REGIME: MAIN CONCEPTS AND ASSESSMENT POSSIBILITIES

S.E. Vompersky[1], N.A. Nazarov[2] and A.A. Sirin[1]

[1] Forest Research Laboratory
Academy of Sciences of the USSR
Uspenskoe, Moscow Region
USSR

[2] Water Problems Institute
Academy of Sciences of the USSR
Moscow
USSR

ABSTRACT

Hydrological experiments have been carried out since 1975 on watersheds at the West Dvina Experimental Station, located in the USSR's European Territory. Summer-autumn runoff regimes have been studied for drained and undrained areas (4 to 40 ha) of ombrotrophic bogs, and low summer runoff has been studied for raised bogs taken as a whole (1.7 to 7.3 km^2). Throughout the year, parallel runoff observations have been taken from river basins (10 to 20 km^2, peatland area 30 to 47%). The mires in these basins were either drained or left in their natural state. Runoff regime was also measured for the Velesa River (870 km^2, peatland area 43%, 7 to 8% of the basin drained), which receives water from the experimental watersheds.

For at least 10 to 15 years after its installation, forest drainage ensures an increase in river runoff both for the summer average and during the summer low-flow period. Winter average and minimum runoffs both increase, except in dry winters. From preliminary data, it appears that forest drainage ensures an increase in peak rainfall flood values, but probably does not promote an increase in maximum spring flood values for floods of low probability. There is a trend of increasing annual runoff after forest drainage.

A computerized mathematical model of snowmelt runoff, developed by the Water Problems Institute of the USSR Academy of Sciences, was used to evaluate the consequences of different scales, degrees and locations of drainage on lowland river runoff for years characterized by various hydrometeorological conditions. The model produces results that are in good agreement with the data available for the Velesa River, but other whole-river-basin data are needed to test the model further.

RÉSUMÉ

Depuis 1975, des expériences hydrologiques ont été effectuées dans des bassins versants à la station expérimentale de la Dvina occidentale, située dans la partie européenne de l'URSS. Les études ont porté sur les régimes d'écoulement d'été-automne dans des secteurs drainés et non drainés (de 4 à 40 ha) de tourbières ombrotrophes ainsi que sur le faible écoulement dans des tourbières bombées considérées dans leur ensemble (de 1,7 à 7,3 km^2). Pendant toute l'année, nous avons effectuée parallèlement des observations de l'écoulement dans des bassins fluviaux (de 10 à 20 km^2, tourbières d'une étendue de 30 à 47 %). Les secteurs de tourbières de ces bassins avaient été soit drainées, soit laissés à leur état naturel. Les régimes d'écoulement ont également été mesurés pour la rivière

Velesa (870 km^2, 43 % de tourbières, de 7 à 8 % du bassin étant drainé) qui reçoit les eaux des bassins hydrographiques à l'étude.

Pendant au moins 10 à 15 ans après l'aménagement du réseau, le drainage forestier assurait une augmentation de l'écoulement fluvial tant pour la moyenne estivale que pour la période estivale de faible débit, sauf pendant les périodes d'étiage de cette dernière. L'écoulement minimal et moyen hivernal a augmenté, sauf pendant les hivers sec. D'après les données préliminaires, il semble que le drainage forestier assure une augmentation des valeurs maximales de crue dues aux précipitations mais ne favorise probablement pas un accroissement des valeurs maximales des crues printanières lorsque les probabilités d'inondation sont faibles. L'écoulement annual a tendance à augmenter après le drainage forestier.

Un modèle mathématique informatisé du ruissellement nival, mis au point par l'Institut d'études des problèmes hydrologiques de l'Academie des Sciences de l'URSS, a servi à évaluer les conséquences des diverses conditions de drainage (échelle, degré et lieu) sur l'écoulement fluvial des basses terres pendant les années caracterisées par diverses conditions hydrométéorologiques. Le modèle a donné des résultats qui concordent bien avec les données disponibles sur la rivière Velesa, mais il faudra obtenir d'autres données sur l'ensemble du bassin pour vérifier davantage le modèle.

INTRODUCTION

The basis of the whole complex of measures to enhance productivity of peatland forests is the regulation of water regime by modifying the outflow from a waterlogged area. The influence of forest drainage on river runoff and water resources is an important indirect consequence of these measures, and assessment of this influence is necessary. The need for scientific analysis of this influence is rendered more urgent by the intensity of social perceptions of it. Such perceptions are not necessarily accurate, of course, but they often form the basis for the arguments of adversaries of forest drainage.

The hydrological consequences of forest drainage (specifically its impact on peak flow) first attracted the attention of experts in the 1930s and 1940s, after major flooding of some rivers in Finland, other Scandinavian countries and the United Kingdom (Ahti 1977, Sirin 1983). About the same time, the first scientifically based ideas about the impact of forest drainage on river runoff were expressed in the USSR by the founder of peatland hydrology, Professor A.D. Dubakh. More attention was directed to this problem in the 1960s in connection with ameliorative activities in forestry. However, the conclusions that appeared in scientific papers and in the public press were concentrated mainly on annual and low-water flow, and were based on the confusion of the hydrological consequences of forest drainage with the modification of river runoff after agricultural amelioration (Sirin 1983, Vompersky and Sirin 1986).

In the mid-1960s forestry research organizations began to be formed in various parts of the USSR (Leningrad, Karelia, Lithuania, Latvia, Komi ASSR, Sverdlovsk, etc.), and integrated studies (including hydrological studies) of forest drainage areas were undertaken (Sirin 1983). Similar hydrological studies were done in Finland, Czechoslovakia and other countries. The methods of investigation and natural conditions of the areas studied differed in each case, and this seriously complicated the interpretation and extrapolation of the information obtained. These shortcomings were taken into consideration as far as possible in the course of our investigations.

OBJECTIVES AND METHODS

Since 1975 investigations have been carried out at specially equipped watersheds of the West Dvina Experimental Station of the Forest Research Laboratory, USSR Academy of Sciences. It is located in the central part of the forest zone of the USSR European Territory (56°N, 32°E) and includes a wide range of drained peatland forests (Vompersky et al. 1988).

The process of hydrological regime formation in various types of drained peatland forests (Vompersky and Sirin 1988) was studied at experimental watersheds (Fig. 1) containing ditches (F = 4-10 ha).

The regime of summer–autumn runoff from drained areas of oligotrophic raised *Sphagnum* bogs was compared with that from undrained areas (F = 30-40 ha). As well, low summer runoff from drained and undrained oligotrophic bogs was compared (F = 1.7-3.7 km).

Runoff from the basins of three small rivers (F=10-20 km, peatland area 30-47%) was measured on a year-round basis. In two of these basins, peatland forests were drained (Fig. 2), and in the third they were preserved in their natural state. Runoff data were also analyzed against the background of the Velesa River (F = 870 km, peatland area 43%, drained portion of basin 7-8%). The Velesa River (Fig. 3) receives water for the experimental watersheds under consideration (Vompersky et al. 1988).

Experimental data were also used in studying the impact of forest drainage on the annual hydrograph of the Velesa River by means of mathematical modeling. A physically based forest watershed hydrology (FWH) model, developed at the Water Problems Institute of the USSR Academy of Sciences (Nazarov 1988), was used (Nazarov and Sirin 1988). The model calculates the temporal annual distribution of snowmelt-rainfall runoff formation as well as particular elements of the hydrological cycle (interception, evapotranspiration, water content and freezing of soil, snow melt, and other factors) under selected meteorological influences (daily precipitation, daily temperature and air humidity deficit), and morphometric and other landscape parameters of the river catchment, for various intensities of forest drainage.

As a supplement to traditional research methods, mathematical modeling can be used to provide a general idea of the influence of forest management, including forest drainage, on processes of runoff formation and on the hydrological regime of an area under consideration. Modeling allows the researcher to check the suggested hypotheses, specify trends in nature, and supplement experimental data with the results of numerical experiments. Finally, modeling provides a possible approach to assessing the potential influence of forest drainage on a particular river basin (Nazarov and Sirin 1988).

Figure 1. Gaugiug station on drained Sphagnum *pine bog (summer low flow).*

Figure 2. Gaugiug station on drainage system (summer low flow).

Figure 3. The Velesa River halfway down the river (summer low flow).

RESULTS AND DISCUSSION

Analysis of the hydrological consequences of forest drainage is complicated both by natural variation (sources of water feeding, type of vegetation, thickness and hydraulic properties of a peat deposit) and by differences in the character and intensity of post-drainage changes in vegetation and other factors of runoff formation (e.g., settling of peat, overgrowing and silting of channels). However, the effects of forest drainage are found mainly in the modification of two principal factors of runoff formation — an increase in the density of the hydrographic network and an increase in the accumulating capacity of a peat deposit after the water level has been lowered.

Under some natural conditions, e.g., the direct discharge of artesian or ground piezometric waters into the drainage network, hydrologic change must be estimated by special techniques. Also, during the first 1-2 years after drainage there is a general increase in runoff owing to the decrease in "secular" storage of mire water, whereas later, evapotranspiration has more influence, and is related to the increase in stand productivity (Heikurainen 1976, Vompersky and Sirin 1986).

Most studies have indicated that there is an increase in the summer low-water runoff after forest drainage, both for specific ameliorated forest plots and for entire river basins. An exception is forest growing on hydromorphic mineral soils. According to studies conducted in Latvia (Aire 1977, Zalitis 1983), drainage of these sites results in a noticeable decrease in summer low-water flow.

The increase in summer low-water flow runoff is explained by two factors. The first is the decrease in total evapotranspiration, which is related to reduced physical evapotranspiration from soil, and reduced transpiration of the living ground cover. On drained, raised bogs the general reduction in evapotranspiration may be almost 100% in midsummer, whereas on mires with more developed tree stands it is lower. The second factor is the increase in volume of peatland water involved in runoff formation and the lengthier storage period after peat has been dampened by snow or rain. This has been confirmed experimentally in many studies comparing the outflow from drained plots with different ditch spacings (Ahti 1977, Sirin 1983, Vompersky et al. 1988), and has been substantiated by other calculations (Pisarikov 1981). The increased discharge of piezometric ground and artesian waters after drainage may also contribute to the increased summer water runoff.

According to data from the West Dvina Experimental Station, the summer low-water flow from drained bogs is more than twice that from undrained bogs. The dry period (where there is no runoff) typical of many bogs in the natural state is much reduced and in some cases is nonexistent in drained bogs. Drainage of 20-30% of the river basin area results in a 10-20% increase, on average, in both the average and the summer low-water runoff, except for the lowest values typical of the driest periods when the outflow from drained peatlands also ceases (Vompersky et al. 1988).

As most experts point out, there is an increase in the summer low-water runoff of up to 50% after forest drainage, the magnitude probably being dependent on the scale of the amelioration (Sirin 1983). Studies performed in Finland (Mustonen 1971) revealed the direct relation between values of the summer low-water stream flow of small rivers and the area drained in the basin.

An increase in winter water flow is also related to an increase in the volume of mire water contributing to runoff formation. The winter stream flow from the drained bogs may surpass the corresponding values from undrained bogs by up to 100%. The values of the average and minimum river runoff increase by up to 30%. However, in dry winters runoff is low or nonexistent (Vompersky et al. 1988).

The impact of forest drainage on maximum values of snowmelt and rainfall runoff is not always clear. This is mainly because of the opposing influences of the raised water-storage capacity of a peat deposit, and the increased channel density of the drained area. In different watersheds and different hydrometeorological situations, these opposing actions have different values and partially or fully compensate their mutual interaction (McDonald 1973, Starr and Päivänen 1981, Vompersky et al. 1988). However, for the maximum flow values of low probability, the storage capacity of a peat deposit has little effect on runoff. At the same time, increased channel density significantly reduces the time lag for peak flow, and this contributes to higher values for peak flow. In addition, drainage stops the flooding of mire margins which, in natural peatland, help regulate the formation of flood flow.

According to studies at the West Dvina Experimental Station, maximum rainfall flows from drained bogs often surpassed those from undrained bogs by five times or more. The data also indicated increases of 30 to 40% in maximum values of rainfall runoff on small rivers, as has been confirmed by other authors (Vompersky et al. 1988). The degree of increase in peak flow depends not only on values of amelioration and on the area of ameliorated forest, but also on the location of the drained area within the river basin and on natural conditions prevailing in the latter.

The influence of forest drainage on spring flood flow is still more complex. The flow depends on differences in thermal properties of a peat deposit, on freezing and snowmelting under the conditions prevalent in various peatland forests and on their modification after drainage. Only characteristic features of the spring flood hydrograph for river basins with drained forests can be recorded with any certainty: the earlier start (by several days), the more gradual decline, and two peaks, the first (as a rule the smaller) being related to the rapid reaction of the drainage network to snowmelt. However, it is difficult to reach definite conclusions about the influence of forest drainage on the peaks of spring stream flow. Often it is specific to each river and depends on natural flow conditions in the particular river basin and on the area, distribution and parameters of drained peatland forests.

Under such conditions, mathemetical models of river flow may be useful for imitating the main processes of runoff formation in relation to temporal distribution of meteorological elements and parameters of a particular river basin (Nazarov and Sirin 1988). The influence of forest drainage is taken into consideration in modeling by modifying the density a) of channels in the hydrographical network (outlet, collecting and main channels) and b) of the draining layer of forest soil (with consideration of drainage standards) for each area of the river basin to be calculated.

The control data for the Velesa River for years before and after amelioration (which took place in the late 1960s and early 1970s) confirm the capacity of the model, are in agreement with experimental results, and provide a basis for mathematical experiments to assess the hydrological consequences of forest drainage. Figure 4 provides fragments of annual hydrographs of the Velesa River runoff calculated under natural (reconstructed) conditions of flow formation, the current condition of flow, and projected higher intensities of drainage for selected years under various hydrometeorological conditions. Results of the mathematical experiments confirmed the conclusion, formed on the basis of natural observations, that there is a potentially significant increase of high and average probability in the maximum values of the spring discharge (under the conditions prevailing in the Velesa River basin).

A series of numerical calculations aimed at verifying a hypothesis suggested by Mustonen and Seuna (1971) was carried out. The hypothesis was that the maximum runoff should increase to the greatest degree, during the process of forest drainage, in the upper part of the river basin. The results of our calculations show that quite the opposite situation is characteristic of the Velesa River Basin. This is explained by the watershed configuration and filtration capacities of the soil and ground, which determine formation and transformation of the flood wave.

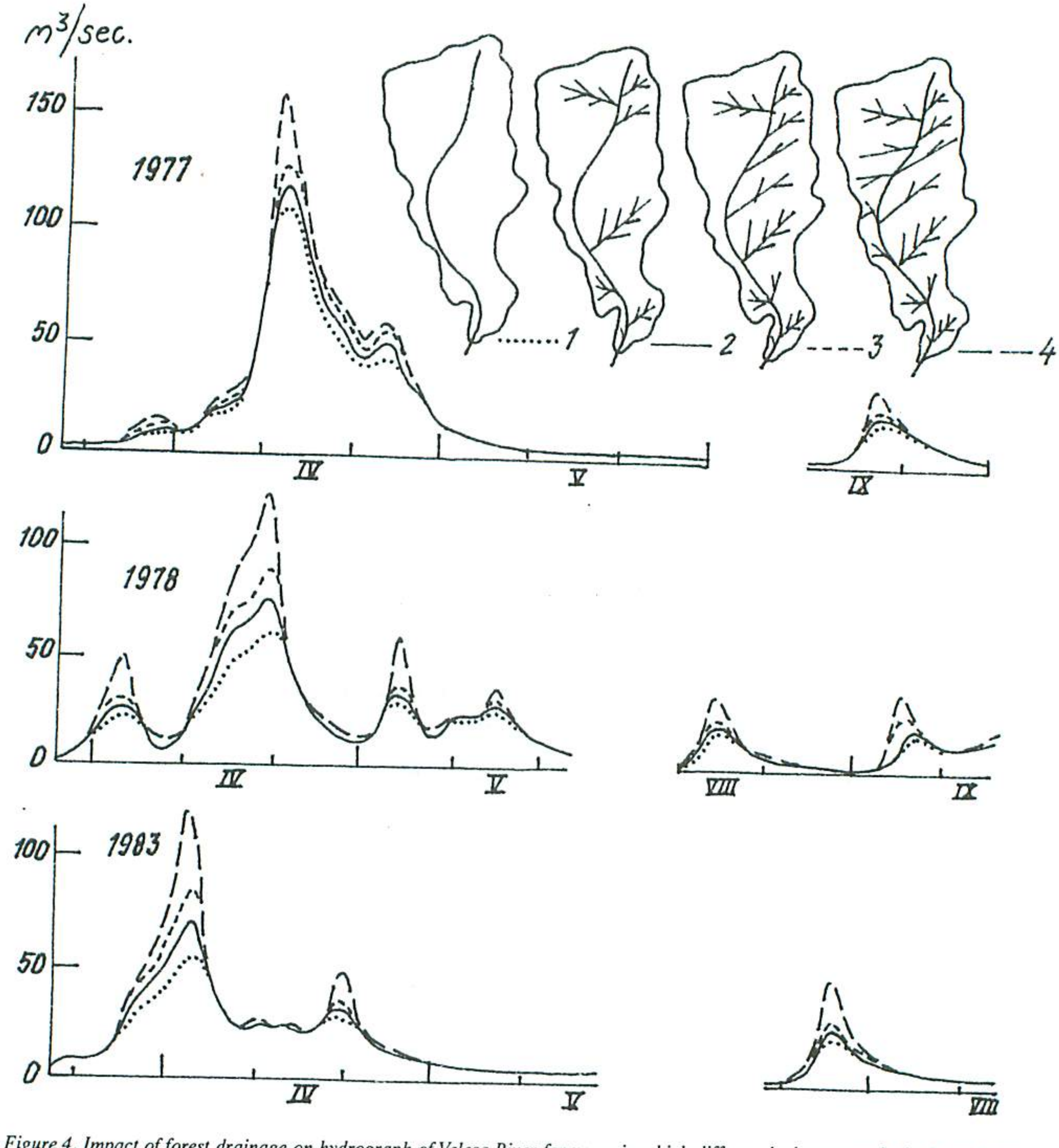

Figure 4. Impact of forest drainage on hydrograph of Velesa River for years in which different hydrometeorological conditions prevailed (based on mathematical experiments). Hydrographs under: 1) reconstructed (natural) conditions, 2) present-day (7-8% of river basin) drainage conditions, 3) projected (15%) drainage conditions, 4) projected (30%) drainage conditions. The relative development of the drainage networks is shown on four theoretical levels.

Investigations also revealed up to a 10-15% increase in annual flow after forest drainage, a figure confirmed by others (Heikurainen 1976, Seuna 1981, etc.). The main reason is the reduction in moisture loss by evapotranspiration in the warm season. However, with a post-ameliorative increase in tree productivity, the annual flow gain may decrease. For instance, according to experiments conducted by staff of the West Dvina Experimental Station, total evaporation during three summer months (June to August) was, on average, 199, 223 and 275 mm for pine (*Pinus* spp.) mixed with spruce (*Picea* spp.) and birch (*Betula* spp.) forests with growing stocks of 20, 80 and 200 m^3ha^{-1} and leaf area indices of 0.8, 1.8 and 6.0, respectively. In the stand with 200 m^3ha^{-1} of standing timber volume, the inflow of additional moisture derived from confined groundwater was not taken into account; hence, the actual evaporation value was probably more than 275 mm.

Moisture loss by evapotranspiration may increase greatly, especially in dense stands of spruce, or where peatlands that were previously open, either fully or in part, have been regenerated. In river basins with well managed peatland forests in all different stages of development, with systematic thinnings and fellings, one could speculate that rather high evapotranspiration could significantly reduce annual outflow. However, it is unlikely, as some experts believe, that outflow would decline to pre-ameliorative levels.

CONCLUSION

Forest drainage does not generally have a negative effect on the natural distribution of river runoff, except in connection with maximum flow after rainfall and snowmelt periods, which is a problem requiring special consideration in particular river basins. However, analysis of the hydrological consequences of forest drainage should not be confined to distribution of river runoff, but should include potential modifications of the quality of river water (solid discharge, chemical composition, temperature regime). These latter considerations are very important, especially for rivers that are used as sources of water supply, or are the living environment of, or spawning grounds for, valuable fish species.

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SURFACE-WATER QUALITY OF DRAINED AND UNDRAINED BLACK SPRUCE PEATLANDS[1]

G. J. Berry
Formis Ltd.
Victoria, British Columbia
Canada

ABSTRACT

A project was initiated in 1984 to describe the environmental impact of forest drainage on black spruce swamp ecosystems and adjacent streams in northern Ontario. Surface water quality was examined upstream and downstream of drainage areas. Chemical and physical parameters were measured and compared with those in Canadian water-quality guidelines. Drainage caused a notable increase in pH, concentrations of ions and alkalinity. Concentrations of Al and Fe exceeded those in the guidelines because of high natural background levels of these elements. Concentrations of suspended solids exceeded those in the guidelines only during periods of high flow. Results indicate that drainage has not significantly degraded the quality of downstream water.

RÉSUMÉ

Un projet a été entrepris en 1984 afin de décrire les incidences environnementales du drainage forestier sur les écosystèmes des pessières noires du nord de l'Ontario. La qualité de l'eau de surface a été analysée en amont et en aval des secteurs de drainage. Des paramètres chimiques et physiques ont été mesurés et comparés avec ceux figurant dans les directives sur la qualité de l'eau. L'aménagement de fossés a entraîné une augmentation notable du pH, des concentrations d'ions et de l'alcalinité. Les teneurs en Al et Fe dépassaient celles figurant dans les directives sur la qualité de l'eau en raison de taux naturels élevés de ces éléments. Les concentrations de matières solides en suspension dépassaient celles des directives uniquement en période de débit élevé. Les résultats indiquent que l'aménagement de fossés n'a pas dégradé de façon significative la qualité de l'eau en aval.

INTRODUCTION

Drainage of forested peatlands to improve tree growth is being investigated in several regions of Canada (Hillman 1987). In Ontario, about 8 million ha of productive black spruce (*Picea mariana*) forest grow on peatland or wet, low ground (Ketcheson and Jeglum 1972). Management guidelines for drainage activities are required to minimize any adverse effects. In 1984 a project was initiated by the Ontario Ministry of Natural Resources, in cooperation with Forestry Canada, Ontario Region, to study forest drainage and develop the necessary guidelines (Koivisto 1985, Rosen 1986).

One objective of the project was to describe the environmental impact of drainage on black spruce ecosystems and adjacent streams. A major question arose from this impact assessment: Does drainage degrade surface-water quality?

The effects of drainage on surface-water quality depend on the soil parent material, peatland type, plant species and climate (Boelter and Verry 1977, Lundin 1988). As a result, the effects will vary among basins that differ in these respects. Generally, drainage causes increases in pH, alkalinity and cation concentrations (Heikurainen et al. 1978, Ahtiainen 1988), possibly because of increased aeration of the peat and increased flow of mineral-soil groundwater into the ditches.

[1] This report was prepared under contract for Forestry Canada, Ontario Region, Sault Ste. Marie, Ontario.

The objective of this study was to characterize the influence of drainage on surface-water quality, with reference to Canadian water-quality guidelines (Anon. 1987).

In this paper, surface water refers to the water in drainage ditches and in the streams adjacent to and receiving water from the drainage areas.

METHODS

Site Description

The Wally Creek Area Forest Drainage Project is located in northeastern Ontario, 30 km east of the town of Cochrane (49° 3′ N, 80° 40′ W), in the Northern Clay Section of the Boreal Forest (Rowe 1972). The topography is flat (< 0.3% slope), with natural drainage towards the northwest. The peat is variable in depth (< 30 cm to > 300 cm) and overlies a heavy clay of lacustrine origin. The forests in the area are uneven-aged (50-140 yr, 8-17 m high) black spruce growing in swamp land that has been site typed according to the Forest Ecosystem Classification (Jones et al. 1983). The sites are characterized by a black spruce canopy, with an understory of *Ledum groenlandicum*, *Vaccinium myrtilloides* and *Chamaedaphne calyculata*. The moss layer is composed of *Sphagnum nemoreum*, *S. fuscum*, *S. magellanicum*, *S. girgensohnii*, *Pleurozium schreberi* and *Ptilium crista-castrensis*.

Ditches in the area, which cover approximately 450 ha, were planned and installed in 1984-1985 to Finnish standards (Fig. 1). Side ditches averaged 90 cm deep, and surround and collector ditches averaged about 120 cm deep. In 1986, a 170-ha area was harvested and 59 ha of this were drained.

Water Collection and Analysis

Grab samples were taken at mid-channel, through the entire depth (i.e., depth-integrated sampling), at eight locations (Table 1, Fig. 1). The sites were located:

- in Wally Creek, upstream and downstream of collector-ditch outlets (Sites 1 and 2)
- in Roy Creek, upstream of any drainage (Site 3)
- in a collector ditch (Site 4)
- in the Foisie River, upstream of most of the drainage network and about 2.5 km downstream of the entire network (Sites 5 and 6)
- around sedimentation ponds (Ponds A and B)

Sites were classified as controls (Sites 1 and 3), treatments (Sites 2 and 4), upstream (Site 5) or downstream (Site 6). Site 5 could not be termed a control because of the influence of the drainage ditches upstream of this site. Although the collector ditch from Site 4 empties into Wally Creek upstream of Site 1, a control, its effects were minimal because of the much greater flows in Wally Creek, as indicated by the areas of the respective basins (Table 1). Samples from Sites 1 to 6 underwent the chemical and physical analyses outlined in Table 2.

Samples at each of the two sedimentation ponds were obtained from the ditch leading into and out of the pond, as well as upstream and downstream of the point of entry of the ditch into the river channel. These sets of samples were analyzed for suspended solids only, and were used to determine the effectiveness of the ponds in removing sediment.

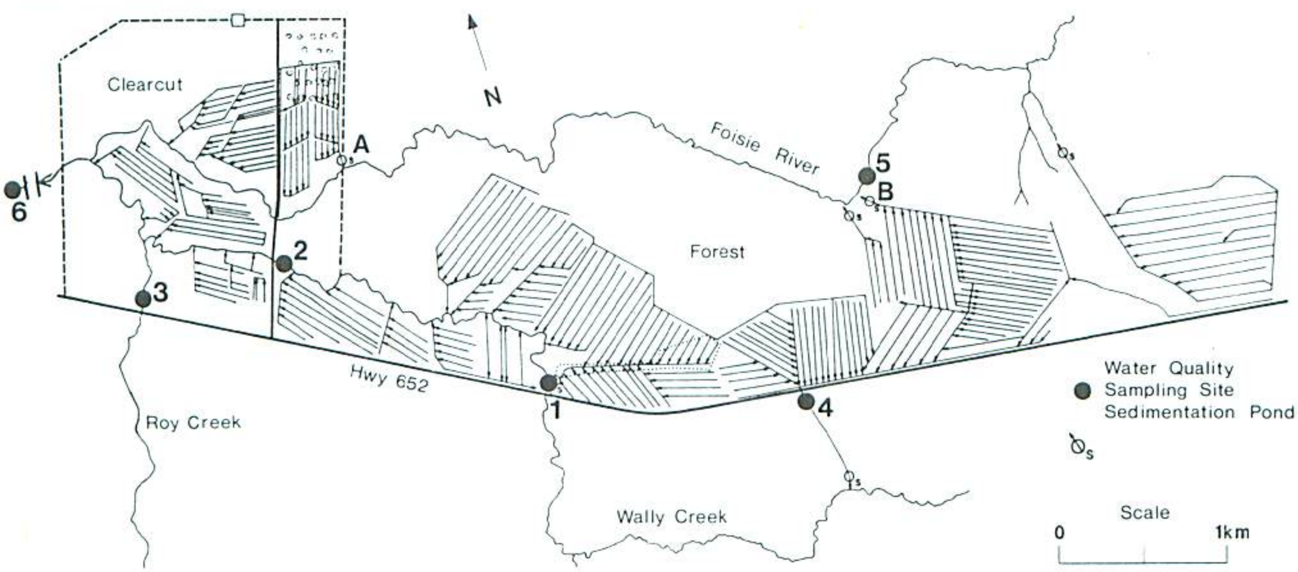

Figure 1. Map of drainage network, with water-quality sampling sites.

Table 1. Water sampling locations

Site	Description	Basin area (ha)	Drained area (ha)	Drained area (%)	Ditch density (m/ha)
1	Wally Creek – upstream of drainage	1297	0	0	0
2	Wally Creek – downstream of drainage	1499	139	9	229
3	Roy Creek – upstream of drainage	685	0	0	0
4	Collector ditch	67	58	87	279
5	Foisie River – upstream of drainage network	766	0	0	0
6	Foisie River – downstream of drainage network	4768	341	7	274
	(forest	4598	282	6	255)
	(cut	170	59	35	368)
Sedimentation pond					
A		–	7	–	386
B		–	43	–	316

Table 2. Chemical and physical analyses

Ions – Ca Mg K Na SO_4 Cl SiO_2
Nutrients – NH_4-N (NO_2+NO_3)-N
Metals – Fe Al Zn Cu Ni Cd Pb Mn
Total Kjeldahl nitrogen (TKN)
Total P
pH
Acidity
Alkalinity
Conductivity
Temperature
Suspended solids
Turbidity

Water samples were collected in 1987 and 1988, beginning before snowmelt and ending at the onset of freeze-up (Table 3). Collections were also made around storm events to determine the effect of periods of high flow on water quality. This collection schedule permitted a wide variety of flow conditions to be sampled.

The data were analyzed by means of a series of t-tests to compare the results of: a) 1987 and 1988, for each site, and b) the corresponding upstream and downstream sites (Sites 1 and 2, 5 and 6) for each year. A Duncan's New Multiple-Range Test was done to compare all the sites with each other. All tests were at the 95% level of confidence.

Table 3. Collection schedule

	No. of samples		Frequency (days)	
	Sites	Ponds	Sites	Ponds
27 May-26 Oct. 1987	15	20	10	7
27 Apr-17 Oct. 1988	27	19	6	9

RESULTS AND DISCUSSION

Ions

The ion concentrations for each site did not differ between 1987 and 1988. Differences among sites were consistent for all ions, and are illustrated by the calcium concentrations (Fig. 2). The median value in the graph is an indicator of the distribution of the data; the closer the mean and the median are, the more uniform is the distribution. If the median occurs above the mean, then the minimum is an extreme value. If it occurs below the mean, then the maximum is an extreme value.

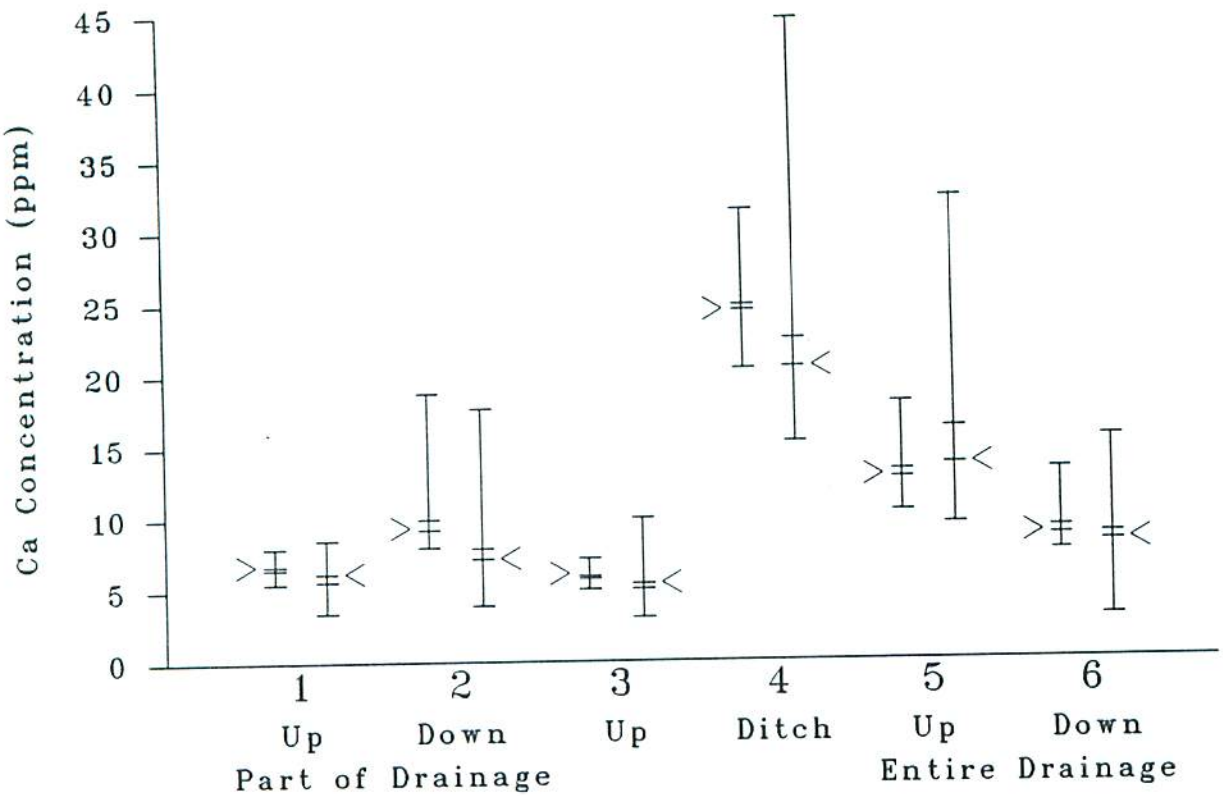

Figure 2. Calcium concentrations at sampling sites (1987-1988) (showing minimum, maximum, mean and median [<]).

The collector ditch (Site 4) had significantly higher ion concentrations than any other site. This can be attributed to three factors: 1) not much water from the undrained area entered the surround ditch; 2) most of the ditches intruded into mineral soil; and 3) 87% of the site 4 basin was drained (Table 1). Small amounts of water were therefore in direct contact with mineral soil. The other downstream sites (Sites 2 and 6) had only 9% and 7% of the area of their respective basins drained, and were influenced to a large degree by subsurface flow from undrained areas. The ranking of sites, from lowest to highest ion concentrations, was:

low	Sites 1, 3
	Sites 2, 5, 6
high	Site 4

There were no significant differences within each group, but there were differences among the groups. This indicates that drainage did increase the concentration of ions.

Direct comparison of Site 5 (upstream) with Site 6 (downstream) showed higher concentrations of ions at the upstream site. This was probably a result of the contribution of ions from the drained area upstream of Site 5. All the ditches in this area were in mineral soil and underwent significant erosion, which enhanced the release of ions.

The concentrations of ions varied with streamflow. Concentrations of Ca, Mg, Na and SiO_2 were low during snowmelt and high during periods of low flow. The other ions (K, Cl and SO_4) had low concentrations during low flow periods and high concentrations during melt. This difference between the two groups was due to different sources of runoff water. The ions in the first group are indicators of groundwater that has been in contact with mineral soil (Boelter and Verry 1977). During periods of low flow, the groundwater had a greater opportunity to increase its ionic concentration because of prolonged contact with the underlying mineral soil. During the melt period, concentrations were diluted by the large amount of superficial meltwater. Further, this water was prevented from percolating to the mineral-enriched groundwater by a layer of frozen peat.

The ions in the second group are abundant in the atmosphere (Boelter and Verry 1977, Foster and Nicolson 1988) and therefore accumulated in the snowpack. They were released as a surge during melt. Low concentrations during periods of low flow resulted from a lack of input via precipitation.

The overall minimum and maximum concentrations measured at the sites are listed in Table 4. Despite the increases caused by drainage, the Freshwater Aquatic and Drinking Supply Guidelines (Anon. 1987) for ions, where given, were not exceeded.

Metals

Concentrations of trace metals were highly variable and did not permit any obvious ranking of sites. Site 6 (downstream) did have higher concentrations of Al, Fe, Zn and Mn than the other sites, but the differences were not statistically significant. The higher concentrations could not be attributed to drainage because the two treatments (Sites 2 and 4) often had lower concentrations than the controls (Sites 1 and 3). The concentrations of Cd, Ni and Pb were at or below the detection limit in more than 80% of the collections. Only Cu tended to have higher concentrations at the treatment and downstream sites than at the control sites. Again, the differences were not significant.

Except for Cd, Ni and Pb, concentrations of metals at all sites were low during periods of low flow and high during storm events. This indicates that, as the water table rose because of precipitation, metals were gained in the upper layers of the peat. Lapakko (1985) observed that concentrations of Fe, Al and Mn did, in fact, decrease as depth increased.

Water-quality guidelines were exceeded only a few times in both years by all metals except Al, Fe and Cu. These latter metals were consistently found at all sites in higher concentrations than are recommended by the guidelines. Concentrations of Al (Fig. 3) and Fe were particularly high. Even the minimum Al concentrations were near or above the limit. The similarity between the controls (Sites 1 and 3) and downstream (Site 6) shows that there were high natural background concentrations. These values were within the range reported by Hillman (1988).

Nutrients, Total Kjeldahl Nitrogen and Total Phosphorus

The nutrient and total P concentrations followed a trend similar to that of the ions. The controls had the lowest values, the collector ditch had the highest values and the other sites were in the middle. The concentrations of total Kjeldahl nitrogen (TKN) tended to be higher at the control sites, an indication that the peat was a source of TKN via the flow of subsurface water. None of the differences was significant. Increased concentrations of NH_4-N as a result of drainage were observed by Hynninen and Sepponen (1983). On the basis of their observation that more total P was released from dry peat than from wet peat, Knighton and Stiegler (1980) hypothesized that concentrations of total P would increase after drainage.

For these measures, no quality guidelines, where given, were exceeded.

pH, Acidity, Alkalinity, Conductivity and Temperature

These parameters, with the exception of temperature, followed the same ranking as the ions. The collector ditch had significantly higher values, while the controls had significantly lower values. As was the case with the ions, high levels occurred during periods of low flow, and low levels occurred during periods of high flow. Contact of groundwater with mineral soil may be the controlling factor. Increases in pH because of drainage have been documented by Heikurainen et al. (1978) and Hynninen and Sepponen (1983). Alkalinity did increase as a result of drainage, but all the sites, except the collector ditch, had values less than 24 mg/L (as $CaCO_3$), indicating a poor buffering capacity (Anon. 1981).

Table 4. Minimum and maximum values

Ion concentration (ppm)			Ion concentration (ppb)			Other water properties			
Ion	Min	Max	Ion	Min	Max	Property	Min	Max	Units
Ca	2.4	43.9	Al	83	1521	pH	4.3	8.2	
Mg	0.6	6.6	Fe	130	1789	Cond.	15	250	µS/cm
Na	0.4	12.8	n	2	100	Acid.	1	81	mg/L $CaCO_3$
K	0.0	1.6	Zn	5	34	Alkal.	0	98	mg/L $CaCO_3$
Cl	0.1	3.8	Cd	<0.2	1.5	Temp.	1	30	°C
SO_4	0.4	6.2	Ni	<2.0	7.9	Turb.	20	270	NTU
SiO_2	0.8	5.3	Pb	<2.0	12.1	Solids	0	540	mg/L
			Cu	1.1	21.3				
			NH_4-N	5.4	152.8				
			(NO_{2+3})-N	<1	934				
			TP	6.8	179.0				
			TKN	10	2640				

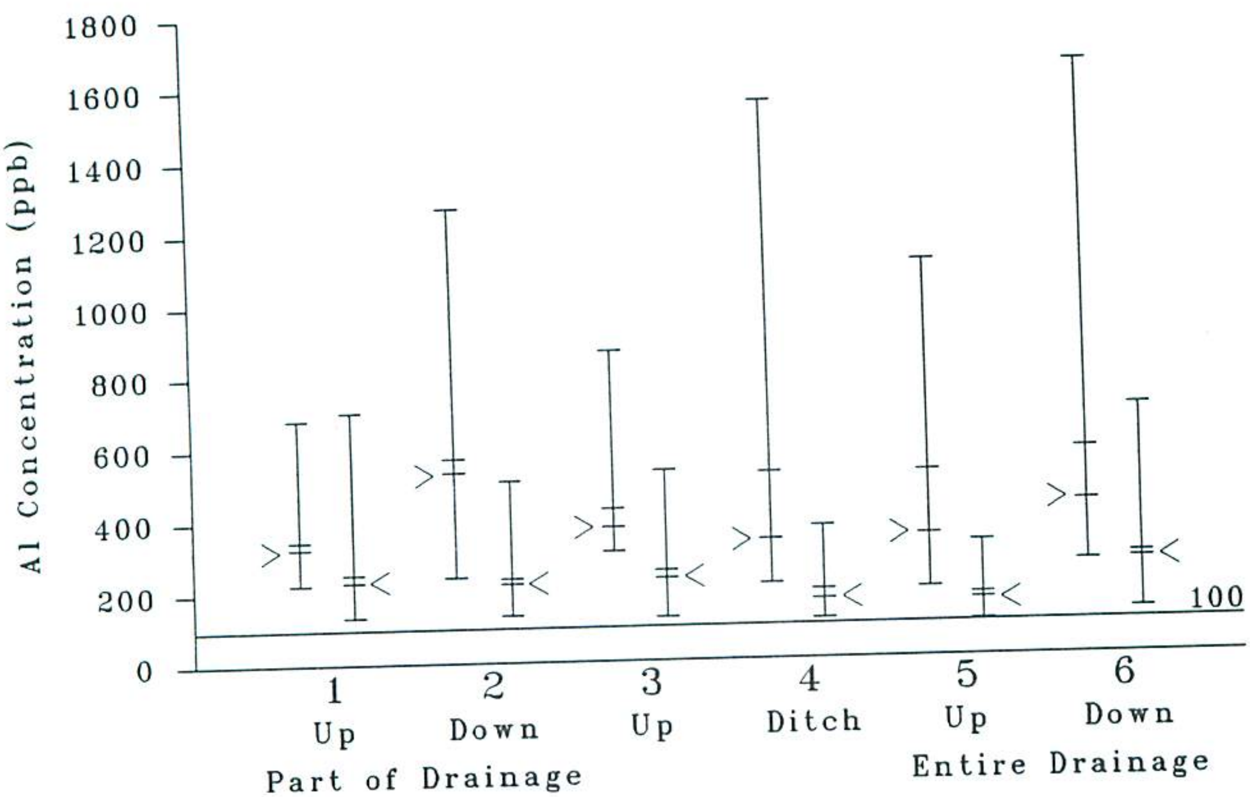

Figure 3. Aluminum concentrations (1987-1988) (showing minimum, maximum, mean and median [<]; also water-quality guideline limit).

Water temperatures were not significantly different from site to site, although the Foisie River tended to be slightly warmer. As might be expected, water temperatures were low in the spring and the autumn, and high in the summer.

No guidelines, where given, were exceeded.

Turbidity and Suspended Solids

Turbidity and concentrations of suspended solids were quite variable. Generally, the higher values were for those sites influenced by ditches intruding into mineral soil. Because of the variability, there were no significant differences from site to site. Levels of these parameters increased during storm events. Guidelines for suspended solids were exceeded by the treatment sites during these storms.

Sedimentation pond A was effective in removing suspended solids. Pond B was not as effective, and the concentration of suspended solids below the point of entry into the river channel exceeded the guidelines. This pond had higher flows than pond A, and it was nearly filled with sediment. In 1987, the mean concentration of solids in the ditch upstream of the pond was less than that downstream of the pond, and this indicates that sediment was removed from the pond during high flows. If cleaned, it would likely become more effective (Heikurainen and Joensuu 1981).

CONCLUSION

Drainage caused an increase in pH, ion concentrations and alkalinity. Natural background variability made it difficult to determine how drainage affected, for instance, concentrations of metals. Water-quality guidelines were exceeded on both drained and undrained sites. Over all, the preliminary results of this study indicate that drainage has not significantly degraded downstream water quality. However, only 7% of the basin defined by the downstream site was drained, and the effect could have been greater if this percentage had been greater.

ACKNOWLEDGMENT

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HYDROLOGIC EFFECTS OF A PRESCRIPTION DRAINAGE SYSTEM ON A FORESTED WETLAND IN NORTHERN MICHIGAN

C.C. Trettin
Department of Forestry
North Carolina State University
Raleigh, North Carolina
USA

J.R. Johnson
Mead Paper Inc.
Escanaba, Michigan
USA

R.D. Mislak
Abitibi-Price Inc.
Alpena, Michigan
USA

ABSTRACT

Forest drainage systems have been used extensively to ameliorate soil water conditions, and to improve silvicultural operations and forest productivity. The most common drainage system is a pattern ditch network. An alternative type is a prescription system, in which ditches are located in the apparent valleys of the landscape. A study was conducted to determine the effects of prescription ditches on water table depth and groundwater flow. Prescription ditches were effective in lowering the water-table in the spring and fall. The ditch system intercepted shallow groundwater flow along the natural gradient except in close proximity to the ditch. The prescription drainage system is effective in enhancing silvicultural operations on coarse-textured mineral soils, and is less costly than the pattern ditch system.

RÉSUMÉ

Les systèmes de drainage forestier ont beaucoup été utilisés pour améliorer la teneur en eau du sol ainsi que les traitements sylvicoles et la productivité des forêts. Le système de drainage le plus répandu est un réseau de fossés qui couvre la superficie à traiter. Un autre type est celui du système de drainage topographique où les fossés sont situés dans les vallées et les dépressions apparentes du paysage. Une étude a été effectuée pour déterminer les effets de l'aménagement de fossés conformes au modelé sur la hauteur de la nappe phréatique et sur le débit de l'eau souterraine. Les fossés ont réussi à abaisser la nappe phréatique au printemps et à l'automne. Ils ont intercepté les eaux souterraines peu profondes le long du gradient de pente naturelle, sauf près du fossé. Le système de drainage du modelé naturel réussit à améliorer les traitements sylvicoles sur des sols minéraux à texture grossière et est moins coûteux qu'un réseau de fossés.

INTRODUCTION

Poor soil drainage adversely affects silvicultural operations and wood fiber production. Management of soil water conditions, through drainage practices, is a common approach to sustaining commercial forestry in the southeastern United States and in Finland (Allen and Campbell 1988, Paavilainen and Päivänen 1988). There are two basic types of forest drainage system: the pattern ditch system and the prescription ditch system (Terry and Hughes 1978). The pattern system is an engineered system of ditches uniformly spaced in a systematic pattern. It is typically applied to peat or mineral soils in which relief is very low and natural surface drainage is not well developed. The ditches are closely spaced to drain water through soil materials that have low hydraulic conductivity. The result is a high-density network of ditches. The design of pattern ditch systems is well established (Campbell 1976, Päivänen and Wells 1978, Rosen 1986, Haavisto and Päivänen 1987) and the effectiveness of the ditches in controlling water table levels has been documented in the United States (Terry and Hughes 1975, 1978), in Europe (Heikurainen 1964, Braekke 1983) and in Canada (Berry and Jeglum 1988, Hillman 1988).

The prescription drainage system differs from the pattern system in the basic design and in the type of site on which it is used. The prescription drainage system is used on sites that have an identifiable drainage pattern, but on which drainage is impeded as a result of blockages or low topographic relief (Terry and Hughes 1978). Drainage is accomplished by opening up the natural drainage patterns. The resulting drainage system has a dendritic pattern and a low ditch density per unit area in comparison with the pattern ditch system. Although the prescription ditch system is recognized as an approach to managing water tables on forested sites, it has not been widely used. Consequently, published data documenting the effects of the drainage system on hydrological characteristics of the wetland are scarce. Trettin et al. (1982) reported that a prescription system was effective in removing perched water associated with snowmelt. A prescription ditch caused a water-table response approximately 300 m away from, and perpendicular to, the ditch.

This paper provides a report on the hydrologic responses of a prescription drainage system and an evaluation of its application. Specific hydrologic parameters considered were the water-table response to ditching and the direction of groundwater flow. The study was based on an operational drainage project, and there was no undrained control. The discussion of the application of a prescription drainage system is based on 12 years of operational experience on a 12,000 ha-tract owned by Abitibi-Price, Inc.

STUDY SITE

The study area is in Alger County, in the northeastern part of the Lower Peninsula of Michigan. The climate is characterized by a mean annual precipitation of 835 mm and a mean annual temperature of 5.2°C. The site is located on an outwash plain. Sediments range from 11 to 35 m in thickness and are underlain by Ordovician limestone. Soils are characterized by the Kinross series, a Typic haplaquod that is sandy, mixed and frigid (Berndt 1967). The Kinross series is poorly drained, with a fine sand solum overlain by about 15 cm of *Sphagnum* moss and peat. The solum is uniform to a depth of 2.5 m, and is acid throughout. Because the water table is typically at or near the surface during the growing season, the soil is considered 'hydric' (Anon. 1985). The overstory vegetation consists primarily of black spruce (*Picea mariana*), tamarack (*Larix laricina*), and jack pine (*Pinus banksiana*). The dominant species in the shrub layer are blueberry (*Vaccinium angustifolium* and *V. corymbosum*), leather leaf (*Chamaedaphne calyculata*), and Labrador tea (*Ledum groenlandicum*).

METHODS

Drainage System

A prescription drainage system was installed on the site in June 1984. Ditches were located in the apparent valleys with the use of aerial photo interpretation, topographic maps, and field reconnaissance. There was no predrainage survey of the site. Two sizes of ditch were used, the primary ditch (4.8 m wide at the top, 1.5 m deep, 1.8 wide at the bottom) and the secondary ditch (2.4 m wide at the top, 1.0 m deep, 1.3 m wide at the bottom). The ditches were constructed by an excavator equipped with a 1-m^3 bucket. Machine operations for constructing a prescription ditch are as follows: First clear a short section of right-of-way, proceed up grade, then rotate and dig the ditch facing down grade. In this manner both land clearing and ditching are accomplished with a single pass of the excavator. The preferred operation is to work up grade, so that water is draining away from the construction; however, for this project, construction permits stipulated a down-grade construction operation. The total length of the ditches was 2635 m (1861 m of primary ditch and 774 m of secondary ditches). A sedimentation basin (70 m long, 4 m deep) was constructed at the terminus of the ditch system.

Measurements

Water-table depths were measured in wells constructed from galvanized pipe 2.5 cm in diameter. The wells were 1.5 m long and perforated throughout the lower 0.9 m, with threaded caps placed on both ends. The wells were located on three transects perpendicular to the ditch and on one parallel transect extending from the north end of the ditch (Fig. 1). Transect lengths were as follows: T1 - 1127 m, T2 - 945 m, T3 - 518 m, and T4 - 588 m. Wells were located 30, 61, 122, and 213 m from the ditch, in both directions; the final spacing of 91 m was repeated between the ditches, when the basic interval was exceeded on transects T1 and T2. The elevation of each well was measured in relation to a reference benchmark located below the ditch outlet in the Sturgeon River. Water-table elevations were computed as the difference in well elevation and water-table depth below the soil surface. Three check plots were located outside the drained area; two were placed west of the grade that divides the basin and one north of the drainage area. Water-table levels were measured monthly during the snow-free period from June, 1984 through September, 1986, and bi-monthly in 1987.

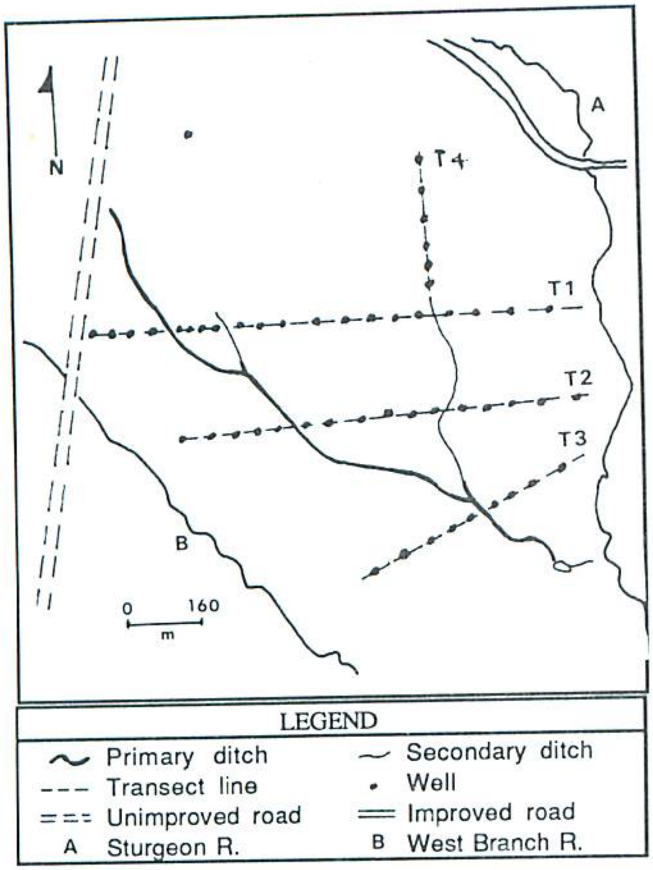

Figure 1. Project layout showing ditches and measurement wells.

Analysis

Water-table drawdown was evaluated graphically, by plotting water-table elevation versus distance, and by plotting the hydraulic head. The hydraulic head was defined as the gravitational head above the reference benchmark. Water-table drawdown was also determined by analysis of variance, by grouping wells on the basis of distance from the ditch and position within transects. The distance classes were 30-61 m, 122-213 m, and 304 m. In all, 12 groups containing the 44 measurement wells were used, on transects 1-3 and the check plots. *A posteriori* comparison of the groups was done according to Fisher's LSD method (Steele and Torrie 1980). Analyses were conducted with Statview 512+ (Abacus Concepts Inc.).

RESULTS

Water Table

The water-table response to ditching can be illustrated by a profile of the water-table that is perpendicular to the ditch. The seasonal progression of drawdown is exemplified by the measurement period of April through September, 1986 (Fig. 2). Typically, the water table is at the surface on this type of site after snowmelt; at the time of the first measurement (16 April) the water table on the check plots was at the surface, while drawdown was evident in the vicinity of the ditches. An effective drainage depth of approximately 0.8 m is indicated by the water-table depth in late May. This effective drainage depth and drawdown profile are consistent over the 4-year measurement period (Fig. 3). The June, 1984 date (Fig. 3) depicts the water table 7 days after construction was completed; this profile illustrates the rapid drainage response on this site, since water was at the surface during construction. The high water table in July 1987 (Fig. 3) is a result of 8.9 cm of above-normal precipitation during the June – July period. It is evident in Figures 2 and 3 that the drainage depth is above the depth of the constructed ditch, reflecting sedimentation that has occurred in the ditches. The water-table response on Transect 2 exhibits similar seasonal fluctuations and a stable base level, comparable with those measured on Transect 1 (Fig. 4). The effective drainage depth on Transect 2 is approximately 0.7 m below the surface, reflecting the decreased elevation of the water table and soil surface. Water-table flux within the drainage area exhibited patterns similar to those of the check wells, although the magnitude of the flux and duration of high-water levels were greatly reduced within the drainage area (Fig. 5). These data demonstrate that the effective drainage depth during the summer months is only 0.1 to 0.2 m greater than that of the check wells; however, larger differences between check wells and wells in the drained area were observed in the spring and fall months. The reduced flux in water-table depth in the drained area has also resulted in a reduction in the high-water period in relation to the check wells. As a result, the period of flooding after drainage is limited primarily to the snowmelt period.

The analysis of variance of water-table depths between distance groups of wells in the drained area and the check wells was significant ($p = 0.05$). The *a posteriori* analysis between groups demonstrated a significant difference between each group and the check wells. Pair-wise comparison of distance classes within transects T1 and T2 showed no significant differences. However, all groups within transects T1 and T2 were significantly greater than those measured in transect T3. The average water table-depth for all drainage groups was significantly greater than the depth for the check wells.

Ground Water Flow

The direction of groundwater flow is perpendicular to the hydraulic gradient. Figure 6 depicts hydraulic head isopleths for two dates in 1986; the direction of flow is indicated by the vectors perpendicular to the isopleths.

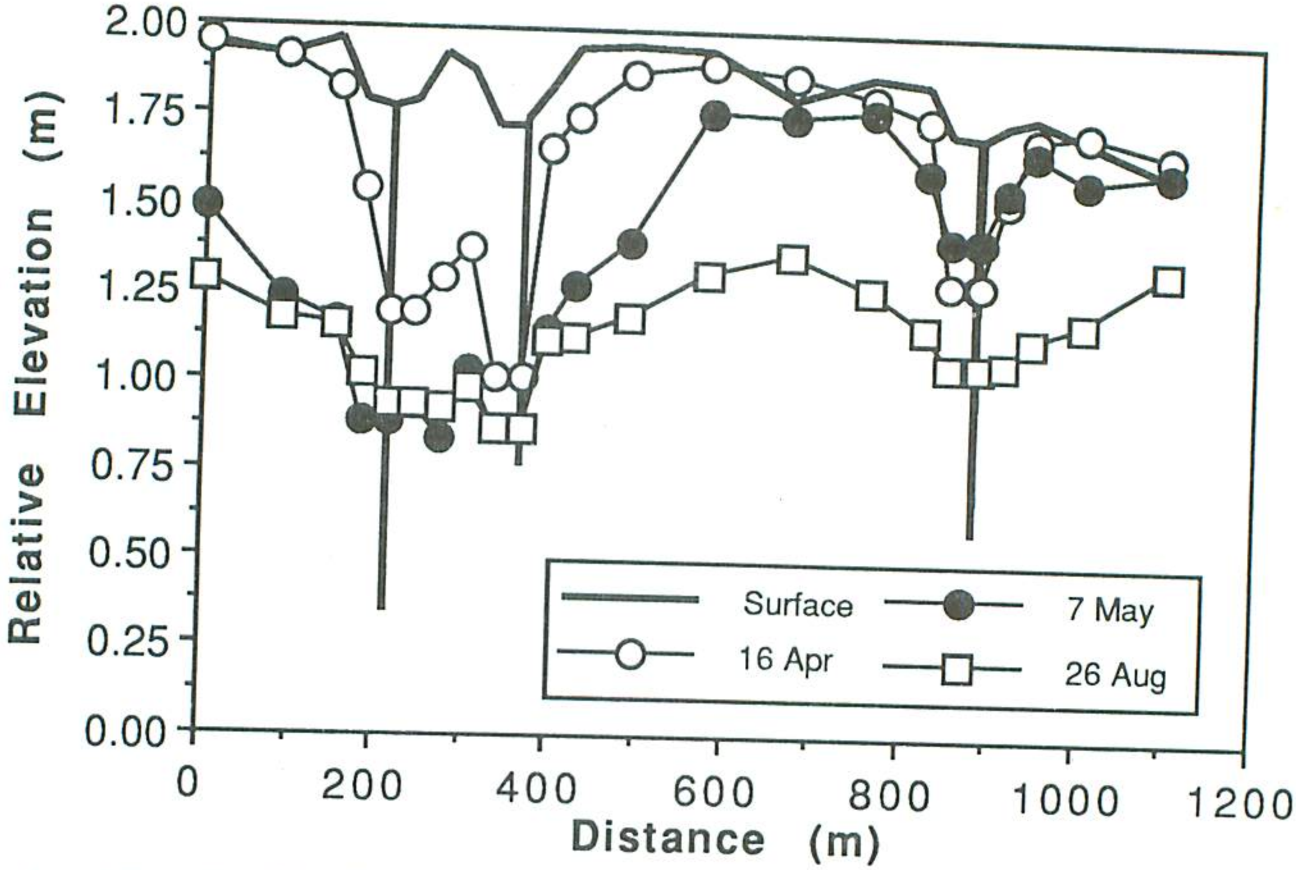

Figure 2. Water-table profiles on Transect 1 for selected dates in 1986.

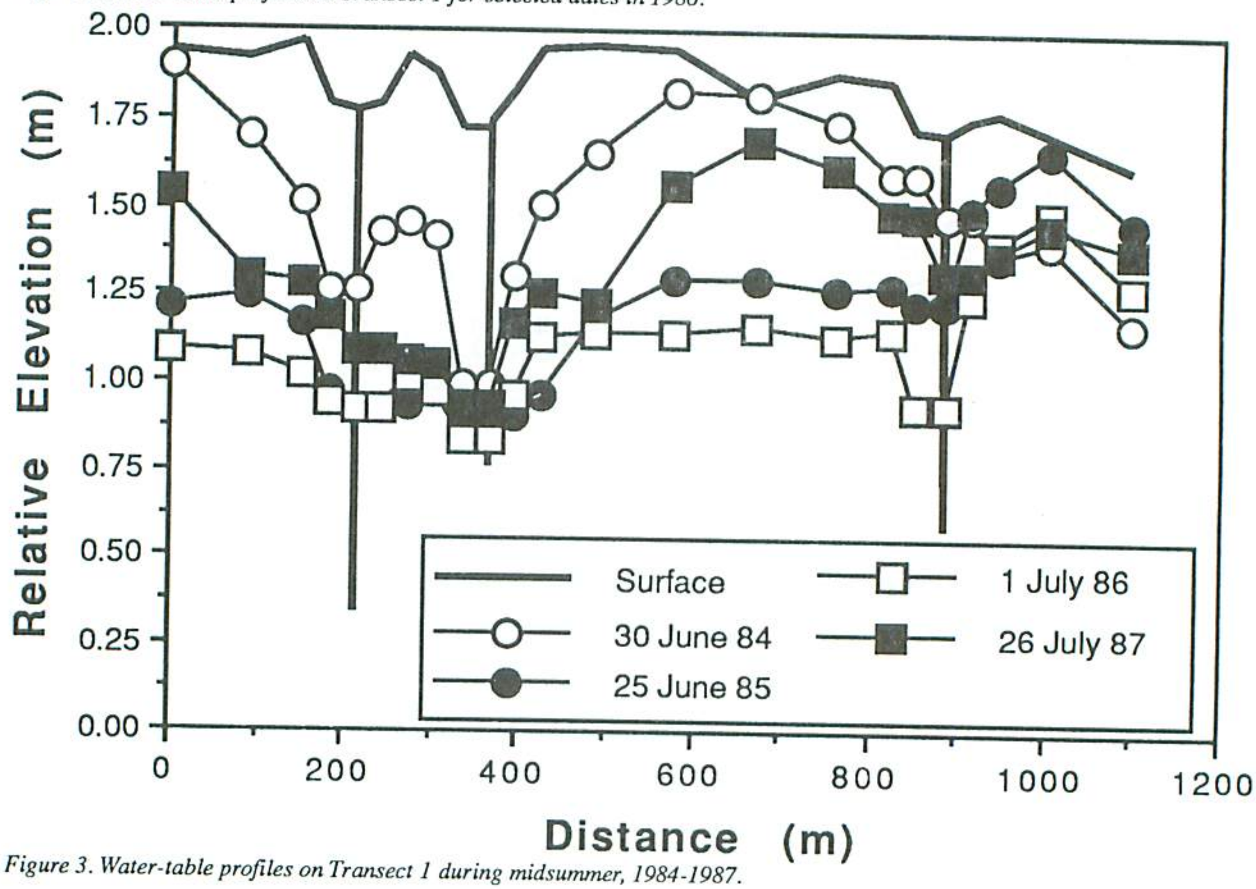

Figure 3. Water-table profiles on Transect 1 during midsummer, 1984-1987.

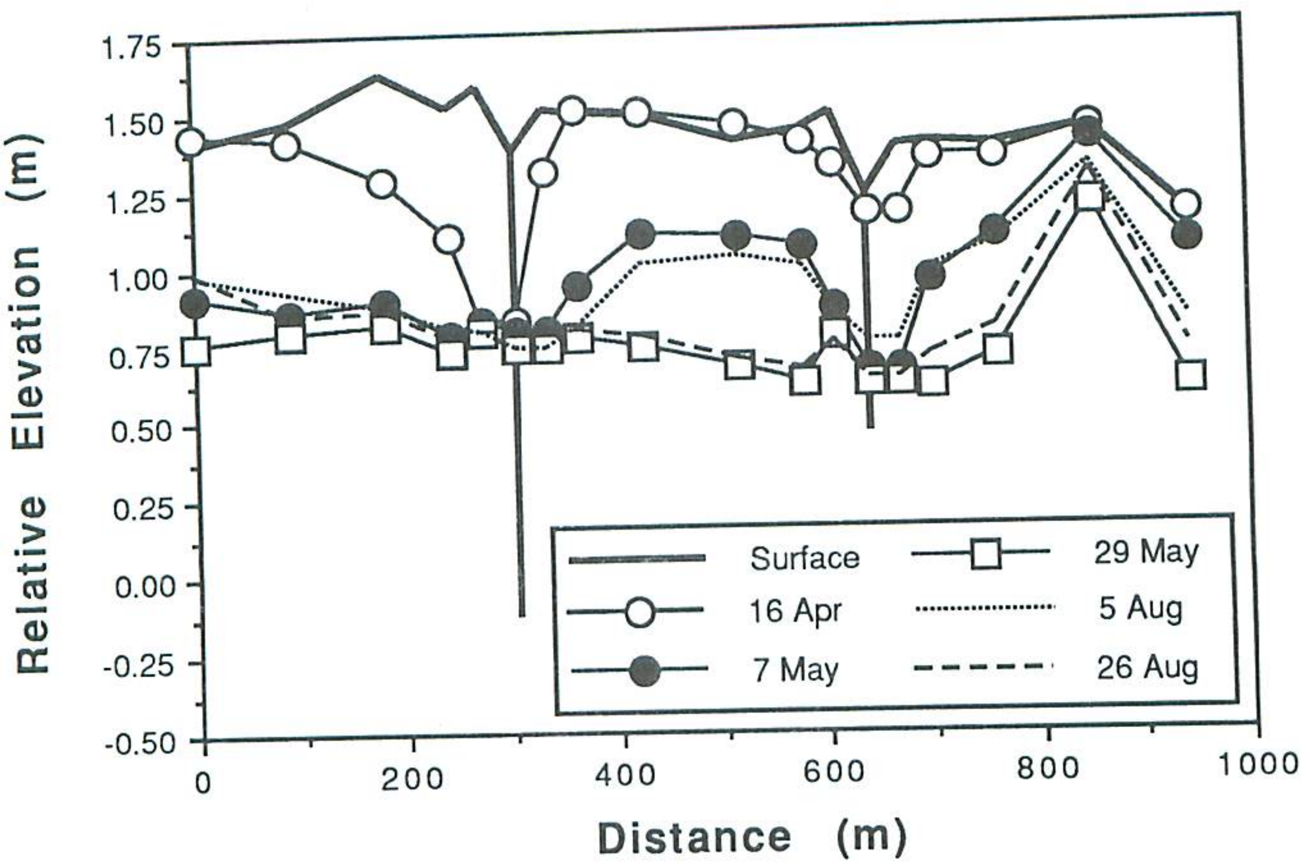

Figure 4. Water-table profiles on Transect 2 for selected dates in 1986.

The April, 1986 date represents the period immediately after snowmelt, while the August, 1986 date represents the summer period, which is characterized by low water-table levels and flow. The basic flow paths were similar for the other measurement dates. The predominant flow is from the north, indicating that much of the groundwater flow has been intercepted by the primary ditch that divides the basin. During periods of steep hydraulic gradients (April, Fig. 6) all ditch segments are affecting water-table drawdown. In contrast, during the summer months it is evident that there is only a minor alteration of the hydraulic gradient isopleth as a result of the secondary ditches (e.g., August, Fig. 6). Water-table drawdown is increased when secondary ditches are placed within 125 m of each other; this was evidenced by the intense drainage at the west end of transect T1, in the area between the primary and the secondary ditch. The overall effect of the ditch on the direction of groundwater flow can be inferred by comparing the natural topographic gradient with the hydraulic gradients associated with the ditches, although to do so one must assume that the natural hydraulic gradient mirrors the surface topography. From an overlay of a hydraulic head isopleth and the surface topography (Fig. 7), it is revealed that the ditch system has intercepted the groundwater flow along its natural flow path and channeled it. Accordingly, the dominant flow into the ditch system occurred along lines similar to what could be expected in an undrained condition, except close to the ditch where the flow was redirected.

Sedimentation Basin

Measurement of the extent of filling between 1985 and 1989 indicates that the average accumulation in the basin during that period was 7.5 cm. This contrasts with 45 cm during the first year after construction. These observations indicate that the ditches have stabilized, and the actual rate of filling is small. It should also be noted that the ditches function as a primary sediment trap, as evidenced by the difference in actual ditch depth and construction depth specifications.

DISCUSSION

A distinguishing characteristic of the prescription drainage system is that it is a non-engineered, low-intensity ditch system applied according to natural drainage patterns in the landscape. It is evident (Fig. 2 and 3) that the reconnaissance techniques used to place the ditches were effective in positioning the ditches within

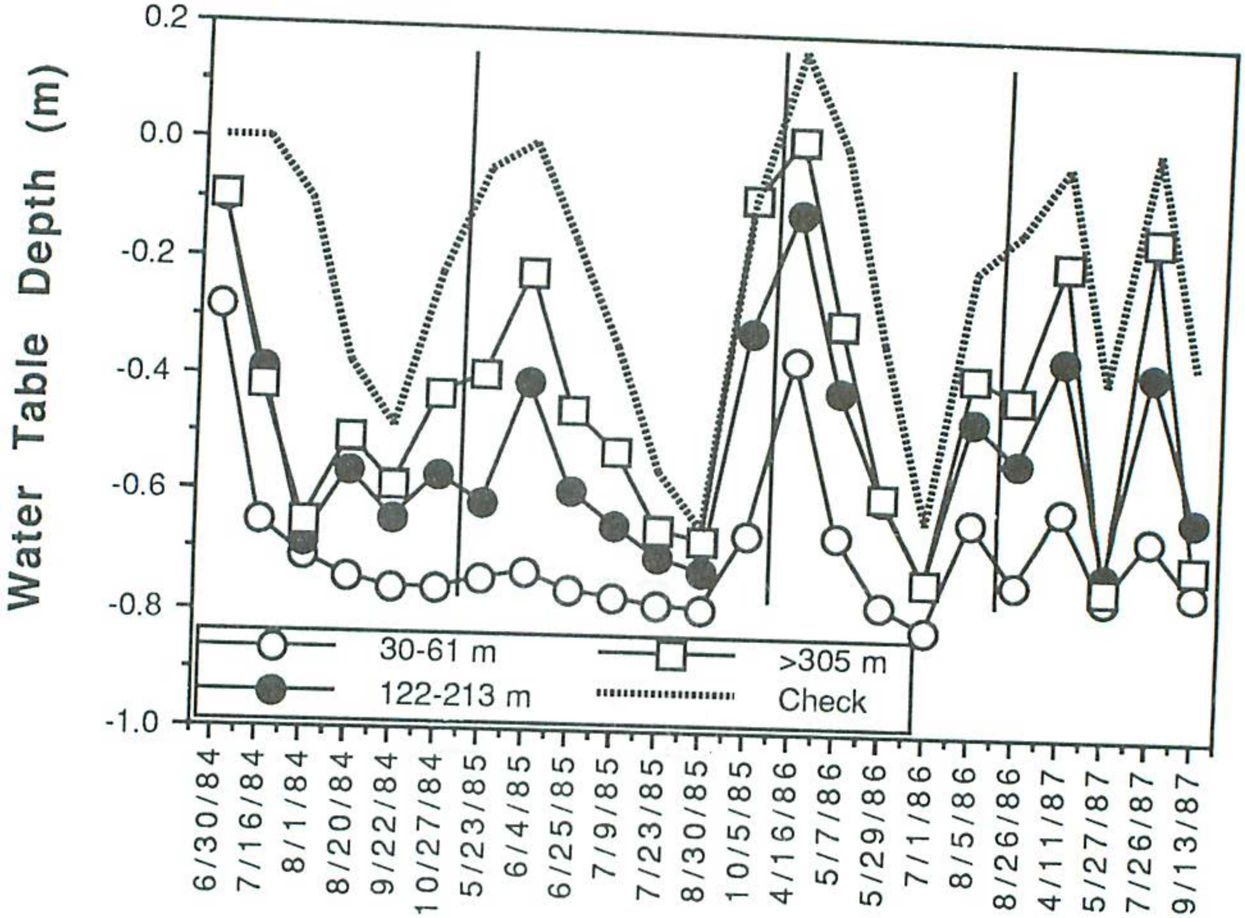

Figure 5. Depth to water table for selected groups of wells on Transect 1, 1984-1987. Groups comprise wells with a common distance from the ditch. Note: lines connect discrete measurements.

the low points in the landscape. It was possible to place ditches effectively, even though the gradient was only about 0.08%, from the sedimentation basin to the western reaches of the ditch. Application of this prescription drainage technique on an operational scale within a 12,000-ha tract has also demonstrated the effectiveness of the system (Misiak 1981). On that tract, approximately 80 km of ditch have been used to manage the surface water on 6250 ha of lowland. The resultant average density of ditches was approximately 12.8 m ha^{-1}, a figure based on the area of lowland sites. The ditching intensity on the West Branch River experimental site, reported in this paper, was approximately 17.6 m ha^{-1}. Comparison of ditching costs for prescription and pattern drainage systems demonstrates that the less intensive prescription system is considerably cheaper per unit of area drained (Table 1).

The prescription drainage system is suited to poorly drained landscape underlain by sandy and loamy soils that either are uniform or have a lithic contact within the upper solum. The presence of a histic epipedon will not inhibit the function of the ditch; however, the system is largely ineffective on deep, organic soils (Trettin, unpubl. data). The effectiveness of the ditch system will vary according to the type of landscape and associated soil materials. Trettin et al. (1982) reported a water-table drawdown at distances of 300 m from the ditch, on a recessional beach terrace that was underlain by lacustrine sediments. In the study reported here, the drainage effect is evident at distances of approximately 150 to 200 m from the ditch. However, the affected area is larger than that represented by the area within the perpendicular distance along the ditch, since flow within the entire drained basin has been altered (Fig. 7).

The effects of the ditch on water-table drawdown are not accurately represented in the water-table profile data (Fig. 2-4). It is evident in Figure 7 that the groundwater flow into the ditch is perpendicular to the ditch, usually within 30-60 m of the ditch; at other points the apparent natural flow gradient has been intercepted by the ditch. Accordingly, in the north-central portions of the drainage area, represented in transect T1, the water table

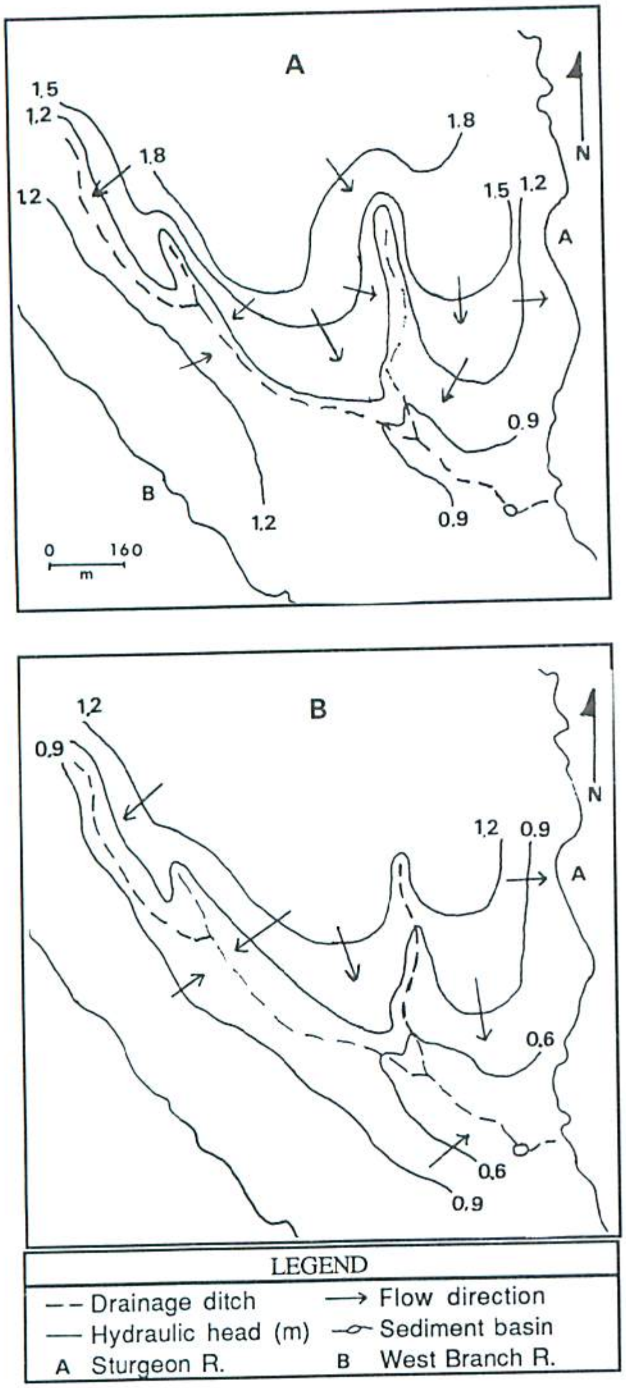

Figure 6. Hydraulic head isopleths for (A) 16 April and (B) 28 August, 1986.

between 550 and 750 m is flowing into the ditch to the south, rather than east or west into the ditches in the transect. This illustrates that the prescription ditch serves to intercept and channel shallow groundwater along natural gradients, and achieves more intensive localized drainage near the ditch (i.e., within 60 m). During spring runoff the effect of ditching on water-table drawdown is

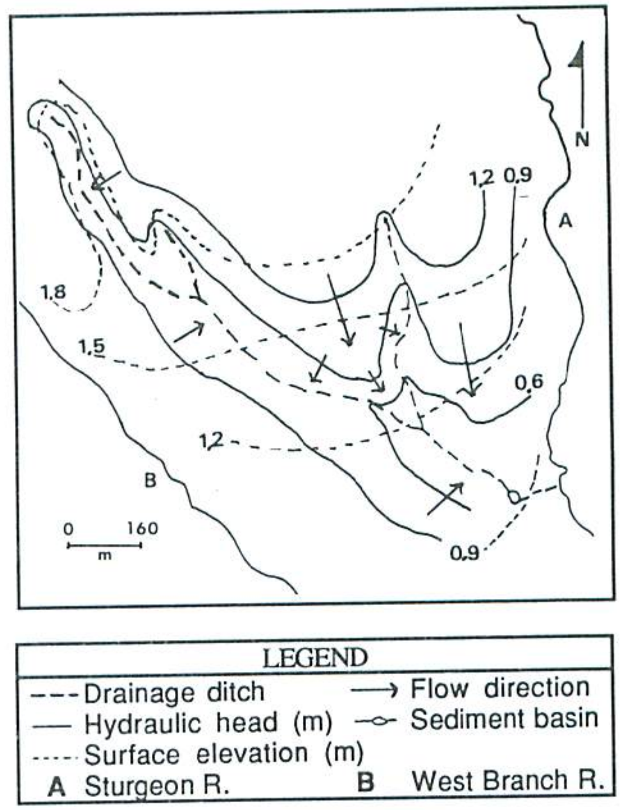

Figure 7. Overlay of 28 August, 1986 hydraulic head isopleth and surface topography.

more evident (Fig. 6). The total hydraulic gradient is approximately 1 m. Flow during the summer months tends to follow the natural gradient, with the ditch intercepting the flow along that path.

Water-table fluctuations are common in this wetland type. There is a distinct seasonal pattern with dewatering occurring in late spring, a period of low water table during the summer, and a rise in groundwater depth in the fall (Fig. 5). Intra-seasonal fluctuations are also evident, particularly during periods of high summer precipitation (1987, Fig. 2). Precise evaluation of the effects of ditching was not possible since there was no control for the study. However, comparison with the check wells, in undrained portions of the basin, indicates that drainage has lowered the water table approximately 0.1 to 0.2 m during midsummer, and the water-table levels during the spring and fall are lowered by 0.3 to 0.7 m. These data indicate that the period of flooding has been reduced and that drainage has resulted in a lower water table in the spring-summer transition and fall transition, but that the midsummer period is not very different.

Table 1. Comparison of cost per unit of area drained for prescription and pattern drainage systems

Drainage	Density ($m\ ha^{-1}$)	Ditching Cost[a] (ha^{-1})	Reference
Pattern	76.9	$49 (U.S.; 1978)	Terry and Hughes (1978)
Pattern	232.4	$270 (Can.; 1986)	Rosen (1986)
Prescription	12.8	$29 (U.S.; 1983)	Misiak (unpubl. data)
Prescription	17.6	$32 (U.S.; 1984)	this study

[a] Currency and year of cost computation are noted.

Application of Prescription Drainage

Prescription drainage has been an important forest management practice for sustaining a commercially viable forest on a 12,000-ha tract in northern Michigan. Experience with the 80 km of ditches installed there has shown that the ditching system increased the flexibility of harvest scheduling and improved equipment operability. The ditches have functioned for 12 years or more without cleaning. This assessment was based on observations of sustained flow in the ditches and subjective assessments of water-table levels. Control of beaver activity in ditches is important to prevent flooding and reversion to predrainage conditions. Rapid stabilization of the spoil banks and effective sedimentation basins are credited with maintaining sediment levels in the drainage waters comparable with those measured in the receiving rivers (Trettin and Sheets 1987). Application of a prescription drainage system over a large area results in a dendritic drainage pattern that is an enhancement of the existing surface drainage network.

SUMMARY

Forest drainage systems can be used to ameliorate soil water conditions. The prescription ditch system is a low-intensity system, applicable to broad, flat landscapes with coarse- to medium-textured soils. Although the drainage system complements the natural, apparent drainage, it does affect the high-water period and flow direction of surface and shallow groundwater from wetlands. Flow into the ditch is both along the natural gradient and through actual drawdown close to the ditch. Operational application of the prescription ditches complements the natural drainage patterns and creates a dendritic drainage pattern when applied to large land areas.

It is evident from the water table and elevation data that the high-water periods could be regulated or designed to limit the intensity of drainage by reducing the ditch depths or increasing the elevation of the outlet. This, in effect, would establish a water management system. This approach would help to ensure that the effects of this forest drainage practice on wetland processes are minimized.

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SEASONAL AND VEGETATIONAL VARIATIONS IN WETLAND CHEMISTRY IN KEJIMKUJIK NATIONAL PARK, NOVA SCOTIA

J.A. Wood and C.D.A. Rubec
Sustainable Development Branch
Environment Canada
Ottawa, Ontario
Canada

ABSTRACT

Results of an investigation of wetland chemistry in several drainage basins in Kejimkujik National Park, Nova Scotia are presented. Seasonal variations in chemistry of many of the major ions were significant in both the peat and the water. Seasonal changes in acidity of both media were accompanied by parallel changes in the C:N ratio in the peat, and in levels of dissolved organic carbon and organic anions in the water. Although there were significant seasonal changes in SO_4 in the water, SO_4 levels in the peat did not change significantly on a seasonal basis. There were significant differences in the major ion constituents between wetlands classified as bogs and the more minerotrophic fens. The fens, however, were very low in pH and base cations, although they had not yet been invaded by the dominant *Sphagnum* vegetation that characterizes ombrotrophic systems. These wetlands are transitional to bogs and are considered highly sensitive to acid deposition. Further alkalinity losses may result in a rapid invasion of carpet-forming *Sphagnum* species.

RÉSUMÉ

Cet ouvrage présente les résultats d'une étude de la chimie des terres humides dans plusieurs bassins hydrographiques du parc national Kejimkujik en Nouvelle-Écosse. D'importantes variations saisonnières au niveau de la chimie d'un grand nombre des principaux ions se sont produites dans la tourbe ainsi que dans l'eau. Des changements saisonniers au niveau de l'acidité de ces deux milieux sont accompagnés de changements parallèles au niveau du rapport C/N dans la tourbe, et au niveau de la COD et des anions organiques dans l'eau. Bien que d'importants changements saisonniers au niveau du SO_4 se soient produits dans l'eau, les teneurs en SO_4 dans la tourbe n'ont pas connu un important changement saisonnier. Il y a également eu d'importantes différences au niveau des principaux constituants ioniques entre les terres humides classées dans la catégorie des bogs et celles classées dans la catégorie des fens plus minérotrophiques. Les fens sont cependant catégorisés comme étant extrêmement pauvres, comme ayant un pH très faible et très peu de cations basiques, bien qu'ils n'aient pas encore été envahis par la végétation dominante de *Sphagnum* caractéristique des systèmes ombrotrophes. Ces terres humides qui sont un état transitoire dans la formation des bogs sont considérées comme étant très sensibles aux dépôts acides. L'invasion rapide d'espèces de *Sphagnum* qui forment des tapis peut entrainer d'autres pertes d'alcalinité.

INTRODUCTION

The seasonal dynamics of wetland soil chemistry and their effects on receiving waters are a neglected area of research. The effect of wetland chemistry on acid deposition remains a major outstanding issue in the Canadian Long-range Transport of Airborne Pollutants (LRTAP) Program. Clear-water acidification models have failed when applied to brown water (Wright 1983, Rogalla et al. 1986). Dissolved organic carbon (DOC), sulfur (S) and nitrogen (N) cycles in waters receiving drainage from wetlands are related to the processes occurring in wetland soils.

Although the general chemical characterization of wetlands and wetland forms has been studied, studies on seasonal changes in wetland soil chemistry are needed, particularly with respect to storage of S, N and metals, carbon (C) production and the effects of all these changes on receiving waters. A study of wetland chemistry in Kejimkujik National Park was begun in 1986 (Kessel-Taylor 1986, Wickware et al. 1987). The senior author concluded field work and analysis for the present study in 1988. The study was confined to wetlands within the Kejimkujik Lake drainage basin, and had two objectives: (1) characterization of the seasonal dynamics in wetland soil and water chemistry, and (2) characterization of chemically minerotrophic and oligotrophic wetlands within the drainage basin.

SAMPLING AND METHODS

Soil and water sampling were carried out on seven wetlands in six sub-basins of the Kejimkujik Lake drainage basin. The sub-basins included: Little River, Mersey River, Atkins Meadow Brook, Heber Meadows Brook, Rogers Brook and West River (Fig. 1). One wetland was sampled within each sub-basin, with the exception of West River, in which two wetlands were sampled. All of the wetlands sampled were open (non-treed). Of the wetlands surveyed, three were bogs (Heber Meadows Brook, Atkins Meadow Brook and a site near the mouth of West River) and the remaining four were classified as graminoid and shrub fens (Wickware 1987). The oligotrophic nature of the bogs was indicated visually by a dense carpet of *Sphagnum* spp. vegetation, while the fens were generally recognized by the predominance of *Carex* species. Water and peat sampling were repeated at the same sites during each of three field visits in 1987.

Field data were collected on 19 May, 14 September and 24 November 1987. These dates were chosen to coincide approximately with maxima or minima in sulfate (SO_4) and dissolved organic carbon (DOC) concentrations in the streamwater. Howell (1988) reports maximum SO_4 concentrations in the streamwater in the spring flood season, followed by a minimum in late summer, and increasing again in late autumn. DOC tends to follow an opposing cycle, with a minimum in spring and late autumn and a maximum in late summer.

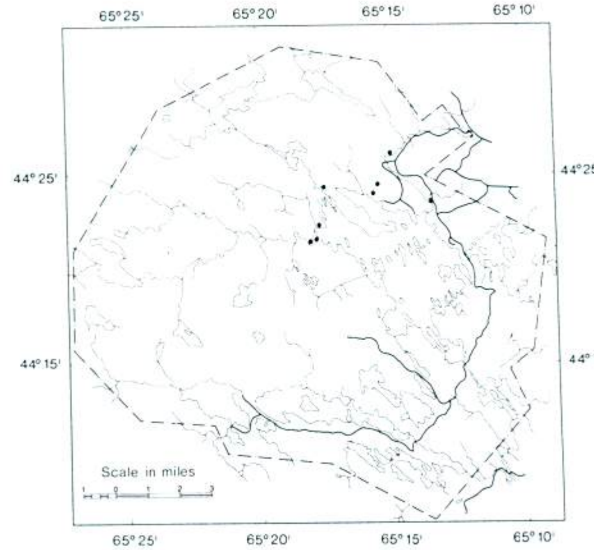

Figure 1. Wetland sampling locations, 1987, in Kejimkujik National Park.

Two peat cores, 2.5 cm in diameter and spaced 1 m apart, were removed from the top 50 cm of each wetland sampling site. Two peat cores per site were taken to obtain some indication of the variation in peat chemistry at each site. The sites were generally located within about 30 m of the adjacent river or stream, into which mobile water from the peat was likely to drain rather than evaporate, as might happen further inland. In the case of Heber Meadows Brook (Fig. 1), peat cores were removed from two sites (two cores per site), one site within 20 m of the Brook and the other about 200 m inland.

Peat samples were homogenized in a blender and the pH was determined by placing a glass electrode in contact with the peat and allowing 30 to 60 minutes for the reading to stabilize. The samples were then air dried, homogenized again and washed with hydrochloric acid (HCl) and barium acetate. Cation-exchange capacity was determined by titration. Total C of the air-dried sample was determined by a Leco carbon analyzer and total N by the Kjeldhal procedure. The sample was oven dried, ashed at 550°C and digested with HCl-$HClO_4$ (hydrochloric acid-perchloric acid). Concentrations of aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), and phosphorus (K) were analyzed by atomic-absorption spectrophotometry, and chlorine (Cl) and SO_4 by ion chromatography.

Porewater and/or surface water samples were removed from the site of each peat core. When free water was observed standing on the surface of the wetland, a surface-water sample was collected. Otherwise, a porewater sample was collected by digging a small hole in the peat and allowing it to fill with water. Porewater samples could not be collected for the September sampling period because of extremely dry conditions at that time.

Streamwater samples were taken from locations a few metres upstream and downstream of each sampling station. Water samples were analyzed for color and ionic constituents at the Water Quality Branch Laboratory, Environment Canada, Moncton, New Brunswick. The pH was determined with a glass electrode. Al, Fe, Ca and Mg were measured by atomic-absorption spectrophotometry, Na and K by flame photometry and SO_4 and Cl by ion chromatography. The color was determined against a platinum-cobalt (Pt-Co) standard. Total N was determined colorimetrically, gran alkalinity by titration, and DOC by ultraviolet (UV) digestion and colorimetry. Organic anions were computed according to the method of Oliver et al. (1983).

ANALYTICAL METHODOLOGY

Ionic constituents of the peat (usually two cores for each wetland) and water were averaged to obtain a single value for each wetland in each season. The averaged peat and water data were then transformed to the natural-log scale for all chemical parameters except the pH and ash content of the peat chemistry data, and the pH, color, conductivity, turbidity, gran alkalinity, and total ion data for the water chemistry. Plots were then prepared for all of the chemical parameters to illustrate the magnitude and direction of the seasonal changes. Outlying data were identified visually and eliminated to prevent a skewed distribution. Tables were produced to show seasonal mean values for each chemical parameter for all seven wetlands (Tables 1, 2 and 3). Wetlands were subdivided into two classes (Tables 4, 5 and 6) on the basis of national wetland classification standards (National Wetlands Working Group, 1987): *Bogs*, which are dominated by *Sphagnum* vegetation, are essentially oligotrophic, and obtain much of their nutrient supply from rainwater; *and fens*, which are mesotrophic to eutrophic in character, and are dominated by *Carex* species.

Table 1. Peat chemistry: seasonal means (7 wetlands, 14 samples)

	May	SE[a]	MS[b]	Sept.	SE	SN[b]	Nov.	SE	MN[b]
pH	3.51	3	*	3.33	3	–	3.26	4	*
H (epm)	0.40	3	*	0.60	3	–	0.80	4	*
Al (epm)	1557.07	28	–	1415.51	25	–	1251.83	21	#
Fe (epm)	137.44	30	–	108.27	15	*	264.81	15	*
Ca (epm)	7.69	31	@	15.49	33	–	15.94	17	*
Mg (epm)	52.00	30	–	33.10	13	#	28.70	20	#
Na (epm)	123.84	20	*	17.70	28	–	16.18	18	#
K (epm)	59.62	27	@	28.37	27	–	33.05	27	*
SO_4 (epm)	18.35	23	–	16.72	21	–	18.16	18	–
Cl (epm)	3.98	40	–	0.84	29	*	6.33	32	–
Tot. C (%)	43.14	15	@	45.33	9	@	38.34	14	#
Tot. N (%)	1.49	12	@	1.83	8	@	1.78	7	@
C:N ratio	28.93	22	@	24.75	13	#	21.52	15	#
CEC (meq/100 g)	82.33	11	–	76.05	8	@	97.23	10	*
Totals:									
Anions (epm)	22.33	24	–	17.57	20	–	24.49	21	–
Cations (epm)	1938.05	20	–	1619.03	23	–	1611.30	18	–

[a] SE = standard error of the mean (%)
[b] Seasonal changes: MS = May-September, SN = September-November, MN = May-November
Note: Differences in seasonal mean significant at:
@ $p < 0.10$
# $p < 0.05$
* $p < 0.01$

Table 2. Streamwater chemistry: seasonal means (7 wetlands, 14 samples)

	May	SE[a]	MS[b]	Sept.	SE	SN[b]	Nov.	SE	MN[b]
pH	4.84	4	*	5.48	4	*	4.43	2	#
H (epm)	0.02	4	*	0.01	4	*	0.04	2	*
Al (epm)	0.02	15	–	0.02	10	#	0.03	15	*
Fe (epm)	0.01	13	*	0.04	24	#	0.02	11	*
Ca (epm)	0.02	12	#	0.03	17	@	0.04	12	*
Mg (epm)	0.03	7	*	0.04	10	#	0.05	6	*
Na (epm)	0.01	4	*	0.16	4	–	0.00	3	*
K (epm)	0.01	8	#	0.01	22	#	0.00	13	*
SO_4 (epm)	0.04	7	–	0.06	22	–	0.08	10	*
Cl (epm)	0.11	5	*	0.14	4	*	0.12	4	*
DOC (mg L^{-1})	9.04	7	–	7.71	18	*	17.50	7	*
N (mg L^{-1})	0.10	1	–	0.16	11	–	0.10	2	–
Org. anions (meq L^{-1})	0.06	7	–	0.06	18	*	0.11	7	*
Gran alk. (mg L^{-1})	-0.84	67	#	-0.95	45	*	-2.24	22	*
Totals:									
Anions (epm)	0.22	4	*	0.29	6	–	0.30	4	*
Cations (epm)	0.20	3	*	0.27	8	*	0.28	2	*

[a] SE = standard error of the mean (%)

[b] Seasonal changes: MS = May-September, SN = September-November, MN = May-November

Note: Differences in seasonal mean significant at:

@ $p < 0.10$
# $p < 0.05$
* $p < 0.01$

Table 3. Porewater chemistry: seasonal means (7 wetlands, 14 samples)

	May	SE[a]	Nov.	SE	MN[b]
pH	4.48	4	4.34	3	–
H (epm)	0.04	4	0.06	3	–
Al (epm)	0.20	35	1.28	39	*
Fe (epm)	0.08	33	0.17	38	–
Ca (epm)	0.01	22	0.04	20	*
Mg (epm)	0.02	14	0.04	13	*
Na (epm)	0.09	11	0.16	9	#
K (epm)	0.01	11	0.01	15	#
SO_4 (epm)	0.03	16	0.09	7	*
Cl (epm)	0.10	10	0.11	8	–
DOC (mg L^{-1})	25.50	24	31.25	16	–
N (mg L^{-1})	0.04	12	0.25	27	@
Org. anions (meq L^{-1})	0.19	24	0.19	16	–
Gran alk. (mg L^{-1})	-2.31	40	-3.21	21	–
Totals:					
Anions (epm)	0.33	16	0.39	9	–
Cations (epm)	0.43	23	1.73	30	*

[a] SE = standard error of the mean (%)

[b] MN = May-November

Note: Differences in seasonal mean significant at:

@ $p < 0.10$
# $p < 0.05$
* $p < 0.01$

For each variable in the three media (peat, streamwater and porewater), pair-wise comparisons were made between seasons for all of the wetlands. Significance levels (probabilities) were determined for F values. These were generated by a two-level factorial analysis of variance (ANOVA) procedure based on SAS GLM (Joyner 1985) for a crossed design (wetland versus season), with correction for unequal weighting as described in Snedecor and Cochran (1967). The data were unequally weighted because, in a few instances, only a single peat core was collected from a wetland, rather than a pair, and this skewed the distribution of data. A correction procedure was required (ibid.). The probability that the difference between any two seasons was random was categorized at three significance levels: 0.10, 0.05 and 0.01 (Tables 1, 2, and 3). For the peat and the streamwater, there were three such comparisons per parameter, May versus September, September versus November, and May versus November, while for the porewater there was only one per parameter (May versus November).

Table 4. Peat chemistry: seasonal and annual means for bogs and fens

	May		Sept.		Nov.		Annual mean[a]	
	Bog	Fen	Bog	Fen	Bog	Fen	Bog	Fen
pH	3.24	3.68 #	3.02	3.51 #	2.86	3.50 #	3.04	3.56
H (epm)	0.67	0.23 #	1.02	0.34 #	1.53	0.37 #	1.07	0.31
Al (epm)	881.07	1962.68 @	629.58	1887.06 #	556.37	1669.11 @	689.01	1839.61
Fe (epm)	87.26	167.54 @	68.56	132.10 #	246.13	276.02 –	133.98	191.89
Ca (epm)	4.66	9.51 –	7.78	20.12 –	12.57	17.96 –	8.35	15.86
Mg (epm)	46.68	55.19 –	34.69	32.15 –	32.33	26.52 –	37.95	37.95
Na (epm)	88.09	145.29 @	9.35	22.71 @	9.64	20.10 @	35.69	62.70
K (epm)	38.83	72.09 @	17.62	34.82 @	12.22	45.54 @	22.91	50.82
SO_4 (epm)	21.63	16.38 –	13.24	18.81 –	14.33	20.45 –	16.40	18.55
Cl (epm)	6.74	2.33 –	0.59	0.99 –	5.25	6.99 –	4.20	3.44
C (%)	56.33	35.23 #	51.53	41.61 @	51.67	30.35 #	53.14	35.73
N (%)	1.22	1.66 –	1.48	2.04 –	1.68	1.83 –	1.46	1.84
C:N ratio	50.44	22.84 #	35.94	20.21 #	31.42	16.67 #	39.27	19.91
Ash (%)	21.71	44.31 @	15.54	36.26 @	15.26	46.98 @	17.50	42.52
CEC (meq/100 g)	97.87	73.01 @	73.52	77.57 –	120.12	83.50 @	97.17	78.02
Totals:								
Anions (epm)	28.37	18.70 –	13.83	19.80 –	19.58	27.44 –	20.59	21.98
Cations (epm)	1147.25	2412.53 @	768.60	2129.29 @	870.78	2055.62 @	928.88	2199.14

[a] Significance levels of annual means not available.

Note: Differences between bog and fen means significant at:

@ $p < 0.10$
* $p < 0.05$
– nonsignificant

Table 5. Streamwater chemistry: seasonal and annual means for bogs and fens

	May		Sept.		Nov.		Annual mean[a]	
	Bog	Fen	Bog	Fen	Bog	Fen	Bog	Fen
pH	4.45	4.99 –	5.45	5.49 –	4.25	4.50 –	4.72	4.99
H (epm)	0.04	0.02 –	0.01	0.01 –	0.06	0.04 –	0.04	0.02
Al (epm)	0.02	0.02 –	0.02	0.01 –	0.03	0.03 –	0.02	0.02
Fe (epm)	0.01	0.01 –	0.05	0.04 –	0.02	0.02 –	0.03	0.03
Ca (epm)	0.02	0.02 –	0.03	0.03 –	0.03	0.04 –	0.03	0.03
Mg (epm)	0.03	0.03 –	0.03	0.04	0.04	0.05 –	0.03	0.04
Na (epm)	0.11	0.12 –	0.17	0.15 –	0.13	0.15 –	0.14	0.14
K (epm)	0.01	0.01 –	0.02	0.01 –	0.01	0.01 –	0.01	0.01
SO_4 (epm)	0.04	0.04 –	0.09	0.05 –	0.07	0.08 –	0.06	0.06
Cl (epm)	0.10	0.11 –	0.13	0.15 –	0.10	0.12 @	0.11	0.13
DOC (mg L^{-1})	11.50	8.06 –	5.85	8.45 –	20.00	16.50 –	12.45	11.00
N (mg L^{-1})	0.01	0.01 –	0.03	0.01 –	0.01	0.01 –	0.02	0.01
Org. anions:								
(meq L^{-1})	0.07	0.06 –	0.05	0.07 –	0.12	0.11 –	0.07	0.08
Gran alk.								
(mg L^{-1})	-1.58	-0.35 –	1.17	0.59 –	-3.40	-1.85 –	-1.27	-0.54
Totals:								
Anions (epm)	0.21	0.22 –	0.29	0.29 –	0.29	0.31 –	0.26	0.27
Cations (epm)	0.20	0.20 –	0.29	0.26 –	0.27	0.28 –	0.25	0.25

[a] Significance levels of annual means not available.

Note: Differences between bog and fen means significant at:

@ $p < 0.10$
* $p < 0.05$
– nonsignificant

Table 6. Porewater chemistry: seasonal and annual means for bogs and fens

	May		Nov.		Annual mean[a]	
	Bog	Fen	Bog	Fen	Bog	Fen
pH	4.18	4.78 #	4.30	4.37 –	4.24	4.58
H (epm)	0.07	0.01 #	0.07	0.05 –	0.07	0.03
Al (epm)	0.16	0.23 –	1.79	0.98 –	0.98	0.61
Fe (epm)	0.07	0.09 –	0.30	0.09 @	0.19	0.09
Ca (epm)	0.01	0.02 #	0.05	0.04 –	0.03	0.03
Mg (epm)	0.01	0.02 #	0.03	0.05 #	0.02	0.04
Na (epm)	0.07	0.11 @	0.20	0.14 –	0.13	0.12
K (epm)	0.01	0.01 –	0.02	0.01 –	0.01	0.01
SO_4 (epm)	0.02	0.04 –	0.08	0.09 –	0.05	0.06
Cl (epm)	0.08	0.12 #	0.11	0.10 –	0.10	0.11
DOC (mg L^{-1})	25.83	25.25 –	47.67	21.40 #	36.75	23.33
N (mg L^{-1})	0.01	0.07 –	0.52	0.09 #	0.27	0.08
Org. anions: (meq L^{-1})	0.15	0.23 –	0.29	0.13 –	0.22	0.18
Gran alk. (mg L^{-1})	-4.10	-0.48 –	-3.67	-2.94 –	-3.89	-1.71
Totals:						
Anions (epm)	0.25	0.39 –	0.49	0.32 –	0.37	0.36
Cations (epm)	0.38	0.46 –	2.43	1.31 –	1.40	0.89

[a] Significance levels of annual means not available.

Note: Differences between bog and fen means significant at:

@ $p < 0.10$
* $p < 0.05$
– nonsignificant

Analysis of variance was also carried out for each variable to test for the difference between bogs and fens. Significance levels were again determined by an F-test, which was obtained from a two-way ANOVA procedure computed by SAS GLM (Joyner 1985). In this case, however, the design was nested instead of crossed. There were two levels of nesting: individual samples (two per wetland) nested within wetlands and individual wetlands nested within the wetland class (bog or fen). The probability of a random difference in any of the chemical parameters between bogs and fens was categorized at two levels of significance: 0.10 and 0.05 (Tables 4, 5, and 6). Significance levels were not available for the annual means because of theoretical difficulties involved in their determination.

Individual variability in peat chemistry is important because of the relatively small sample size, both of individual peat cores (14) and of wetlands (7). If the variation between pairs of parallel peat cores (1 m apart) in each wetland exceeds the variation between wetlands for a particular chemical parameter, then the difference between seasonal changes or between wetland classes (bogs and fens) will not be significant. In Tables 1 to 6 many of the differences between seasons, as well as between wetland classes (bogs versus fens), were not significant (i.e., $p > 0.10$). In most cases, this was due to a high variation between wetlands rather than between parallel peat cores within each wetland. Individual sample variation within each wetland was relatively low. This is demonstrated in Table 7, in which F values for each chemical parameter were computed for the peat by means of a one-way ANOVA procedure based on SAS GLM (Joyner 1985).

The F values (Table 7) are the ratio of the mean square of each chemical parameter for the individual peat cores in each wetland to the mean square for all wetlands. Probabilities of a random occurrence (significance levels) are also listed. At $F = 1$, the probability is 0.50. As F becomes larger, the probability decreases toward zero. At the $p = 0.05$ level of significance, the F value generally ranges between 3 and 4.

Most of the F values in Table 7 are relatively high ($F > 4$) and the probabilities are low ($p < 0.05$), an indication that the variation in chemistry within each wetland (i.e., between parallel peat cores) was much lower than the variation between wetlands. Consequently, in Tables 1 to 6, "between"-wetland variability and not "within"-wetland variability was generally responsible for most of the cases in which seasonal differences or differences between wetland classes were not significant.

Table 7. Comparison of F values for differences between sites for peat parameters as well as differences between samples from the same site

	May		Sept.		Nov.	
	F-value	Prob.[a]	F-value	Prob.[a]	F-value	Prob.[a]
pH	10.39	0.002	117.06	0.0001	16.87	0.0003
H	10.39	0.002	117.06	0.0001	16.87	0.0003
Al	33.31	0.02	33.07	0.0001	23.41	0.0001
Fe	6.11	0.01	8.48	0.004	0.83	0.59
Ca	47.06	0.0001	29.19	0.0001	4.15	0.03
Mg	1.78	0.21	36.86	0.0001	19.00	0.0002
Na	2.52	0.11	46.84	0.0001	1.87	0.20
K	63.64	0.0001	50.71	0.0001	69.82	0.0001
SO_4	7.49	0.005	2.82	0.09	4.57	0.02
Cl	1.72	0.23	0.77	0.63	1.32	0.35
C	4.79	0.02	4.83	0.02	25.04	0.0001
N	1.80	0.21	11.30	0.001	1.42	0.31
C:N ratio	11.37	0.001	8.04	0.004	8.44	0.0037
CEC	12.17	0.001	3.50	0.05	11.35	0.001
Totals:						
Anions	6.91	0.007	1.93	0.19	1.88	0.20
Cations	3.76	0.04	47.61	0.0001	4.66	0.02

[a] Prob. = probability of random occurrence

RESULTS

For comparative purposes in Tables 1 to 6, concentrations of hydrogen (H), Al, Fe, Ca, Mg, Na, K, SO_4 and Cl in peat and streamwater are expressed in equivalents per million (epm). These units are convenient because peat chemistry cannot be expressed on a volume basis in meq L^{-1} (1 epm = 1 meq L^{-1}). Organic anions are reported in meq L^{-1}. Ash contents and C and N values of peat are expressed in percent (%) dry weight. The cation-exchange capacity (CEC) is given in meq/100 g dry weight of soil.

Ion balances in streamwater [i.e., (total cations – total anions) / (total cations + total anions)] were within the 10% range of acceptable variability (Howell 1988, and personal communication). For peat, ions do not need to be balanced. The much larger number of cations reflects the predominantly negative charge of the organic colloids. For porewater, the balances were poor in November (Table 3), although the balance only slightly exceeded acceptable limits in May. Because the peat was rather dry in November, porewater samples squeezed from the peat had large amounts of solid organic matter in the water. Although the water samples were filtered, there may have been an ion balance because colloidal organic matter with adsorbed cations passed through the filter, resulting in an excessive number of associated cations appearing in the water as "dissolved" cations.

SEASONAL CHANGES

Significant seasonal changes in peat chemistry included changes in Na, K, Mg, Ca, Fe, Al, H and N concentrations, as well as in the CEC and the C:N ratio. Changes were particularly numerous between May and November, indicating an annual cycle in these constituents (from spring to autumn) rather than a biennial cycle. Cycling may be related to seasonal changes in H, which in turn are related to the hydrologic cycle that affects organic acid production.

It is well known that the solubility of Al and Fe is highly dependent on pH (Shotyk 1988), as is the CEC of organic colloids (Stevenson 1982). As pH declined from May to November, Al levels decreased as expected. However, Fe and CEC both increased, contrary to what was expected. This was an indication that other factors had an overriding influence.

Between May and November, H in the peat increased considerably. There was a similar increase in H in porewater and streamwater during the same period, as expected. The increase in H in streamwater was accompanied by a significant decline in gran alkalinity during the same period. The increase in H in streamwater between May and November corresponded with a significant increase in organic anions during this period. There was no significant change in the organic-anion content of the porewater during this period, as might be expected if the wetland pore/surface waters were major contributors to DOC in the streamwater. However, porewater data cannot be relied upon too heavily because of the lack of an ion balance in November. A significant fluctuation in SO_4 levels in the soil was anticipated. SO_4 storage in wetlands often fluctuates as a result of oxidation and flushing of sulfur associated with seasonal fluctuations in the water table. However, SO_4 did not show any significant seasonal trend in peat, although there was a significant increase in SO_4 in streamwater and porewater from May to November. If we ignore the porewater data because of its unreliability, the acidity balance of the peat appears to be controlled mainly by C:N ratios regulating the production of organic anions, rather than by SO_4, whereas the acidity of the streamwater is controlled by both anions. Howell (1988) and Kerekes et al. (1986) found that acidity in the streams of the Kejimkujik area was associated with both ions.

Over all, the data indicate that SO_4 cycling in Kejimkujik streams is not accompanied by significant SO_4 cycling in soil chemistry. It is possible that SO_4 cycling in the streams is still controlled by small, insignificant changes in SO_4 concentrations in the soil. Small changes in soil chemistry can produce very large changes in water chemistry because the concentrations of elements in soil are several orders of magnitude larger than those in the water. Further study of seasonal changes in SO_4 levels of the surface waters of wetlands in this area is required to establish if this is the case. However, it is possible that SO_4 levels in the streams are controlled more by inputs from surrounding upland areas than by inputs from wetland soils.

Large increases in organic-anion concentrations in streams in this area late in the summer have been reported by Howell (1988). Production of organic acids appears to be related to the C:N ratio in peat (Table 1). The C:N ratio declined significantly between May and November (Table 1), and this corresponds with increases in organic-anion concentrations in the streamwater (Table 2). The C:N ratio is also an indication of the oxidation rate of organic matter (Stevenson 1982). As decay and oxidation occur, the C:N ratio decreases since C is consumed by microbial activity, whereas N is more conservative. Microbial decay produces byproducts such as organic acids, carbon dioxide (CO_2) and methane (CH_4). H and the C:N ratio are inversely related in a positive-feedback process. As H increases, the level of microbial activity is depressed, the C:N ratio increases, and production of organic acids is enhanced. The C:N ratio and its effects on H are influenced by the hydrologic cycle. In late summer, reported increases in organic anions likely occur because of drawdown of the water table and increased oxidation of carbon.

Concentrations of H were much greater in peat than in water; this indicates a significant dilution factor in the latter, as organic acids are most heavily concentrated in the boundary layer next to the solid material in peat. Individual pH values for peat showed a considerable range, varying between 2.6 (Heber Meadows Brook) and 3.9 (Mersey River). For streamwater, pH ranged between 4.2 (Heber Meadows Brook) and 6.8 (Rogers Brook), and for porewater, between 4.1 (Heber Meadows Brook) and 5.5 (Little River).

There were considerably more significant changes in chemistry in streamwater than in peat. All of the cations and anions, with the exception of Na and K, increased between May and November. Similar increases in the other ions were reported by Howell (1988) for several of the streams and rivers in Kejimkujik National Park. By contrast, only H, Fe, Ca and N increased in peat during this period. In streamwater, Na and K both decreased during this period.

Seasonal changes in water chemistry (Tables 2 and 3) were very small in comparison with changes in peat chemistry, whereas metal concentrations were several orders of magnitude lower in water than in peat. This illustrates the very substantial storage capacity of peat. The largest differences were in Al and Fe concentrations; those in peat exceeded those in water by six and five orders of magnitude, respectively. Concentrations of Ca, Mg, K, Na and SO_4 were two to three orders of magnitude greater in peat than in water. Total cations and total anions were, respectively, five and three orders of magnitude greater in peat than in water. Al comprised over 80% of the total cations in peat, whereas in streamwater it was only a small fraction of the total cations. Al formed a somewhat larger fraction of the total cations in porewater than in streamwater (Table 3) because of suspended solid organic material in the porewater.

The very high ratio of cations to anions in peat (67:1 in November and 95:1 in September) reflects the negative charge of organic colloids. By contrast, a charge balance is maintained in streamwater, conserving the electroneutrality of the medium. The relative abundance of metallic cations in peat, determined from the seasonal means (not shown in Table 1), is Al > Fe > Na > K > Mg > Ca, with the values of 1408 > 191 > 53 > 40 > 38 > 13 epm, respectively. By contrast, the relative abundance in streamwater is Na > Mg > Ca > Al > K > Fe, with values of 0.139 > 0.39 > 0.031 > 0.025 > 0.021 > 0.007 epm, respectively. In peat, the abundance follows approximately a lyotropic series, reflecting the combined effects of the ionic radius and the charge density of the ion (Taliburdeen 1981). The exception is the reversal of divalent Ca and Mg with monovalent Na and K. This suggests an overabundance of Na and K in the nutrient supply that is probably due to the proximity of these sampling sites to the ocean.

CHEMICAL CHARACTERISTICS OF BOGS AND FENS

Several significant chemical differences were noted between wetlands classified as bogs (dominated by *Sphagnum* vegetation) and those classified as fens (predominantly with graminoid vegetation). The bogs included Heber Meadows Brook, Atkins Meadow Brook, and the lower site on West River (Fig. 1). *Cladina stellaris, Cladina mitis, Cladina rangiferina, Sphagnum fuscum, Sphagnum rubellum, Sphagnum angustifolium* and *Polytrichum commune* characterized the lichen and moss layer. *Chamaedaphne calyculata, Kalmia angustifolium, Ledum groenlandicum, Kalmia polifolia, Empetrum nigrum* and *Oxycoccos microcarpon* dominated the shrub and low-shrub layer. The fens were characterized by various shrub and graminoid species; a noticeable absence of *Sphagnum* vegetation indicated more nutrient-rich conditions. *Carex stricta, Calamagrostis canadensis, Carex rostrata* and *Carex bullata* characterized the graminoid layer, whereas *Spirea latifolia, Myrica gale* and *Alnus rugosa* were predominant in the shrub layer. *Osmunda regalis, and Solidago* spp., were common herbs.

Several significant distinctions ($p < 0.10$) between bogs and fens were apparent in the peat chemistry, in particular for values of H, Al, Fe, Na, K, C:N ratio, ash content and total cations (Table 4). Large differences occurred for Ca, C, and total anions as well, but the probabilities were higher (i.e., $p = 0.10$ to 0.20). Values higher than $p = 0.10$ are not indicated in Table 4. Significant distinctions were somewhat different in the porewater of bogs and that of fens (Table 6); they were found for Ca, Mg, and Cl (but not in the peat), and for H, Fe and Na, but not for Al and K. With the exception of Mg, the distinctions were not consistent on a seasonal basis (Table 6). There were almost no significant distinctions in the streamwater (Table 5). Of the streams and rivers tested, each drained a variety of bogs and fens as well as vegetated upland areas. Their chemistry reflected this combined influence; hence, no significant distinctions were expected.

Over all, annual H concentrations in bog peats were three times higher than those in fens, bogs having a mean annual value of 1.07 epm and fens a value of 0.31 epm. Concentrations of Al, Fe, Ca, Na and K in bogs were approximately half those in fens, reflecting the more eutrophic nature of these wetlands. Mg, Cl, SO_4 and total anions did not show the annual or consistent seasonal distinctions between bogs and fens that were apparent with the other ions.

Although CEC was insignificantly higher in bogs than in fens, the total cation levels were lower, reflecting the more oligotrophic nature of bogs. Significantly higher C:N ratios in bogs suggest that carbon oxidation by microbial activity is much lower in bogs. This is probably related to the higher H concentrations generally associated with *Sphagnum* species, which suppress microbial activity. The successive invasion of wetlands by *Sphagnum* vegetation is a positive-feedback mechanism that reduces gran alkalinity and encourages the development of oligotrophic conditions (Gorham et al. 1987). Increased acidity and reduced oxygen levels associated with the invasion of *Sphagnum* spp. further diminish the supply of base cations and enhance the competitiveness of these species over others (Goodwin and Zeikos 1987). This also reduces the decomposition rate which, in turn, leads to further accumulation of peat, a gradual reduction in nutrient supply and the establishment of oligotrophic and, eventually, ombrotrophic conditions.

Although not all of the driving forces behind the transition from fen to bog have been determined conclusively, the characteristics of sites in transition have been identified. Surveys of peatlands in Sweden and Minnesota indicate a bimodal pH distribution of wetlands, with fens at pH 6 and bogs at pH 4. There are comparatively few sites with intermediate values. A similar bimodal distribution occurs in base saturation, with most fen peats at values over 50% and bog peats at values less than 25%. Wetlands at intermediate values are regarded as transitional to bogs (Gorham et al. 1987). As wetlands change from minerotrophy to ombrotrophy, ash contents decline and base saturation drops to very low levels as the nutrient supply from ground and surface water is cut off. Fens with a pH of 5 or less, Ca concentrations in surface water less than 0.15 to 0.25 meq L^{-1}, and low base saturation (25% to 50%) are likely to be in transition to bogs (Gorham 1953, Gorham et al. 1987).

The chemical characteristics of the fens in this study indicate that they are well within the transitional category. The pH values and base cation levels are very low for fens with graminoid vegetation (mean annual pH = 4.58; Ca = 0.03 meq L^{-1}, Table 6). In general, their pH and nutrient status indicate that they would be more appropriately categorized as extremely poor fens (Sjörs, 1952). Wetlands in this category are considered most sensitive to anthropogenic input of acids (Gorham et al. 1987). These fens do not have sufficient base cation reserves to buffer significant acid loadings. Gorham et al. (ibid.) suggest that acid deposition accelerates the positive feedback process described above, enhancing the successive invasion of *Sphagnum* species. For example, *Sphagnum angustifolium*, an acidophilic species, is present in many of the fens. *Sphagnum magellanicum* and *Sphagnum fuscum*, which are both strongly acidophilic species, occur in isolated hummocks in some of the fens, although the density of occurrence is still quite low. Over all, the low base status of the fens and the presence of *Sphagnum* spp. suggest that conditions are favorable for rapid vegetational succession of the more acidophilic *Sphagnum* species.

SUMMARY

The results of this study provide an overview of wetland chemistry in Kejimkujik National Park. There are significant seasonal changes in many of the major ions in the peat. Seasonal changes in acidity appear to be associated mainly with C:N ratio rather than with SO_4. Even more significant seasonal changes occur in the major ion chemistry of streamwater. Seasonal changes in acidity of the water are associated with both SO_4 and organic anions.

There are significant chemical distinctions in the major ionic constituents in wetlands classified as bogs and those classified as fens. The fens, however, are generally very low in base cations and in pH, an indication that they are probably in transition to bogs. They therefore have little buffering capacity and are considered to be sensitive to acid deposition.

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Section VIII
Economics and Prescriptions

COST-EFFECTIVENESS OF FOREST DRAINAGE AND FERTILIZATION IN NORTHERN ONTARIO PEATLANDS

B. Payandeh
Forestry Canada
Ontario Region
Sault Ste. Marie, Ontario
Canada

ABSTRACT

The economic feasibility of draining and fertilizing a black spruce (*Picea mariana*) stand and 24 possible methods of planting a clearcut area near Cochrane, Ontario were evaluated with a forestry investment decision model, "FIDMEPC".

On the basis of the cost estimates used and assumptions made, drainage of the existing stand was the most cost-effective treatment if it reduced the rotation age by more than 30 years. Drainage plus fertilization was the second best alternative if it reduced the rotation age by more than 40 years. Fertilization of the undrained site ranked a distant third, if it reduced the rotation age by more than 20 years; otherwise, it was uneconomical.

Of the 24 alternatives considered, planting bare-root stock on a mechanically prepared but undrained site without and with weed control ranked first and second, respectively. Planting containerized seedlings on a mechanically prepared but undrained site with weed control ranked third, followed by planting bare-root stock on a mechanically prepared and drained site with weed control. Planting containerized seedlings on an unprepared site with no weed control ranked 24th and was the least cost-effective method considered.

RÉSUMÉ

La faisabilité économique du drainage et de la fertilisation d'un peuplement d'épinettes noires (*Picea mariana*) et de 24 méthodes de reboisement possibles d'une zone de coupe rase près de Cochrane en Ontario a été évaluée à l'aide d'un modèle de décision d'investissement en foresterie, "FIDMEPC".

D'après les estimations des coûts et des hypothèses utilisées, le drainage du peuplement existant constituait le traitement le plus rentable s'il permettait de réduire l'âge d'exploitabilité de plus de 30 ans. Le drainage et la fertilisation constituaient la deuxième meilleure solution s'ils réduissaient l'âge d'exploitabilité de plus de 20 ans; sinon il n'est pas économique.

Des 24 solutions envisagées, le reboisement avec du matériel à racines nues sur un site préparé mécaniquement mais non drainé, avec ou sans contrôle des mauvaises herbes, se classait respectivement au premier et au deuxième rang. La plantation de semis en conteneurs sur un site préparé mécaniquement mais non drainé, avec contrôle des mauvaises herbes, arrivait au troisième rang, suivi de la plantation d'un stock à racines nues sur un site préparé mécaniquement et drainé, avec contrôle des mauvaises herbes. La plantation de semis en conteneurs sur un site non préparé, et sans contrôle des mauvaises herbes, arrivait au 24e rang et était la méthode envisagée la moins rentable.

INTRODUCTION

Black spruce (*Picea mariana*) is the most important pulpwood species in Ontario. It occupies an estimated 17.4 million ha, or about 41% of the province's productive forest land and 20% of the total land area (Ketcheson and Jeglum 1972). Because of its desirable pulping qualities, black spruce makes up about 60% of the roundwood used by the pulp and paper industry in Ontario (Hearnden 1975).

Nearly 50% of the black spruce in northern Ontario occurs on peatland sites (Ketcheson and Jeglum 1972). Because of excess water, poor aeration, inadequate nutrient availability, and adverse climatic conditions, its productivity on such sites is usually very low (McEwen 1966, Payandeh 1973a). However, productivity can be improved by drainage, fertilization and/or thinning (Stanek 1968, 1977; McEwen 1969; Payandeh 1973a, 1973b and 1982).

Large areas of peatland sites supporting Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) have been drained and/or fertilized successfully in Finland, the USSR and several other European countries (Heikurainen 1982a, 1982b; Payandeh 1982). Several small-scale forest drainage experiments have been carried out in North America (Stanek 1968, 1970; McEwen 1969; Richardson et al. 1976; Smith 1978[1]; Alban and Watt 1981; Richardson 1981; Jeglum et al. 1982; Payandeh 1982). With few exceptions, these researchers provide only a physical description of their experiments and limited casual observations on growth improvement resulting from drainage and/or fertilization.

A detailed growth analysis of a 40-year drainage experiment in northern Ontario was provided earlier (Payandeh 1973a). It was concluded that both individual tree growth and stand growth responded well to drainage, with younger and more vigorous trees on better sites showing the greatest response. An economic analysis of this experiment (Payandeh 1973b) indicated that the annual rate of return increased by 2.0 to 3.4% as a result of drainage, depending on site quality.

A growth and yield study of peatland black spruce in northern Ontario was begun in 1969 at the Forest Research Laboratory in Sault Ste. Marie (now Forestry Canada, Ontario Region). The objectives of this study were (1) to provide a basis for sound management of this forest by developing and refining methods of predicting volume and value growth, as influenced by drainage and fertilization, and (2) to evaluate the economic feasibility of such intensified forest management practices under Canadian conditions.

A 5-year growth response of peatland black spruce to fertilization and drainage was reported earlier (Payandeh 1982). Despite high variability and constraints imposed on the experimental areas, the overall results indicated that both minor thinning and the application of phosphorus fertilizer alone depressed growth. The best growth response observed was from the application of NPK (U TSP KC 112 kg/ha), which yielded about 7 m^3/ha of extra wood in comparison with the control over the 5-year period. Most other treatment combinations applied produced positive but nonsignificant growth responses.

Recently, an operational forest drainage project was established by the Ontario Ministry of Natural Resources (OMNR) in cooperation with Forestry Canada, Ontario Region in the Wally Creek area 26 km east of Cochrane, Ontario (Rosen 1985). The purpose of this project was to determine the economic feasibility of forest drainage and to demonstrate its establishment on an operational level. Rosen (ibid.) provides a brief description of the project, its physical layout, ditch spacing, etc. The drainage system was established mainly in two adjacent areas: (1) a 55-year-old peatland black spruce stand, and (2) a clearcut area. The main objective of the project was to examine the effects of drainage and fertilization on the growth of the existing stands and on the regeneration, survival and growth of plantations.

"FIDMEPC", a computer model developed recently (Payandeh and Basham 1989), is suitable for comparing long-term forestry investment alternatives. Any set of forestry investments, including silvicultural treatments such as drainage and fertilization, may be compared as long as the differences between such operations can be expressed in terms of differences in costs, probability of success, stocking level, rotation age, expected yield and quality, future prices, etc. Up to four investment alternatives may be compared in a single run by one of the following four economic criteria: 1) cost-effectiveness[2], 2) cost:benefit ratio, 3) present net worth, and 4) internal rate of return.

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[1] Smith, W. 1978. Nutrient analyses for a black spruce lowland drained by blasting or digging. Lakehead Univ. Sch. For., B.Sc. thesis.

[2] The cost-effectiveness criterion used in this study is based on future cost/unit of output. It does not require future price estimation and does not account for the difference in quality of the product. It is more applicable to a situation in which the objective is to minimize cost of production rather than to maximize profit. An alternative with the lowest future cost/unit of output would be the most economical one.

The purpose of this paper is to evaluate the economic feasibility of drainage and fertilization of peatland black spruce by means of the above-mentioned computer model. The analysis will be carried out for both the existing stands and the clearcut area within the Wally Creek project.

INPUT DATA AND ASSUMPTIONS

Most of the input estimates were provided by several OMNR foresters[3]. Some of the input estimates used here were derived from the literature (e.g., Mullin and Howard 1973; Olson et al. 1979; Chaudhry 1981; Bradley and Lothner 1982). Although attempts were made to use current cost estimates and actual data where possible, it should be noted that, as long as the input estimates are unbiased, the relative comparison of the alternatives should be valid.

The effect of treatments on the existing stand may be expressed in terms of either increase in yield or reduction in rotation age or both. Here, it is assumed that the treatments will result in a reduction of the rotation age, i.e., the same volume of wood may be harvested in a shorter rotation if the site is drained and/or fertilized. As indicated in Figure 1, the analysis is carried out for three possible rotation ages under such treatments, plus the control, for a total of 10 possibilities. For example, the three rotation ages assumed for the drained stand are 80, 90 and 100 years, i.e., it is assumed that drainage might reduce the rotation age by 40, 30 or 20 years, respectively.

The input estimate for the existing stand is summarized in Table 1. The first input estimate used is the annual cost (land rent or land tax and fire protection) of \$2.00/ha, which is assumed to be the same with or without treatment. The cost of treatments applied, i.e., drainage, fertilization, and drainage plus fertilization, is based on the actual cost incurred, but has been expressed in each case as a subjective probability estimate to represent the variability encountered in application as a result of site conditions. The subjective estimates for the cost of draining the site (including \$6-\$40/ha for planning and topographic survey, \$56-\$70/ha for line clearing, \$150-\$160/ha for digging ditches, and \$8-\$10/ha for sedimentation pond construction) are: (a) low estimate = \$250.00, (b) high estimate = \$280.00, (c) the probability that the cost of drainage/ha would be less than the low estimate = 0.10, (d) the probability that the cost of drainage/ha would be less than the high estimate = 0.90, and (e) the absolute minimum cost of drainage/ha = \$240.00.

[3] Calvert, R. 1984. Ont. Min. Nat. Resour., Reg. Office, Timmins, Ont. (pers. comm.).

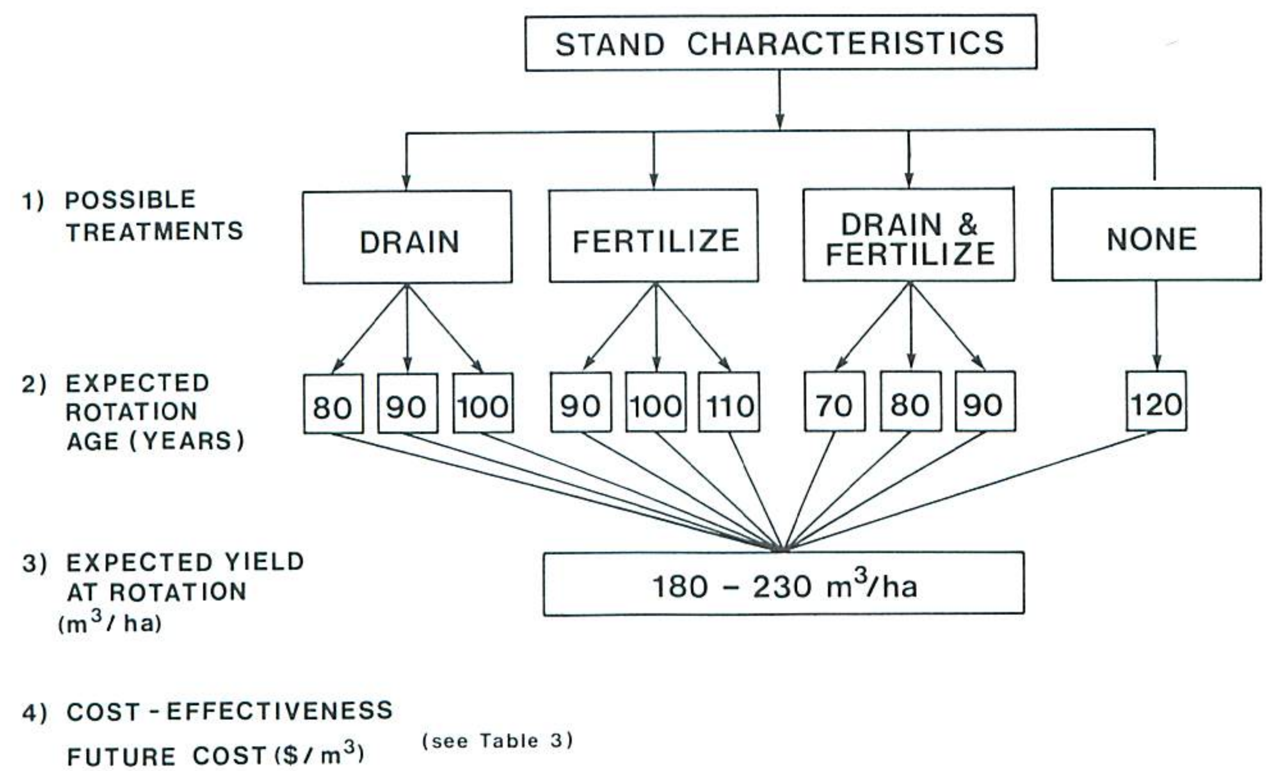

Figure 1. Schematic of 10 alternatives for stand improvement in a 55-year-old peatland black spruce stand at the Wally Creek drainage project near Cochrane, Ontario.

Table 1. Input estimates used by the model "FIDMEPC" to compare the cost-effectiveness of forest drainage and/or fertilization in a 55-year-old peatland black spruce stand in the Wally Creek drainage area, Cochrane, Ontario. An interest rate of 8% and an inflation rate of 3% were used

Input estimate	Treatment	Point estimate ($/ha)	Subjective estimates: Low ($/ha)	High ($/ha)	Prob. low	Prob. high	Minimum ($/ha)
Annual	(1)[a]	2.00	—	—	—	—	—
	(2)	2.00	—	—	—	—	—
	(3)	2.00	—	—	—	—	—
	(4)	2.00	—	—	—	—	—
Periodic[b] cost	(1)	—	250	280	0.10	0.90	240
	(2)	—	600	750	0.10	0.90	550
	(3)	—	850	1030	0.10	0.90	790
	(4)	—	—	—	—	—	—
Yield (m^3/ha)	(1)	—	180	230	0.10	0.95	150
	(2)	—	180	230	0.10	0.95	150
	(3)	—	180	230	0.10	0.95	150
	(4)	—	180	230	0.10	0.95	150
Rotation age (years)	(1)	80, 90, 100					
	(2)	90, 100, 110					
	(3)	70, 80, 90					
	(4)	120					

[a] Treatments 1, 2, 3 and 4 represent drainage, fertilization, drainage plus fertilization, and control, respectively.
[b] Treatment costs are applied as a single periodic cost occurring at 55 years of age.

Similarly, the three subjective estimates of the cost/ha of fertilization (150 kg/ha N, 100 kg/ha P and 100 kg/ha K broadcast manually), together with the high and low probabilities, are: $600.00, $750.00, $550.00, 0.10 and 0.90. The estimated cost/ha of drainage plus fertilization is simply the sum of the estimated cost/ha of drainage plus that of fertilization: (a) low estimate = $850.00, (b) high estimate = $1030.00, (c) the probability that the cost of drainage and fertilization would be less than the low estimate = 0.10, (d) the probability that it would be less than the high estimate = 0.90, and (e) the absolute minimum cost of drainage plus fertilization = $790.00/ha.

As shown in Table 1, it was assumed that the yield at rotation age would be the same for all treatments, i.e., (a) low estimate = 180 m^3/ha, (b) high estimate = 230 m^3/ha, (c) the probability that the yield would be less than the low estimate = 0.10, (d) the probability that the yield would be less than the high estimate = 0.95, and (e) the minimum yield = 150 m^3/ha, but the rotation age would be reduced by 20 to 40 years for drainage, 10 to 30 years for fertilization and 30 to 50 years for drainage plus fertilization, respectively.

For the clear-cut area, the main objective was to minimize the cost of stand establishment. Analyses were carried out for a number of possible alternatives in the form of a "decision-tree" similar to that used in the recent Finnish study by Päivänen and Lappi (1983). As shown in Figure 2, the alternatives considered included three possible methods of site preparation, two possible treatments (drainage or no drainage), two possible planting stocks, and weed control. The site preparation methods considered were: mechanical (light, in conjunction with bare-root planting, and heavy, in conjunction with planting of containerized seedlings), fire (prescribed burning), and no site preparation (in conjunction with full-tree harvesting). Table 2 summarizes the subjective probability estimates used for the 24 possible combinations of alternatives shown in Figure 2. It was assumed that weed control would be applied twice, at 2 and 4 years after planting; i.e., weed control was used as a periodic cost in the analysis starting at year 2 and ending at year 4 after planting, with a 2-year interval. The cost of drainage for the clear-cut area is about $60/ha less than that for the existing stand because the former does not require line clearing.

Figure 2 indicates clearly how differences among various treatments are reflected in differences in cost, as differences among the expected results are reflected in terms of probability of success, the number of years required for trees to reach a height of 1 m or the so-called "free-to-grow" status (see Chaudhry [1981], p. 18-19 for

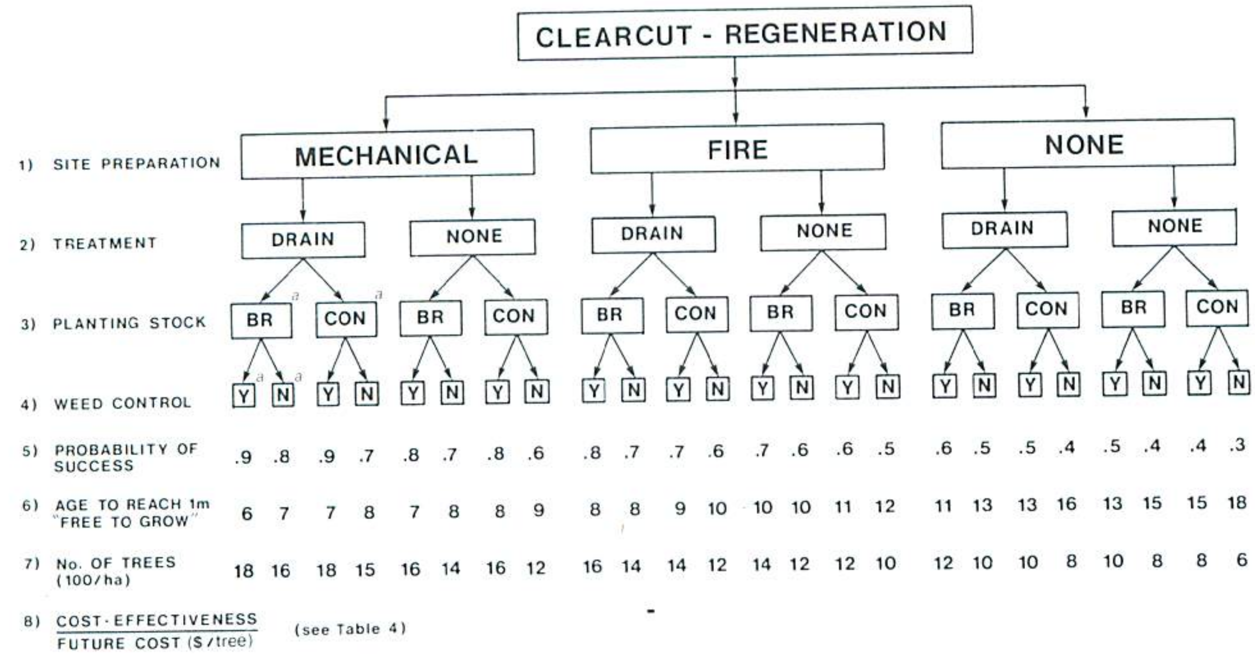

Figure 2. Schematic of decision tree for regeneration options on a clear-cut site at the Wally Creek drainage project near Cochrane, Ontario, where: BR = bare-root, CON = containerized seedlings, Y = weed control, N = no weed control.

definition) and the resulting density of a plantation that has attained "free-to-grow" status. For example, comparison of the first and second alternatives in Figure 2 indicates that the effects of weed control are expressed in terms of higher probability of success (0.9 and 0.8), higher growth rate (i.e., 6 years to attain "free-to-grow" status vs 7 years), and higher density (1800 trees vs 1600 trees). Similarly, comparison of the first and third alternatives suggests no difference in the probability of success or the density of bare-root and containerized stock on mechanically prepared and drained sites with weed control, but it assumes a somewhat higher growth rate for the bare-root stock than for the containerized stock (6 years vs 7 years to reach a height of 1 m).

Cost-effectiveness was chosen as the most appropriate economic criterion for this study for two main reasons: (1) the investment has been made by OMNR on Crown land and, therefore, the objective should be to minimize production cost rather than maximize profit; (2) it is very difficult, if not impossible, to assign a market value to very young plantations.

RESULTS AND DISCUSSION

Although it is not possible to test the validity of assumptions made for various alternatives (e.g., reduction of rotation age by 10 to 50 years was assumed for various combinations of treatments), nevertheless, the model may be used to answer as many "what if?" questions as desired. However, as long as the underlying assumptions for various alternatives are on a relative and unbiased basis, the relative economic comparison of such alternatives should be valid.

The results of the analyses for the existing black spruce stand are summarized in Table 3. The first column of this table ("probability of exceeding") refers to the remaining columns. The second line of Table 3 indicates, for example, that there is a 10% chance that the future cost/m^3 of black spruce pulpwood harvested from this stand will exceed \$68.05 if permitted to grow naturally with no treatment and at a rotation age of 120 years. It also indicates that, if the site is drained, there is a 10% chance that the future cost/m^3 of pulpwood will exceed \$14.99, \$24.12 and \$38.47 for rotation ages of 80, 90 and 100 years, respectively; if the site is fertilized, the future cost/m^3 will exceed \$35.59, \$58.46 and \$93.37 for rotation ages of 90, 100 and 110 years, respectively. Similarly, it shows that there is a 10% chance that the future cost/m^3 will exceed \$16.72, \$27.00 and \$43.68 if the site is drained and fertilized for rotation ages of 70, 80 and 90 years, respectively. The second line also suggests that there is a 10% chance that the future cost/m^3 of pulpwood from this stand will be between \$68.05 and \$76.78 if the site is untreated (for a rotation age of 120 years), between \$24.12 and \$26.97 if the site is drained, between \$35.59 and \$42.65 if the site is fertilized, and between \$43.68 and \$49.86 if the site is drained and fertilized (e.g., for a rotation age of 90 years).

Table 2. Summarized input estimates of model "FIDMEPC" for comparing the cost-effectiveness of several possible regeneration systems, including the use of drainage as a means of site preparation for a clear-cut area in the Wally Creek drainage area near Cochrane, Ontario.

<table>
<tr><th rowspan="3">Input estimate</th><th rowspan="3">Type</th><th rowspan="3">Point estimate ($/ha)</th><th colspan="5">Subjective estimates</th></tr>
<tr><th rowspan="2">Low</th><th rowspan="2">High</th><th>Prob.</th><th>Prob.</th><th rowspan="2">Minimum</th></tr>
<tr><th>low</th><th>high</th></tr>
<tr><td>Site</td><td>mech.1[a]</td><td>–</td><td>110</td><td>140</td><td>0.10</td><td>0.90</td><td>100</td></tr>
<tr><td>preparation</td><td>mech.2[b]</td><td>–</td><td>250</td><td>320</td><td>0.10</td><td>0.90</td><td>230</td></tr>
<tr><td></td><td>fire</td><td>–</td><td>140</td><td>180</td><td>0.10</td><td>0.90</td><td>120</td></tr>
<tr><td>Treatment[c]</td><td>drainage</td><td>–</td><td>190</td><td>220</td><td>0.10</td><td>0.90</td><td>175</td></tr>
<tr><td>Establishment</td><td>bare-root[a]</td><td>–</td><td>250</td><td>350</td><td>0.05</td><td>0.95</td><td>225</td></tr>
<tr><td></td><td>containerized[b]</td><td>–</td><td>140</td><td>230</td><td>0.10</td><td>0.95</td><td>130</td></tr>
<tr><td>Weed control</td><td></td><td>–</td><td>35</td><td>60</td><td>0.10</td><td>0.90</td><td>20</td></tr>
<tr><td>Expected[d]</td><td>1[e]</td><td>0.9</td><td>0.85</td><td>0.95</td><td>0.10</td><td>0.90</td><td>0.80</td></tr>
<tr><td>stocking</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td></tr>
<tr><td></td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td></tr>
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<tr><td></td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td></tr>
<tr><td></td><td>24</td><td>0.3</td><td>0.05</td><td>0.55</td><td>0.10</td><td>0.90</td><td>0.00</td></tr>
<tr><td>No. of</td><td>1[e]</td><td>1800</td><td>1500</td><td>2200</td><td>0.10</td><td>0.90</td><td>1400</td></tr>
<tr><td>trees/ha</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td></tr>
<tr><td></td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td></tr>
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<tr><td></td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td><td>|</td></tr>
<tr><td></td><td>24</td><td>600</td><td>350</td><td>900</td><td>0.10</td><td>0.90</td><td>300</td></tr>
</table>

[a] Light mechanical site preparation and its related cost estimates are used in conjunction with bare-root planting.

[b] Heavy mechanical site preparation and its associated cost estimates are used in conjunction with container planting.

c cost of drainage without line clearing

[d] Point estimates for the probability of success and number of trees/ha are approximated by subjective probability estimates.

[e] Input estimates for the first and 24th are given as examples.

Similarly, the third line of Table 3 indicates that there is a 20% chance that the future cost of pulpwood/m^3 will exceed $65.40 if the site is untreated, $14.15, $23.01 and $36.67 (for rotation ages of 80, 90 and 100 years, respectively), if the site is drained, $34.23, $55.98 and $89.52 (for rotation ages of 90, 100 and 110 years, respectively) if the site is fertilized, and $16.03, $25.81 and $41.87 (for rotation ages of 70, 80 and 90 years, respectively), if the site is drained and fertilized. Conversely, the third line of Table 3 indicates that there is an 80% chance that the future cost/m^3 of pulpwood will be from $48.00 to $65.40 if the site is left untreated, from $10.57 to $14.15 if the site is drained, from $24.47 to $34.23 if the site is fertilized, and from $11.56 to $16.03 if the site is drained and fertilized (for the rotation ages of 80, 90 and 70 years, respectively).

According to the results summarized in Table 3 and on the basis of the assumptions made and input estimates used for the existing black spruce stand, drainage of the site is clearly the most cost-effective alternative if it reduces the rotation age to 80 years. The second alternative is fertilization plus drainage if it reduces the rotation age to 70 years. The third alternative is drainage of the site if it reduces the rotation age to 90 years, and so on. Table 3 also indicates that, unless fertilization reduces the rotation age by more than 10 years, it is not a feasible treatment. Fertilization treatment ranks fifth if it can reduce the rotation age to 90 years. The expected future cost/m^3 of pulpwood from the untreated stand is two to five times as much as that of pulpwood from the drained stand mainly because of the shorter rotation assumed for the latter (80-100 years vs 120 years).

Table 3. Output of the model "FIDMEPC" for comparing the cost-effectiveness of drainage, fertilization and drainage plus fertilization of a peatland black spruce stand near Cochrane, Ontario. An interest rate of 8% and an inflation rate of 3% were used.

Probability of exceeding	Future cost ($/m^3)									
	Drainage			Fertilization			Fertilization and drainage			None
	Assumed rotation age (years)									
	80	90	100	90	100	110	70	80	90	120
0.00	17.29	26.97	41.99	42.65	66.71	109.04	20.68	31.56	49.86	76.78
0.10	14.99	24.12	38.47	35.59	58.46	93.37	16.72	27.00	43.68	68.05
0.20	14.15	23.01	36.67	34.23	55.98	89.52	16.03	25.81	41.87	65.40
0.30	13.63	22.53	35.68	33.08	53.54	85.68	15.53	25.00	40.40	63.38
0.40	13.33	21.86	34.57	32.20	52.03	83.44	15.07	24.41	39.40	62.01
0.50	13.04	21.41	33.78	31.48	50.67	81.54	14.70	23.68	38.22	60.22
0.60	12.71	20.94	33.06	30.60	49.18	79.32	14.29	22.97	37.35	58.78
0.70	12.41	20.43	32.65	29.74	47.58	76.81	14.02	22.36	36.52	57.41
0.80	12.12	19.84	31.27	28.93	46.16	75.02	13.56	21.69	35.32	55.84
0.90	11.68	18.91	30.04	27.42	43.88	72.88	13.00	20.43	33.27	54.23
1.00	10.57	16.68	26.34	24.47	38.49	64.02	11.56	18.78	29.22	48.00

Results of the analysis for the clearcut area are summarized in Table 4. For the sake of simplicity and brevity the 24 possible combinations of alternatives are coded by four subscripts i, j, k, and m, where: i = 1 = mechanical, i = 2 = fire, i = 3 = none; and j = 1 = drained, j = 2 = undrained; and k = 1 = bare-root stock, k = 2 = containerized stock; and m = 1 = weed control, m = 2 = no weed control. For example, alternative 2112 is a site that has been prepared by prescribed burning, drained, planted with bare-root stock and had no weed control. Similarly, alternative 1122 is a mechanically prepared and drained site planted with containerized stock, with no weed control, etc.

The second line of Table 4 indicates, for example, that there is a 10% chance that the future cost of each "free-to-grow" tree will exceed $0.58, 0.60, 0.63, 0.79, 0.50, ..., and $3.62 for alternatives 1111, 1112, 1122, 1211, ..., and 3222, respectively. It also means that there is a 10% chance that the future cost of each "free-to-grow" tree will be from $0.58 to $0.65 for alternative 1111; from $0.60 to $0.67 for alternative 1112; from $0.63 to $0.77 for alternative 1121; and from $3.62 to $7.60 for alternative 3222, respectively. Similarly, the third line of Table 4 indicates that there is a 20% chance that the future cost of each "free-to-grow" tree will exceed $0.55, $0.57, $0.61, $0.72, ..., and $3.01 for alternatives 1111, 1112, 1121, 1122, ..., and 3222, respectively. Conversely, the third line of this table indicates that there is an 80% chance that the future cost of each "free-to-grow" tree will be between $0.40 and $0.55 for alternative 1111; between $0.39 and $0.57 for alternative 1112; and between $0.37 and $3.01 for alternative 3222, respectively.

If one may assume that the effects of treatments are additive, closer examination of the results will reveal additional information. For example, comparison of the results for alternatives 1111 and 1112 on the second line suggests that there is a 10% chance that the application of weed control on a drained site may result in a saving of $0.02/tree, i.e., the cost would be $0.58/tree with weed control and $0.60/tree without it. Similarly, a comparison of alternatives 1111 and 1121 suggests that there is a 10% chance that, on a drained site, planting of bare-root stock will be cheaper than planting of containerized stock by $0.05/tree, i.e., $0.58 vs $0.63. Comparison of the results for alternatives 1111 and 1211 (Table 4, line 3) indicates that there is a 20% chance that planting of bare-root stock on a mechanically prepared and drained site with weed control application will be more expensive than planting of similar stock on a mechanically prepared but undrained site (by $0.07/ tree, i.e., $0.55 as opposed to $0.48). Comparison of the results for alternatives 2112 and 3112 (columns 11 and 19 of Table 4) indicates that there is a 20% chance that planting of bare-root stock on a site that has been prepared by prescribed burning, drained, and had no weed control will be $0.66/tree cheaper than planting of similar stock on a drained site without site preparation ($0.75 as opposed to $1.41). It also indicates an 80% chance that planting of bare-root stock on a site that has been prepared by prescribed burning, drained, and had no weed control will be $0.27 – $0.80/tree cheaper than planting of similar stock on an unprepared but drained site (i.e., $0.75 – $0.48 = $0.27, $1.41 – $0.61 = $0.80). It should be obvious that numerous such comparisons may be made from the results presented in Table 4.

Table 4. Output of model "FIDME" for comparing the cost-effectiveness of various treatment combinations for the regeneration of a clearcut area in the Wally Creek drainage project near Cochrane, Ontario. An interest rate of 8% and an inflation rate of 3% were used.

Future cost per "free-to-grow"[a] tree — Alternative combinations (ijkm)[b]

Probability of exceeding	1111	1112	1121	1122	1211	1212	1221	1222	2111	2112	2121	2122
0.00	0.65	0.67	0.77	1.03	0.57	0.55	0.75	1.01	0.88	1.16	1.20	1.30
0.1	0.58	0.60	0.63	0.79	0.50	0.48	0.54	0.74	0.76	0.82	0.80	0.97
0.2	0.55	0.57	0.61	0.72	0.48	0.46	0.52	0.67	0.73	0.75	0.74	0.88
0.3	0.53	0.55	0.59	0.69	0.46	0.43	0.50	0.62	0.70	0.71	0.72	0.83
0.4	0.52	0.53	0.57	0.66	0.44	0.42	0.49	0.60	0.68	0.69	0.69	0.78
0.5	0.51	0.52	0.55	0.63	0.42	0.40	0.47	0.58	0.66	0.66	0.67	0.75
0.6	0.50	0.51	0.54	0.60	0.41	0.39	0.46	0.56	0.65	0.65	0.66	0.72
0.7	0.49	0.50	0.53	0.58	0.40	0.38	0.45	0.54	0.63	0.63	0.63	0.69
0.8	0.47	0.48	0.51	0.55	0.39	0.37	0.43	0.52	0.61	0.60	0.61	0.66
0.9	0.45	0.46	0.49	0.51	0.37	0.36	0.41	0.48	0.58	0.57	0.57	0.62
1.0	0.40	0.39	0.46	0.39	0.32	0.31	0.35	0.41	0.50	0.48	0.48	0.51

Probability of exceeding	2211	2212	2221	2222	3111	3112	3121	3122	3211	3212	3221	3222
0.00	0.83	1.45	0.88	1.73	2.22	2.55	1.97	3.23	2.70	4.46	3.27	7.60
0.1	0.70	0.76	0.68	.95	1.46	1.74	1.46	2.26	1.66	2.91	2.08	3.62
0.2	0.66	0.67	0.64	0.84	1.24	1.41	1.25	1.88	1.33	2.44	1.83	3.01
0.3	0.64	0.63	0.61	0.75	1.02	1.24	1.13	1.66	1.15	2.18	1.59	2.59
0.4	0.61	0.61	0.59	0.67	0.96	1.07	1.05	1.51	0.92	1.82	1.43	2.21
0.5	0.60	0.58	0.56	0.61	0.91	0.97	0.94	1.36	0.85	1.47	1.24	1.92
0.6	0.58	0.56	0.54	0.58	0.85	0.91	0.88	1.19	0.76	1.24	1.04	1.58
0.7	0.57	0.54	0.52	0.54	0.81	0.86	0.82	1.07	0.69	1.00	0.86	1.24
0.8	0.55	0.51	0.50	0.51	0.76	0.82	0.77	0.98	0.64	0.79	0.72	0.95
0.9	0.52	0.48	0.47	0.47	0.72	0.76	0.72	0.88	0.59	0.68	0.58	0.62
1.0	0.44	0.40	0.40	0.38	0.59	0.61	0.54	0.59	0.46	0.42	0.42	0.37

[a] When trees reach a height of 1 m and are relatively free of competition from adjacent vegetation (see Chaudhry (1981) for definition).

[b] For the sake of brevity, various alternatives are shown by the letters i, j, k and m, where: i = 1, 2 and 3, indicating one of the three possible methods of site preparation; j = 1 if the site is drained and j = 2 if the site is not drained; and k = 1 for bare-root stock and k = 2 for containerized seedlings; and m = 1 for weed control and m = 2 if no weed control was applied.

The most important use of the results given in Table 4 is in ranking the relative economic desirability of the 24 alternative ways of regenerating the clear-cut area in question. On the basis of cost estimates and other inputs and assumptions, Table 4 indicates that alternative 1212, i.e., planting of bare-root stock on a mechanically prepared but undrained site with no weed control, will be the most cost-effective alternative, and will be followed, in order of cost-effectiveness, by alternatives 1211, 1221, 1111, 1121, 1112, 1222, 2212, 2121, 1122, 2112, 2112, 2122, 2111, 2211, 2222, 3111, 3211, 3121, 3112, 3221, 3122, 3212 and 3222.

In summary, the results of this analysis suggest that drainage will be the most cost-effective treatment for the existing black spruce stand in question, followed by drainage and fertilization. Of the 24 alternative methods considered for regenerating the clear-cut area, planting of bare-root stock on a mechanically prepared but undrained site without weed control ranked first, with planting of bare-root stock on a mechanically prepared site with weed control ranking second in terms of cost-effectiveness. Planting of containerized seedlings on a mechanically prepared and undrained site with weed control ranked third, followed by planting of bare-root stock on a mechanically prepared and drained site with weed control.

The results of this study further demonstrate the flexibility and utility of the model "FIDMEPC" (Payandeh and Basham 1989) for evaluating numerous and seemingly complicated investment alternatives. If properly used, the model should be a valuable aid to forest managers in making rational economic decisions about various silvicultural investments, including stand amelioration treatments and treatments related to forest regeneration.

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PRESCRIPTIONS AND PROGRAMS FOR FOREST DRAINAGE IN QUEBEC

F. Trottier
Ministère de l'Énergie et des Ressources
Service des traitements sylvicoles
Québec, Québec
Canada

ABSTRACT

The history of forest drainage in Quebec is brief. Although a large proportion of the province's forests are on wet soils, interest in forest drainage is fairly recent. Over the past 3 years, 5000 ha per year have been drained, mainly in clearcut areas on private woodlots. The establishment of a drainage system can help to maintain site productivity when the water table is rising: planted seedlings have a better survival rate and initial growth. The ground has an increased carrying capacity as well.

The methods applied in forest drainage are derived from Finnish standards and from drainage practice in agriculture. The cost of a drainage operation is about $300-$400/ha, including planning and digging.

A landowner can obtain financial and technical help from the government. On crown land, logging companies may pay their stumpage dues in drainage work if it is necessary to maintain the productivity of a given area.

RÉSUMÉ

Le Québec ne possède qu'une courte histoire en matière de drainage forestier. Bien que les sols forestiers humides y couvrent de grandes superficies, ce n'est que tout récemment que ce type de traitement sylvicole a pris une envergure significative. Le majorité des 5000 hectares réalisés annuellement depuis trois ans le sont sur des superficies coupées à blanc en forêt privée. Les travaux aident à maintenir la productivité du site, à améliorer le taux de suivie des plants reboisés et à augmenter la capacité portante du sol.

Les méthodes en usage se sont inspirées des techniques finlandaises ainsi que des pratiques du secteur agricole. Les coûts d'opération sont de l'ordre de 300 à 400$ l'hectare.

Des programmes d'aide ont été mis sur pied en forêt privée pour aider à la réalisation de ces travaux. Sur forêt publique, selon les contrats d'approvisionnement et d'aménagement forestier qu'elles négocient avec le gouvernement, les compagnies forestières peuvent réaliser des travaux de drainage en paiement des droits d'exploitation. En outre, le drainage est utilisé pour la mise en production des arrérages (backlog).

INTRODUCTION

Wetlands cover an important part of Quebec's forest lands. In the Abitibi and Lac Saint-Jean regions and in the St. Lawrence plain, wet soils cover from 25% to over 50% of the forested area (Rivest[1], Zoltai and Pollett 1983). These lands have always been considered an obstacle to forest operations, mainly because they restrict access to these territories. Furthermore, these lands are generally classified as "unproductive". However, certain wetlands have a high production potential and, in many regions, contribute significantly to wood supplies (Bolghari 1986). It has recently been found that some drainage techniques help develop this potential for production. In Quebec, the first forest drainage tests were conducted some 30 years ago on peatlands. Dynamite was used at that time[2,3,4]. Later, some phytosociologists who had recorded a high content of nutrients in many peatlands suggested that the lands be developed through drainage (Grandtner 1960, Lafond and Ladouceur 1969, Simard 1974). Stanek (1970a,b, 1975) appraised the effects of drainage and fertilization on the growth of young black spruce (*Picea mariana*). Once the water tables had been sufficiently lowered, significant growth increases were obtained within 5 years.

Agricultural drainage programs also provided many examples of forest drainage since some of the waterways that drain fields also pass through tree stands and peatlands. Trottier (1986) noted the growth of a stand along one of these waterways dug in 1953. The high volumes obtained near the watercourse dropped rapidly as one moved away from it. Observations of tree growth response along ditches on small private properties have also been recorded[5].

In effect, although studies of growth gains after drainage are few in Quebec as in the rest of Canada (Hillman 1987), they nevertheless show that appreciable increases can be obtained by carrying out such work. The creation of assistance programs for the development of private woodlots, and the new Forest Act which fosters silvicultural treatments in public forests, have contributed greatly to this expansion.

In the following pages, I shall describe the forest drainage projects executed under these programs. I shall also explain the objectives of drainage and the standards applied during the projects.

OBJECTIVES

In the past few years, Quebec's forest policies have emphasized forest regeneration. Foresters have therefore undertaken drainage and land preparation work in wet and poorly regenerated cutover areas. Drainage helps maintain if not increase the productivity of sites on which the water table can rise considerably after logging operations. Furthermore, drainage improves the soil's properties for planting and makes the site more accessible by increasing its carrying capacity. The results of this work are quickly noticeable. Improving the survival rate of the plants by 15%, even without considering eventual growth gains, is enough to justify the costs.

Drainage work has also been undertaken on stands in the intermediate stage of growth to increase the growth rate. This practice, which is quite common in Finland, remains marginal in Quebec, although economic studies seem to indicate that significant yields can be realized from it (Nadeau and Parent 1982).

In the past few years, the areas drained have increased considerably. Over the past three years, more than 3,500 ha of private woodlots have been drained annually. In public forests, the Ministère de l'Énergie et des Ressources has experimented each year on areas totalling 500-1000 ha (Fig. 1).

Most of the work is done on private woodlots, often by a single owner. As is shown in Figure 2, the areas concerned are relatively small.

METHODS

Preliminary Stages

Before undertaking a project, it is important to assess the seriousness, scope and cause of the soil moisture problem. The drainage classes used are those of the Canada Soil Information System (Day and McMenamin 1982) to characterize soil moisture. Soils in which drainage is poor and very poor (classes 6 and 7) are mostly organic and mineral types that are gleyed in the upper 50 cm. These soils can benefit greatly from drainage. It is also worth executing such work on imperfectly drained soils (class 5) where a plantation is planned.

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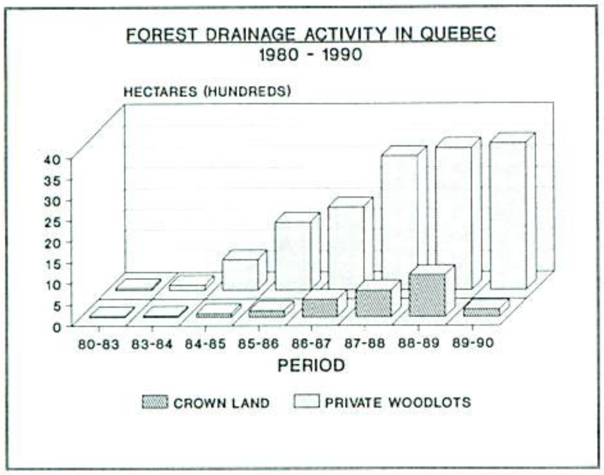

Figure 1. Forest drainage in Quebec, 1980-1990.

Before proposing solutions, the planner must discover the cause of the drainage problem by examining the land carefully. The water that floods a parcel of land can come from rain and upslope runoff. The relative contributions from these sources depend on the physiography of the peatland and location of the area intended for drainage (Feodoroff and Guyon 1972).

It is often necessary to cut off outside contributions of water by digging a 'protection' ditch around the area to be drained. Once the source of the water is definitely known, a large area can be drained by digging only one ditch.

Within the area to be drained, there is a variety of possible ditching patterns, and these depend largely on the depth of the permeable soil or presence of pans:

1. Deep permeable soil: Where the entire area is underlain by deep permeable soil, a network of parallel ditches is required.
2. Permeable soil of variable depth: In this case, the land is dotted with small wet areas. Digging a number of ditches in the depressions and linking them to a main ditch will suffice to drain a large area.
3. Thin permeable soil: Where the permeable soil is thin (50 cm or less), it is impossible to evacuate surplus waters effectively by draining. The soil surface must then be bedded to facilitate surface runoff. This method is difficult to apply in forests because of tree stumps. On the other hand, it is quite appropriate for abandoned farmlands, which are numerous in the clay zone of the Abitibi region. Another solution consists in plowing 30-cm furrows 10 m apart. Tests are under way in Abitibi to assess the effectiveness of this method.
4. Impermeable layers: If a hardened layer situated near the surface forms a perched water table, infiltration of surplus waters by deep plowing or subtilling might be preferable.

   The use of machinery for logging operations may cause soil compaction and the formation of small wet depressions. A network of shallow ditches can be used to evacuate the accumulated surplus waters.

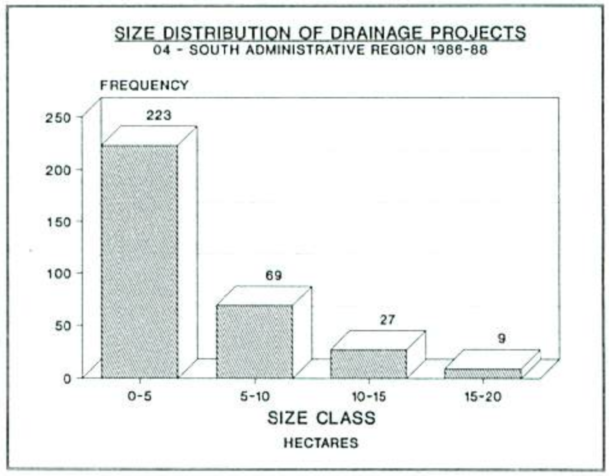

Figure 2. Distribution, according to size, of forest drainage projects carried out on private woodlots in the 04-South Administrative Region, 1986-1988.

Planners must appraise the relevance of the drainage project by studying the reaction capacity of the stand, which depends mostly on its development stage (Heikurainen and Kuusela 1962) and on the vigor of the trees. When a stand outgrows the pole stage (i.e., when trees are over 20 cm in diameter), it is time to harvest and regenerate it. Finally, planners must analyze the fertility level of the peatland. Schneider (1985) summarized the main phytosociological studies on Quebec's peatlands and classified black spruce and larch (*Larix* spp.) stands in seven groups according to their fertility level and their capacity to react to drainage.

Designing the Drainage Network

Drainage networks have two basic functions: lowering the water table and evacuating the water outside the site. Forest engineers must bear in mind these two functions when preparing a drainage plan.

In Quebec, most drainage projects cover only small areas, where ditches are dug to drain a few humid depressions. It is therefore rarely necessary to set up a complete system of parallel ditches. In practice, where three or four parallel ditches must be dug, their distance apart varies from 30 m to 60 m, depending on the physical properties of the soil, the width of the boundaries, the thickness of the permeable layer and the vegetation. The scope of drainage projects normally does not justify undertaking exhaustive preliminary studies.

Where the area to be drained is wider, and a larger network of parallel ditches must be installed, the optimal distance between the ditches must be determined. In such cases, the Guyon model can be used (Lagace[6], Guyon 1972). This method is currently used in Quebec agriculture, and was verified by Belleau[7] for wooded peatlands.

where E = spacing (m);

$$E^2 = \frac{8.9\ K_2\ d't_1}{u \cdot ln\left[\left(\frac{2d' + h_1\,^{K1/K2}}{2d' + h_0\,^{K1/K2}}\right)\frac{h0}{h1}\right]}$$

K_1 = hydraulic conductivity (m/day) in the ditch zone. This value is obtained in the field by applying the auger hole method (Van Beers 1970);

K_2 = hydraulic conductivity (m/day) below the ditch zone;

t_1 = unitary downdraw period: 1 day;

h_0 = height of water table above the water level in the ditch at TTY = 0 (m). The water table is fixed at 20 cm from the surface of the soil as an initial condition.

h_1 = height of the water table above the water level in the ditch at t = t1 (m). h1 = h0-0.05, for a drawdown rate of 5 cm per day. This is the drawdown rate that is suggested for forest drainage (Dutil et al. 1989).

d' = Hooghoudt's equivalent depth;

μ = drainage porosity. This value represents the equivalent portion of soil drained of its water after drawdown of the water table. As an example, we suggest the following values (Anon. 1978):

Range of drainage porosity values

Hydraulic conductivity (K)	Drainage porosity (m)	
(m/day)	Clay and Silt	Sand
0.1 < K < 0.5	0.02 – 0.03	0.03 – 0.05
0.5 < K < 1.0	0.03 – 0.05	0.05 – 0.08
1.0 < K < 5.0	0.04 – 0.06	0.08 – 0.10
K < 5.0	0.05 – 0.07	0.10 – 0.12

The ditches are generally 70 cm deep in mineral soils and 90 cm in organic soils. Their form varies according to soil cohesion.

Although drainage intensity is very important, the network's transportation function must be planned much more carefully. A poorly designed drainage network can have very serious consequences for the environment. Moreover, the useful life of a poorly developed ditch is rather short. Therefore, when developing a drainage system, one should respect the following drainage principles (Lagace 1979):

1. The main collection ditch proper must be adequate to evacuate the flood flow without causing any damage;
2. The ditches must be developed in such a way that they are not subject to abnormal erosion;
3. The slopes must be as stable as possible.

Before the required dimensions are calculated, the volume of water the ditch will have to evacuate must be assessed. This calculation can be performed in a number of ways. The method proposed by the Soil Conservation Service, modified by Hoang and Desforges (see Anon. 1986), yields good results in agricultural environments and in small, private woodlots.

$$Q = \frac{AxCxH}{57(5.28xS)^{-0.43pf/0.27}}$$

where Q = peak discharge
A = watershed area
C = runoff coefficient
H = total precipitation
S = average slope of the watercourse
pf = percentage of forest cover

[6] Lagace, R. 1987. La théorie de l'ingénieur français Guyon. Course notes, Rur. Eng., Univ. Laval. 13 p.

[7] Belleau, P. 1988. Drainage d'une pessière noire sphaigne et nemopanthe mucronne. Univ. Laval, M.Sc. thesis. 82 p.

In forest environments, recurrence is generally from 2 to 5 years for ditches and 20 for culverts. The concentration period for watersheds of less than 12 km^2 is 6 hours (McNeely 1982 *in* Anon. 1986).

The size required is assessed by means of an algorithm to determine the proper dimensions. Verification is performed by successive iterations. The velocity of the water flow must not be greater than that proposed by Fortier and Scobey (1926 *in* Anon. 1986).

Developing the Network

Network construction begins with determining the location of the ditches and clearing a 5-m right-of-way. When a laser guidance system is used, a network of altimetric landmarks must also be installed. This network is to control the quality of the excavation. The ditches are generally dug with medium-capacity hydraulic excavators (less than 25 tonnes) equipped with wide tracks to keep the pressure on the soil to a minimum (less than 40 kPa). Track-equipped backhoes are lighter and particularly suitable in organic soils. Nevertheless, there are only a few of these machines in Canada.

The excavator used to dig the ditches is equipped with parabolic or trapezoidal buckets. The excavator moves in the direction of the ditch line, with the soil being deposited on either side of the ditch. This equipment can remove from 75 to 150 m^3 of soil per hour, depending on its power and the type of soil. The cost of the secondary ditches ranges from $0.75 to $1 per linear metre.

When a drainage system is dug, all the required measurements must be taken to reduce to a minimum the impact of the project on the environment. For example, sedimentation basins must be included to recover the suspended solids resulting from the work and to protect the receiving watercourses against sedimentation (Anon. 1986). The ideal excavation period is during the driest summer months.

On the basis of the projects implemented over the past three years in public forests, drainage costs can be estimated as follows:

	Wooded environment	Cleared environment
Preliminary work and supervision	$25/ha	$25/ha
Prior work	100	75
Clearing corridors	50	–
Excavation	205	205
Maintenance	50	50
Total	$430	$355

In Quebec, drainage projects fall under certain laws and regulations. Therefore, authorization from the following bodies must be obtained before work can begin:

1. Regional county municipalities: Regulations concerning the protection of river banks or certain wetlands must be respected.
2. Ministère de l'Environnement: A permit is required before drainage work is begun. For some large-scale projects, an impact study must also be conducted.
3. Municipality: Municipal bylaws apply where projects involve many owners.

DRAINAGE PROGRAMS

Strictly speaking, the forest sector does not have an official drainage policy. Nevertheless, various levels of government have created assistance programs to carry out certain silvicultural treatments, including drainage, on private woodlots. The Ministère de l'Énergie et des Ressources grants eligible owners $0.50 per linear metre for drainage ditch excavation. It allocates more than $0.30/m to owners for technical assistance from a specialist of their choice. However, most of the work done on private woodlots is by private woodlot owners' associations, which must provide technical aid. As a rule, these sums do not cover all technical expenses, but many owners consider them quite helpful. Under its Eastern Quebec Development Plan, the federal government grants $1/m for the excavation of secondary ditches. The program's technical staff is responsible for planning projects and digging collecting ditches that are used by many owners.

In compliance with timber supply and forest management agreements that they signed with the Ministère de l'Énergie et des Ressources, companies can carry out drainage projects in public forests to pay their stumpage dues whenever they need to do so to meet their production objectives. The amount granted for drainage covers all the technical and development costs. For denuded sites the rate is $1.20/m; for wooded sites it is $1.50/m. Moreover, any increase in the productivity of an area under a timber supply and forest management agreement means an increase in annual allowable cut. The additional volumes thus obtained are allocated free of charge to forest operators who have carried out silvicultural treatments.

CONCLUSIONS

When carried out effectively, drainage projects achieve many objectives without endangering other forest values. The implementation of various drainage programs will help foresters to become familiar with this technique. It will also help to ensure better management of treed wetlands.

Forest drainage is a good example of the on-site use of peat and peatlands. Before large-scale drainage programs are undertaken, it is important to have precise information on the yield of wooded peatlands and to adapt working methods to Quebec's peatlands.

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PROSPECTS FOR DRAINAGE AND OTHER PEATLAND PRESCRIPTIONS IN NORTHERN ONTARIO

D.L. Rogers
Department of Forest Resource Management
University of California
Berkeley, California
USA

ABSTRACT

Drainage and fertilization are currently not practised as silvicultural activities in the forested peatlands of northern Ontario. There are many factors, including administrative, sociological and economic ones, that will influence whether, and at what rate, these activities will be incorporated into silvicultural practice. This may be an opportune time to make changes, because there is a perception of future local shortages in wood supply, and interest is focusing on acceleration of growth. As well, there are several comprehensive field studies of growth response to fertilization and drainage in the Northern Region, providing local information on both implementation and effects. The main efforts required at this point to encourage change towards more intensive peatland forestry practices such as fertilization and drainage are: 1) acceptance of these practices according to environmental-impact guidelines; and 2) preparation of specific prescriptions, including cost: benefit information. The increasing involvement in and commitment to forest management by private forestry industry should add support and impetus to the inplementation of new silvicultural practices such as drainage.

RÉSUMÉ

Le drainage et la fertilisation ne sont pas des méthodes sylvicoles couramment employées dans les tourbières boisées du nord de l'Ontario. Le recours à ces pratiques et leur rythme de mise en application dépendent notamment des facteurs administratifs, sociologiques et économiques. Toutefois, puisque des pénuries de matière ligneuse à l'échelle locale sont à prévoir pour bientôt, on porte maintenant une attention particulière à la nécessité d'accélérer la croissance et il pourrait donc convenir d'entreprendre des activités de drainage et de fertilisation. Plusieurs études générales au champ sur la croissance procurée par la fertilisation et le drainage dans le nord de l'Ontario ont permis d'obtenir des données locales sur la mise en oeuvre et les effets de ces méthodes. Afin d'encourager le recours à des méthodes d'aménagement forestier des tourbières plus intensives, comme la fertilisation et le drainage, il faut respecter les directives concernant les incidences sur l'environnement lors de la mise en oeuvre de cette méthode et élaborer des prescriptions particulières qui comportent des renseignements sur les coûts et avantages. L'engagement grandissant de l'industrie forestière à l'égard de l'aménagement forestier devrait venir appuyer et favoriser l'inclusion de nouvelles pratiques sylvicoles (comme le drainage) aux plans d'aménagement forestier.

INTRODUCTION

To attempt to change forestry practices in Ontario is to accept a challenge. Change is a process that involves much more than the availability of biological information about the effects of forestry prescriptions on target tree species. The fiscal situation and economic implications of the change, their impact on the private sector, the structural flexibility of the primary managers (government), the environmental impact and the socio-political climate are all significant factors in determining the feasibility of any proposed change. These considerations may be summarized by the observation that there are three criteria for change in forestry practices: motivation, information and feasibility. This paper addresses the prospects for changing silvicultural practices in northern Ontario's peatlands, in particular for promoting the use of peatland drainage and fertilization. This is accomplished by establishing the context in northern Ontario, examining current peatland forestry practices, discussing the factors that determine the change towards more specific and intensive peatland management, and concluding with a speculative summary of the prospects for change.

NORTHERN ONTARIO CONTEXT

The context for this discussion is the administrative unit known as the Northern Region of the Ontario Ministry of Natural Resources (OMNR). Black spruce (*Picea mariana*) is the main commercial species, as indicated by both the Forest Resource Inventory and the harvest data. The Region encompasses the Northern Clay Section of the Boreal Forest of Ontario (Rowe 1972) (Fig. 1). It has been estimated that approximately 50% of this land area is covered by peatland and dominated by pure black spruce stands (Ketcheson and Jeglum 1972).

The scale and the disposition of the Northern Region coincide well with a discussion of peatland forestry. It is a large region, encompassing one-third of the province's Crown forest land (8.4 million ha). Of this, 80% is managed by forest industries under Forest Management Agreements (FMAs), and the remainder is managed directly by OMNR. Forestry is a very significant part of the Northern Region's economy, as it provides more than 8000 local jobs and forms the economic base of 10 communities. The forests support five pulp mills, seven panelboard plants and 16 large sawmills in the Region, in addition to numerous smaller operations. Approximately 7 million m^3 of wood are harvested annually, representing approximately one-third of the province's total harvest.

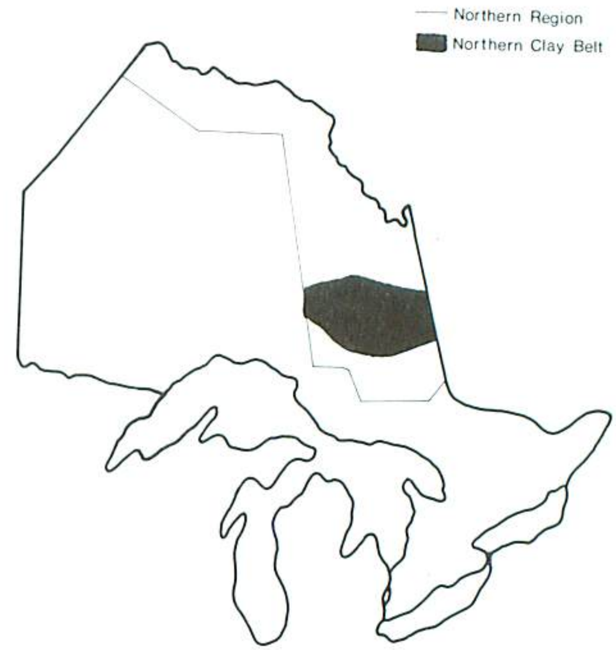

Figure 1. Location of the Northern Region of the Ontario Ministry of Natural Resources (solid line). Shaded area shows the Clay Belt section of the Region.

Silviculture in the Northern Region is dominated by four activities: harvesting, site preparation, planting and tending (Table 1). In 1986/1987, approximately 70,000 ha were harvested and more than 50% of this area was regenerated artificially. Planting outweighed all other regeneration methods by a ratio of 3:1. Tending, predominantly in the form of chemical control of broadleaved competition, was also carried out on a large scale, over approximately 36,000 ha of previously established forests. Site preparation was conducted on approximately two-thirds of the harvested land.

Table 1. Silvicultural profile (1986/1987) of the Northern Region of Ontario

Activity			Area (thousand ha)
Harvesting			69.8
Site preparation			43.0
Regeneration	- Low cost	11.5	
	- Planting	29.2	
	Total		40.7
Potential regeneration area			60.7
Regeneration ratio[a]			0.67
Tending			35.7

[a] regenerated area/potential regeneration area

Note: The potential regeneration area is not the same as the total area harvested, as some areas are considered to be untreatable. This could be a result of several factors, including remote location or small, scattered distribution of sites, low site quality or potential environmental damage as a result of regeneration activities.

CURRENT PEATLAND FORESTRY

Peatland prescriptions in the Northern Region fall into two main areas: systems for classifying peatland and methods of harvesting. For the former, three classification systems have been recognized. The first is a typing system devised by a major forest company in the Region (Spruce Falls Power and Paper Company Ltd.) that was originally developed as an aid for planning harvesting requirements. This typing system, based on forest cover and slope, recognizes five site types on the company's FMA limits. Of these, approximately three site types would qualify as peatland, being dominated by peatlands with > 40 cm of organic matter (Ketcheson and Jeglum 1972). The second classification system, proposed in 1974, divides black spruce-dominated swamps into four categories based on associated vegetation (Jeglum et al. 1974). The third typing system, the one most commonly in use, is based on vegetation associations and their relationships with soil types in the greater Claybelt Region. Developed in 1983, the Forest Ecosystem Classification recognizes 23 vegetation types and 14 soil types, which, when combined, offer 14 'operational groups' (Jones et al. 1983). These classification systems are used in varying degrees by government and industry staff in determining harvest and regeneration options and prescriptions.

The two main driving forces behind peatland harvesting prescriptions have been minimization of environmental damage (mainly to soils) and acceleration and cost minimization of regeneration. Minimization of site damage has been addressed through the use of specialized equipment, timing of operations and harvesting designs that change the pattern of contact with the site. Specialized regeneration methods have concentrated on leaving natural seed sources, protecting young advance growth and preparing the sites for artificial regeneration. Jeglum et al. (1983) present a comprehensive summary of these current practices.

Most of the current peatland silviculture philosophy concerns the connections between harvesting and regeneration at both the planning and operational levels. When the private sector is managing the forest there is the additional requirement of an acceptable payment schedule for this kind of regeneration, which begins at the time of harvesting. Two forest companies, Spruce Falls Power and Paper Co. Ltd. and the Quebec/Ontario Paper Co., have successfully negotiated and carried out a combined harvest/regeneration prescription on their forest limits.

The Spruce Falls Power and Paper Co. Ltd. has an FMA area in which approximately 71% of the productive forest area consists of black spruce forests on peatlands or peatland-dominated terrain. During government-industry negotiations for the timber management plan for the 1985-1990 period, two new silvicultural options were incorporated into the ground rules. These two options, known as 'Harvesting and Regeneration Options' (HARO), were directed mainly at peatland areas. For these prescriptions, it was understood that the company would harvest the peatland sites during the frost-free part of the year, utilizing a full-tree, high-flotation logging system. Regeneration techniques that could then be employed include careful logging to preserve advance growth, use of equipment with low bearing pressure and altered forwarding techniques, direct seeding, and light-to-heavy site preparation, followed by planting of bare-root or containerized stock, or any combination of the above. The two HARO prescriptions, HARO I and HARO II, are differentiated by the site type for which they are suitable, wetland and more productive upland sites, respectively.

The rationale for site selection for these systems and the total area to be allowed under HARO I and HARO II are planned and agreed upon by OMNR and the company. However, the entire regeneration prescription may not be fully decided upon until the time of harvest. The main administrative differences in this approach are: 1) OMNR pays a flat rate to the company for regenerating certain identified sites, rather than paying for each activity separately; 2) the company assumes the risk of successfully establishing the forest; and 3) both parties have considerably more flexibility. The potential and assumed advantages of these prescriptions are: an overall cost reduction for regeneration, reduced environmental damage, better survival of planted and seeded stock, and increased company involvement, awareness and commitment to the silvicultural process (Arnup 1987).

The Quebec/Ontario Paper Company, operating on its FMA area (the Driftwood Forest), initiated a small harvest/regeneration trial on approximately 125 ha during the 1988/1989 winter harvest. The same 'CLASP' (Careful Logging and Site Preparation), process is followed; the technique involves the use of harvest corridors and protection of unmerchantable, advanced growth. Although the trial is not yet concluded, it is obvious that the use of careful logging to protect advanced growth minimizes the area needing site preparation and planting, thus reducing silvicultural costs or allowing the treatment of more area with the same budget.

These combined harvest/regeneration prescriptions appear to be very successful in minimizing site damage, enhancing regeneration, reducing rotation age and minimizing regeneration costs, and are likely to continue to be incorporated into peatland forestry practices. However, beyond aerial tending, there are currently no other accepted peatland prescriptions, such as drainage or fertilization, aimed at enhancing growth and shortening rotation length for the commercial tree species.

FACTORS IN THE CHANGE TOWARDS SPECIFIC AND INTENSIVE PRESCRIPTIONS

Motivation

In view of the importance of forestry to the economic base in the Northern Region, a perceived wood shortage would likely provide a strong incentive for developing silvicultural prescriptions that enhance growth. Indeed, there is some evidence of a wood-supply shortage in the not-too-distant future. The current age-class distribution for black spruce is skewed towards the older age classes, with more than half of the black spruce working-group area being covered by stands more than 100 years old (Fig. 2). With current harvesting and regeneration levels, a wood supply shortage (currently being quantified by OMNR staff) is predicted in the next 10 to 30 years (Table 2). This shortage will be manifested most obviously as local supply problems in terms of volume and/or product-size availability, rather than a general regional shortage. Accelerated growth of stands in the 40- to 80-year age group, in particular, would ameliorate or even resolve this predicted shortage. It is noteworthy that the perception of the wood supply situation is very much dependent on how often the Forest Resource Inventory is updated and on the accuracy of our growth-prediction models. As both become more detailed and sophisticated, our perception of the wood supply, particularly of shortages, will be more keen, providing more motivation for change.

Another component of motivation is how closely the proposed change corresponds with the dominant societal values in the affected region. As previously discussed, forestry and related activities are critical to the economy of the Northern Region. Therefore, one can assume that a majority of the public would support measures to ensure an adequate and constant wood supply to the various industrial users. Harvesting and all other silvicultural activities are planned in accordance with the **Timber Management Planning Manual** and associated guidelines (e.g., for moose, fisheries, heron habitat, etc.) for the province of Ontario. These guidelines describe a process by which other values (e.g., tourism, wildlife, heritage) are identified and reconciliations with forestry

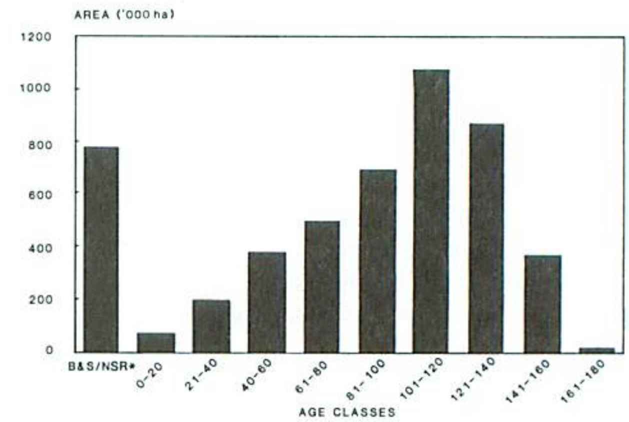

Figure 2. Age-class distribution of black spruce in the Northern Region (from Hauer 1989).

**B&S/NSR=barren and scattered/not sufficiently regenerated*

use are negotiated. In spite of this opportunity for public involvement in forest-land management, the public information sessions are very sparsely attended, and most conflicts are negotiated on a case-by-case basis. This reinforces the image of a "pro-wood" local population in the Northern Region (Anon. 1988).

Table 2. Regional supply/demand projections (Anon. 1989)

Projected supply (million m^3)			
	1987[a]	2000[b]	2020[c]
Conifers	6.5	5.4	7.3
Hardwoods	1.0	2.5	1.9
Total	7.5	7.9	9.2
Projected demand (million m^3)			
	1987[a]	2000[d]	2020[c]
Conifers	6.5	7.4	7.3/ 9.0
Hardwoods	1.0	1.5	1.9/ 1.9
Total	7.5	8.9	9.2/10.9

[a] projected harvest
[b] Strategic Land Use Plan (Anon. 1982)
[c] Forest Production Policy (Anon. 1973)
[d] assumes 1% annual 'creep' (projected increase in demand)

A final key element in motivation is an acceptable level of risk associated with the proposed change. Risk is related to the extent to which the new practice has been demonstrated and on what scale. It very much reflects the availability of information about the new practice, the predicted margin between cost and benefit, and the perceived reaction by OMNR, forest industry and the public.

Information

Considerable information has been accumulated locally on the construction of drainage ditches, the efficacy of drainage and fertilization treatments, and their environmental impact. A large-scale (500 ha) drainage trial in northeastern Ontario, initiated as a cooperative venture in 1984 by Forestry Canada and OMNR, is currently and potentially the basis for much of this information. (See also other papers in this Proceedings, including those by Rothwell, Warner, Berry and Jeglum.) The project was based on a Finnish model and directed by a Finnish consultant, and the establishment phase was completed successfully. The process was carefully documented by OMNR staff and the publication **Guidelines for Establishing a Drainage System in Forested Peatlands** has been prepared (Rosen 1989). The costs of establishing such a system, including all aspects of planning, line clearing and digging, were approximately $265/ha (Rosen 1987). Hence, the implementation and cost information is not only available, but current and locally established.

The second, and perhaps most significant, body of information required is about the efficacy of the treatment. In Ontario, the first peatland drainage project was carried out in 1929 by Abitibi-Price Inc. in the Clay Belt; 26 ha of forested peatland were drained by 2.6 km of hand-dug ditches (Payandeh 1973). In this study it was concluded that both individual-tree and stand growth responded well to drainage, with younger and more vigorous trees on better sites showing the greatest response. Other drainage experiments established in 1961 (Stanek 1968) and 1969 (Payandeh 1982) showed similar, though less consistent, results. Perhaps the most comprehensive source of information will be forthcoming from the cooperative Forestry Canada/OMNR study in the Wally Creek Drainage Area. Here, studies have been established to determine the effect of ditch spacing, fertilization x drainage interactions, the response of seedlings of various species to drainage, and the effects of drainage on immature stands and advance growth. Most of these studies have yet to be assessed and analyzed. Initial indications from the seedling drainage/fertilization study indicate a somewhat complicated picture, in which the benefits of fertilization and drainage are very much a function of individual treatment levels, treatment interactions and interactions with the type and degree of site preparation (Abraham 1989). In summary, it would appear that there is considerable information available, or potentially available, to provide a quantitative indication of the positive value of fertilization and drainage. However, much of this information has yet to be gleaned from assessment data and prescriptions formulated from all studies combined.

Beyond the operational aspects of drainage and its efficacy, there is a need for information on environmental impact. In accordance with the Environmental Assessment Act, an environmental assessment is required before any activity including all forestry practices, that could damage the environment, is undertaken. Current silvicultural practices are being implemented under a temporary waiver while the hearing on the Class Environmental Assessment for Timber Management is taking place. The application for a class environmental assessment does not include provisions for fertilization or drainage, as they are neither historically nor currently a part of forest management in northern Ontario. Hence, even if present forestry prescriptions are allowed to continue under the class environmental assessment, any new prescription, such as drainage or fertilization, would necessarily be required to undergo a rigorous environmental review. Although a respectable body of this information is already available (see other papers in this Proceedings), it is uncertain if it is sufficient and if drainage, with or without fertilization, would be environmentally acceptable under existing legislation.

Feasibility

Even if there is sufficient motivation and information to launch a new practice, there may still be limiting factors in terms of feasibility. These factors concern generally administrative, operational and economic conditions and, as such, may change over time. Hence, although technological and biological factors may remain relatively constant, a new practice may well be more feasible, for example, in 1995 than in 1990.

One aspect of feasibility in the Northern Region is the scale at which the new practice can be applied, both collectively and at the level of individual operations. For example, Quebec/Ontario Paper Co. staff would not consider their CLASP procedure in anything smaller than 20-ha blocks. Scale is a function of both economics and administrative capacity.

Obviously, any new practice must be economically feasible. In view of the fact that there is Crown land ownership and private industry management, economic feasibility does not necessarily mean a direct cost:benefit comparison. In the context of regeneration payments under FMAs, feasibility would depend on the relative cost of other silvicultural practices considered to be alternatives.

A third, significant component of feasibility is the flexibility of the organizations and industries involved. Again, because of the government/industry involvement in forest management, there must be a mutually acceptable arrangement for financing the practice and for auditing both the efficacy of the results and compliance with agreements. Ground rules and guidelines are now being developed for a new general relationship between OMNR and the companies with existing FMAs. These will likely give more responsibility and flexibility to the companies, thereby facilitating the adoption of new silvicultural practices.

SUMMARY AND PROSPECTS

As we have seen, the prospects for peatland drainage and other specific prescriptions in peatland forestry are influenced by much more than biological and economic considerations. Factors of particular importance in the northern context that currently favor such a trend are: the perception of a future wood shortage; the availability of technology to support decisions; the availability of operational-scale demonstrations with documentation of operational implementation and the cost of peatland drainage; and the development of more open relations between government and the private sector in silvicultural management, so as to give the industry more flexibility and permit it to take the initiative more frequently.

At this point, the major constraints to more intensive peatland prescriptions would appear to be the uncertainty of both the environmental impact and the public acceptance of any real or perceived impact; as well, the lack of information about the benefits of such prescriptions is a problem. The environmental assessment requirements should not be automatically assumed to be limiting, as the environmental-impact data collected so far are very promising. More could be done towards building a supportive case. The most helpful action that could be taken by OMNR at this time would be a thorough analysis, interpretation and summary of all local studies of growth response to drainage. The best approach to providing this information is now being discussed by OMNR and Forestry Canada, Ontario Region. This information, once collected, may encourage private-sector initiative and may have a strong influence on the implementation of operational drainage activities. In conclusion, although current peatland prescriptions are generally directed at harvesting/regeneration activities, an analysis of present trends and conditions suggests a good possibility for the use of more growth-enhancing prescriptions, such as drainage, in the future.

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Section IX
Concluding Comments and Recommendations

CONCLUDING COMMENTS

Peatland forestry is the practice of growing trees on organic soils. It can be done on the whole range of peat soils, and encompasses the entire sphere of forest management activities — road building, harvesting, site preparation, regeneration, stand tending, site-improvement, etc. The primary site improvement activities on peatland are drainage and fertilization.

Canada is the second largest country in the world, and much of it is covered by boreal forest or northern temperate forest. In these regions, vast areas of forested and wooded peatlands, and forested sites with wet or water-logged mineral soils, are found. Much of this is productive or potentially productive forest land. Because of problems associated with excess water in the substrate, tree growth can be less than optimum, and harvesting without disturbance of the peat soils presents special problems.

Forestry operations on peatlands are significant in certain parts of the country, most notably in the provinces of Ontario and Québec. The potential for peatland forestry is also significant in several other provinces. Black spruce (*Picea mariana*) dominates in a large high percentage of forested peatlands, and a substantial portion of the total volume of black spruce harvested comes from peatland and wet mineral soils. Since black spruce is the most desirable tree species for the pulp and paper industry, it is important for the economy of northern Canada that peatland forests be managed for continued and, if possible, increased wood-fiber production.

In Canadian peatland forestry, extensive forestry practices are generally employed. The emphasis is on harvesting and wood extraction, and there is a heavy dependence on natural regeneration. Some management practices have been developed to minimize damages to soil, and to promote natural regeneration. In contrast with Canada, countries such as Finland, Sweden, and the USSR, which also have considerable areas of forest on peatlands, have developed intensive forest management techniques for these sites. For example, in Finland approximately 58% of the peatlands have been drained for forestry purposes, with the result that there has been a net increase of about 25% in the growing stock available for harvesting. To achieve this significant effect on the economy of Finland, growth rates of stands have been materially enhanced and, as a consequence, the rotations have been markedly shortened. Furthermore, large areas of marginally productive peatlands have been brought into production.

Numerous Canadian foresters have visited countries such as Finland, Sweden and the USSR, where peatland forestry plays an important role in the economy. They have returned with ideas, information, and technology to be incorporated into forest management schemes in Canada. It would appear that the provinces of Quebec, Ontario, and Alberta have the greatest potential for intensifying forest management activities on peatland sites and improving growth of forests on them. Only in Québec, where about 20,000 ha have been drained to date, has there been a significant effort to drain peatlands for forestry.

Only a few years ago, there was concern about the extent of the 'mucking-up' of wet sites and the destruction of advance growth by logging with narrow-tired skidders in the snow-free season. This type of damage has been reduced considerably in recent years by harvesting the wetter sites in the winter when the snow and frozen ground protects the organic soil, and by the use of wide tires and tracks on logging equipment. In recent years, we have witnessed the development of new systems of harvesting in which careful logging practices are implimented to conserve advance growth. It is anticipated that, in the near future, even better types of harvesting equipment and systems of harvesting will be developed, and intensive management techniques such as peatland drainage, forest fertilization and thinning will become more common.

In many parts of Canada, there is insufficient funding available for regeneration, and it is unrealistic to produce enough planting stock to artificially regenerate every hectare harvested. It is commonly thought that the best lands and those closest to the mills should receive the highest investment of planting and other intensive treatments. Conversely, the poorer lands and those furthest from the mills may be best managed by using low-cost methods of regeneration, such as natural regeneration from seed and careful logging to conserve advance growth.

Since the productivity of peatlands is generally considered to be potentially lower than that of other types of lands, it may be questioned whether intensive forest management on peatland sites is warranted. However, in some forest holdings, a high proportion of the productive forest land is in wet or peat-covered areas, and because these constitute most of the forest land being managed, they should be maintained in a productive state. Also, although some of the peatland sites may not be prime land, they have certain other advantages for forest management; for example, black spruce regenerates readily by natural means, competition problems may be insignificant, and tending may not be necessary.

It is not realistic to classify all wetland and peatland forests in the lowest category of productivity, because some of these forests are in fact rich or moderately rich in terms of nutrients and have the potential to become highly productive if the water table is lowered. Some of the sites are close to the mill, and for these, the cost of transporting wood to the mill would be relatively low; hence the cost of site amelioration treatments could be justified. There is concern in the industry that wood-supply shortages may occur in some regions in the next 20 to 30 years, i.e., when the old-growth forests have been exhausted but second forests are not yet ready for harvest. With drainage of mid-rotation peatland stands, we may be able to increase their growth and reduce the time required until they are ready for harvest, thus helping to fill the wood-supply shortfall.

Since the cost of artificial regeneration by planting is high, planting may be directed to the richest sites that have been drained. Poorer sites may warrant extensive regeneration, which is less expensive. For black spruce we should consider direct seeding, natural seeding associated with modified methods of harvesting, and careful logging to conserve advance growth. Black spruce is admirably suited to natural regeneration — regeneration by seed from its semi-serotinous cones, and vegetative reproduction by layering of its branches. In addition to black spruce, there are several other tree species which can be grown on wetland sites. Tamarack (*Larix laricina* [du Roi] K. Koch) and jack pine (*Pinus banksiana* Lamb.) have performed exceptionally well, and other species such as lodgepole pine (*P. contorta*) and Scots pine (*P. sylvestris* L.) on the poorer sites, and white spruce (*Picea glauca* [Moench] Voss) on the richer sites, need to be tried.

In Canada, drainage and water management offer important opportunities for improving forest management, and should be tried more generally in both research and operational trials. However, if drainage is to become acceptable in Canada, three general areas of knowledge must be strengthened or consolidated: 1) **growth responses** of black spruce, tamarack and other species must be better documented according to site types; 2) **economic assessments** must be made to help the manager with investment decisions; and 3) **environmental impact assessments** of all components of wetland ecosystems must be carried out to meet the requirements of environmental assessment legislation.

The most attractive sites for drainage are those that are already forested, and that have one or more of the following attributes: (1) they already show moderately good growth, (2) they are on shallow-peated sites so that drainage will allow roots to exploit underlying mineral soils, (3) they are already well stocked to desirable species, and (4) they are in mid-rotation so that the time for carrying interest on the initial investment is relatively short. Harvested cutovers may also require drainage, because the water table rises after cutting ('watering-up'), sometimes above the surface in depressions, owing to removal of evapotranspiration and interception by the forest canopy.

Two types of drainage may be envisaged: **patterned drainage** (systematic, intensive, with a high density of ditches), and **prescription drainage** (dendritic, extensive, with a low density of ditches). Patterned drainage may be more appropriate for forested peatlands, whereas prescription drainage may be better for cutovers. Both types of drainage would be expected to improve tree growth and accessability to logging operations, hunters, fishermen and other recreationists, and to increase the diversity of ecosystems and wildlife.

At this time in Canadian forestry, research and development in anticipation of and prior to large-scale drainage programs are essential. We must obtain as much information as possible about drainage, so that we can be prepared for a rapid increase in drainage activity. We should capitalize on the results of current and previously established drainage trials, and we need to undertake additional well designed trials and experiments to gain more knowledge and experience. We know that black spruce responds well to drainage, and we have vast areas of black spruce-dominated peatland. We can learn from our own experience and borrow from the experts in Scandinavia and elsewhere. We need vision and motivation to embark on new approaches to forest management, and we need to be confident of our ability to do so. In this way, Canada can remain a leading supplier of quality black spruce fiber to the world.

J.K. Jeglum

RECOMMENDATIONS

After the Peatland Forestry Symposium had taken place, those who presented papers met to review the presentations and to discuss recommendations for further action. Each of the sections had been assigned a rapporteur whose job it was to summarize the papers, and to prepare a few key recommendations arising from his particular section, directing them especially to Canada, but also more broadly to the global community of peatland foresters. A synthesis of these recommendations follows.

It is recommended that:

1. Workers in peatland forestry attempt to standardize the classification of wetland, mire and peatland.

Because of the great variation in climate, geology and vegetation, it may be possible to agree only on higher units of classification. Classifications within each country, or within each climatic-physiographic region or province in a large country, should be developed specifically to meet the unique biophysical conditions and level of forestry practised in that area.

2. Terminology of peatland forestry be better defined and standardized.

We would like to note the initial efforts by IUFRO Working Party S1.05.01, in its draft report entitled 'Peatland Terminology for Forestry: English, German, Russian, Swedish, Finnish', compiled by Leo Heikurainen of Helsinki, Finland, in 1977.

3. Wet forest land be classified according to practical ecosystem types, and these ecosystems be identified and mapped in forest resource inventories.

Assessment of the areal extent of peatland forests and forests on wet mineral soil, is required in all forest management units to improve planning and management of wetland forests. Existing data and information should be gathered, analyzed, assimilated and summarized.

4. Holistic ecosystem studies of the structure and function of peatland forests be undertaken, with the focus on the impact of forest harvesting methods and drainage on long-term site productivity and carbon balance.

This work should address the problems of full-tree harvest and roadside-slash piles; biomass and nutrient cycling; mineralization and nutrient release; carbon balance as influenced by increased release of greenhouse gases and by increased uptake of carbon dioxide as a result of improved tree growth; hydrological inputs and outputs; detailed studies of soil microorganisms; etc.

5. Studies of the ecology and dynamics of peat environments, both temporally and spatially, as they relate to root growth of trees, be continued.

Changes in root-substrate regimes caused by drainage, various harvesting regimes, fertilization and other treatments need to be studied. Such biologically important factors as temperature, moisture, aeration, oxygen and other soil gases, nutrients, microflora and fauna, rates of decomposition and nutrient release, regimes (flow and timing), should be included.

6. Techniques and models be developed to describe and predict physiological and growth responses of trees and seedlings to changes in substrate conditions.

Drainage indirectly influences ecological factors which, in turn, influence physiological processes. Concern has been expressed about the possibility of overdrainage, and about the moisture stress on trees immediately after drainage. Studies of the response of seedling and tree root systems to drainage are required. Measures of allocation of biomass production among fine roots, coarse roots, stems and foliage in different site types, with and without drainage, should be undertaken.

7. Research be undertaken to determine concentrations and fluxes of methane and carbon dioxide in natural and drained peatlands.

Drainage may produce effects in peatlands that are similar to those that may be caused by climate warming, such as drying and surface peats, lowering water tables, increasing rates of decomposition, and causing more of these two gases to be released. As well, methane should be studied for its influence on hydraulic conductivity and drainability of various types of peat.

8. Studies of foliar nutrients be initiated to determine the need for fertilization and to determine and/or monitor effects of drainage on tree nutrition.

Drainage is known to stimulate tree growth and to cause increased uptake of nutrients. At the same time, nutrient release and cycling are increased, and there is some potential loss of elements by leaching, e.g., potassium. In certain types of peatland, nutrient imbalances may occur. Methods and techniques should be developed to diagnose nutrient status, nutrient deficiencies, and fertilization requirements in peatland forests.

9. The environmental impact of peatland forestry activities on wildlife — terrestrial fauna, birds, amphibians and aquatic life — be studied in more depth.

Changes in diversity and successional trends attributable to peatland forestry activities should be explored. Environmental impact assesments of drainage should include water-quality evaluations of nutrients and suspended solids, and assessment of the effects of sediments on the oxygen content of fish-spawning gravels.

10. A coordinated set of well designed drainage trials, using patterned drainage systems, and encompassing a range of biogeoclimatic regions, be undertaken in Canada.

The selection of research areas should be based upon the Wetland Regions of Canada map, produced by the National Wetlands Working Group. These areas should encompass a range of different site types, nutrient conditions, ditch spacings, and wetland tree species, and include both forested and clearcut peatlands. For all trials, the following four aspects of drainage should be monitored and assessed: 1) hydrological characteristics before as well as after drainage, 2) growth responses of trees and/or seedlings in relation to ditch spacing and distance to water level, 3) economic feasibility, and 4) environmental impacts.

11. Experiments in prescription drainage be established in forested and cutover wetlands.

This type of drainage, with a low density of ditches placed strategically in the natural lows of the landscape, is relatively inexpensive. It might be effective in shallow basins, which 'water-up' after cutting, and in wet swales behind beach ridges in poorly drained sands with iron pans. The main advantages of prescription drainage are that it provides foresters and other users with better access to the area, improves tree productivity, stimulates regeneration, and improves the diversity and abundance of several kinds of wildlife.

12. Better technical guides to the installation of drainage systems be developed, so as to minimize their adverse effects.

Channel hydraulics should be used to establish slope criteria that minimize erosion and ditch-filling. Guides to sediment pool and pond sizes, shapes and inlet/outlet locations should be developed. Opportunities for coordinated planning of channels and sediment ponds so as to enhance waterfowl and aquatic habitat should be explored.

13. Main effort be directed to drainage and tending of wetlands and peatlands that are already treed, before working on the open wetlands.

Drainage of treed wetlands is a relatively inexpensive method of increasing the area of productive land because the trees are already established on the site. There is considerable room for improvement of tree growth and forestry on sites that are already treed, in view of the extensive forestry practised in Canada. Spacing and/or thinning systems and equipment need to be developed, and growth studies need to be undertaken to determine optimum thinning strategies.

14. Forests on highly productive peatlands and wet mineral soils be subjected to more ecological and silvicultural research.

Highly productive, nutrient-rich sites on which the peat layer is often shallow offer a good opportunity for intensive forestry, because they are limited only by excessive water in the rooting horizons and probably are not suffering nutrient deficiencies or imbalances. They should be the subject of more experiments in drainage, drainage combined with mounding, and plowing so that we can determine how best to manage them intensively.

15. Growth and yield models for the important tree species on various peatland site types in Canada be constructed on the basis of data available from drainage experiments. Cost-benefit relationships and investment decision models should be developed.

With such models it is possible to assist the forest manager in making investment decisions concerning drainage, site preparation techniques, fertilization, and thinning for various peatland and wetland site types, and to compare costs with those for upland sites.

16. A policy of peatland forest management be developed that is based on a sound, ecologically based philosophy.

A change in approach is rapidly developing in forestry practices in Canada, from a primary emphasis on wood extraction to a more environmentally sound approach based on developing sustainability, and taking into account the desires of a wide range of users. This new approach could involve moving toward classification of forest lands into dominant-use and multiple-use areas;

management techniques that do not degrade or reduce the productive capacity of the land; thinning and selection harvesting; prompt and acceptable levels of regeneration; promotion of mixed forests and mosaics of forest types of different development stages; promotion of aesthetically pleasing forest landscapes that also favor diverse wildlife habitats; and establishment of special ecological and gene pool reserves, old-growth forests, and wilderness areas.

17. Interprovincial and international cooperation be encouraged and promoted.

Coordinated planning and study must be promoted among researchers and land managers to ensure rational and effective use of resources and opportunities in the development of peatland forestry. This can be accomplished by 1) workshops, seminars, symposia, and participation in working groups in peatland forestry such as the International Peat Society Commission III, the IUFRO Working Group on Peatland Forestry, and a formally recognized Canadian Working Group on Peatland Forestry; 2) development of shared data sets for hydrology, tree growth, nutrient contents, and vegetation; and 3) technology transfer through papers and reports, manuals and guidelines, visiting scientists, technical experts, and student exchanges.

Compiled by J.K. Jeglum