EARLY GROWTH RESPONSE IN TREES FOLLOWING PEATLAND DRAINAGE

G.R. Hillman and J.J. Roberts

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ABSTRACT

The growth of black spruce (*Picea mariana* (Mill.) BSP) and tamarack (*Larix laricina* (Du Roi) K. Koch) on two drained peatlands, at McLennan and Wolf Creek in central Alberta, was greater than on undrained control areas 9–10 years after drainage. On the drained plots, diameter growth was 1.6–2.3 times, height growth 2.7–3.5 times, and volume growth 4.4–9.7 times that on the undrained control plots. There were no clear differences in growth among various ditch spacings (30, 40, 50, and 60 m), and correlation between tree growth and distance of trees from the nearest ditch was poor. These results suggest that drawdown of the water table was sufficient to create unsaturated zones that facilitated equitable tree growth across the strips between ditches. Tree ring analyses revealed that increases in growth could begin as early as 3–4 years after drainage. The successful regeneration of black spruce on the control plots at McLennan and the reasonable size of black spruce and tamarack ingrowth on control plots suggest that both species are able to germinate and survive on wet sites initially, but high water tables inhibit their further development. Additional periodic measurements of both species are necessary to determine long-term growth patterns after drainage and to assess the financial feasibility of peatland drainage as a practical option in forest management.

RÉSUMÉ

À McLennan et Wolf Creek dans le centre de l'Alberta, l'épinette noire (*Picea mariana* (Mill.) BSP) et le mélèze laricin (*Larix laricina* (Du Roi) K. Koch) affichent une croissance supérieure dans deux tourbières drainées, 9-10 ans après le drainage, par comparaison à leur croissance mesurée dans des placettes témoins non drainées. Dans les placettes drainées, les accroissements de la hauteur, du diamètre et du volume ont été, respectivement, de 2,7 à 3,5, de 1,6 à 2,3 et de 4,4 à 9,7 fois plus élevés. Aucun effet net de l'espacement des fossés (30, 40, 50 ou 60 m) sur la croissance ne s'observe, et la corrélation entre la croissance et la distance des arbres du fossé le plus proche est faible. Ces résultats semblent indiquer que l'abaissement du niveau de la nappe phréatique a été suffisant pour créer des zones non saturées qui ont facilité une croissance comparable des arbres dans les bandes entre les fossés. D'après des analyses dendrométriques, l'amélioration de la croissance pourrait débuter 3 ou 4 ans après le drainage. Le succès de la régénération de l'épinette noire dans les placettes témoins à McLennan et la taille raisonnable du recrutement des deux essences dans les placettes témoins

semblent indiquer que ces essences peuvent germer et survivre dans les terrains humides au début, mais que le niveau élevé de la nappe phréatique inhibe subséquemment leur croissance. Il faudra continuer de mesurer périodiquement les arbres des deux essences afin de déterminer les patrons de croissance à long terme et d'évaluer la faisabilité financière du drainage des tourbières comme option pratique d'aménagement forestier.

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INTRODUCTION

In the 1980s, the construction and expansion of pulp mills and sawmills in Alberta increased considerably. At the same time, crown lands continued to be withdrawn for uses other than forestry. The predictable decline in the available wood supply resulting from these activities prompted the Alberta Forest Service to seek other means to expand the forest land base for wood fiber production. The first and most obvious consideration was the 4×10^6 ha of peatland supporting stagnant, noncommercial stands of black spruce (*Picea mariana* (Mill.) BSP) and tamarack (*Larix laricina* (Du Roi) K. Koch) in the province.

The objective of draining peatland is to provide a suitable rooting environment for trees by enhancing soil aeration, soil temperature, and water regimes and by promoting nutrient exchange between the soil and the trees. Peatland forestry in North America is relatively new; consequently, long-term growth and yield data for black spruce and tamarack growing on such peatlands before and after drainage are scarce. Most of the data that are available for these species were obtained by measuring trees along highways, railways, or agricultural ditches (Päivänen and Wells 1978; Wang et al. 1985; Trottier 1986; Dang and Lieffers 1989; Lieffers and MacDonald 1990) or in sample plots on an engineered ditch network (Stanek 1968; Hillman et al. 1990; Sundström 1992). Although all the studies cited provide some growth and yield data, the amount of long-term (50–100+ years) growth and yield data is very limited.

In 1985, the Alberta Land and Forest Service and the Canadian Forest Service jointly established engineered ditch networks to study the growth of forest stands after drainage and the environmental impact of drainage on three peatland types in central Alberta (Hillman et al. 1990). The purpose of this paper is to report on the results from two of the study sites, McLennan and Wolf Creek, obtained 9–10 years after drainage. Both sites support black spruce and tamarack. The McLennan site supports mostly young black spruce with a minor component of older tamarack. At the Wolf Creek site, about two-thirds of the stand consists of tamarack; the rest is black spruce.

The objectives of the study were to determine (1) if, at 9–10 years after drainage, significantly more growth in diameter, height, basal area, and volume, and significantly more natural regeneration occurred in black spruce and tamarack in drained areas; (2) the effects of ditch spacing on these tree growth variables; and (3) the functional relationships between distance of trees from the nearest ditch and four growth variables (growth in tree diameter, height, basal area, and volume).

METHODS

Description of Study Areas

McLennan

The experimental drainage area is a treed fen, characterized by a bog cap in places, supporting 30- to 60-year-old black spruce and tamarack. Stem densities range from 250 to 3 400 stems•ha^{-1} for tamarack and black spruce, respectively. The peatland is located within the Dry Mixedwood Subregion of the Boreal Forest Natural Region of Alberta (Alberta Environmental Protection 1994) about 15 km north of McLennan, Alberta, at 55°52'N, 116°54'W (Fig. 1) and at an elevation of 660 m. The mean annual temperature at Peace River (1971–2000) is 1.2°C, and the average January and July temperatures are −16.6°C and 16.0°C, respectively. The average annual precipitation is 402.3 mm, 264.1 mm of which falls during May through September; the average annual snowfall is 119.3 cm (Atmospheric Environment Service 2002).

The eastern portion of the experimental area slopes gently (0.6%) from the southeast toward a string of beaver ponds located to the northwest, whereas the western portion slopes (0.4%) from south to north (Fig. 1). Groundwater flow into the experimental area is primarily from south and west. A water track—defined as vegetation types marking the path of mineral-influenced waters through a peatland (Sjors 1948; Heinselman 1963) —located along the western edge of the experimental area feeds into the nearest beaver pond. One short, well-defined stream channel just north of the drainage network also drains into the beaver pond. The soil consists of peat more than 1.5 m thick, overlying clay. A more detailed description of the experimental area and its climate, vegetation, and soils was provided by Hillman (1992).

Wolf Creek

The experimental drainage area is located about 30 km southeast of Edson, Alberta (53°25'N, 116°03'W; Fig. 2) at an elevation of 950 m. It experiences a subhumid continental climate with long, cold winters and moderately warm summers. It is occasionally subject to warm chinooks during the winter (Dumanski et al. 1972). The mean annual air temperature at Edson (1971–2000) is 2.0°C, and the average January and July temperatures are –11.8° and 14.6°C, respectively. The average annual precipitation is 562.4 mm, 415.6 mm of which falls during May through September; the average annual snowfall is 176.5 cm (Atmospheric Environment Service 2002).

The experimental area, which is about 132 ha in extent, lies close to a confluence of two Wolf Creek tributaries, downstream of a large (>2 500 ha) treed fen. The fen is bounded on the northeast and southwest by tributaries of Wolf Creek (Fig. 2). Before drainage, peat thickness at 42 locations across the peatland averaged 1.70 m (standard deviation 0.88 m; range 0.38–3.54 m). The shallow peat lies near the stream channels, and the deep peat lies near the center of the confluence area. Peat thickness also increases upslope from the confluence area, i.e., toward the southeast. Groundwater flows in the direction of the topographic slope (0.6%), from southeast to northwest, toward the north tributary of the confluence. Uplands with mineral soils located at the south end of the fen provide the fen with a steady water supply.

The peatland lies within the Lower Foothills Subregion of the Foothills Natural Region of Alberta (Alberta Environmental Protection 1994), and, as is the case in much of Alberta's forested

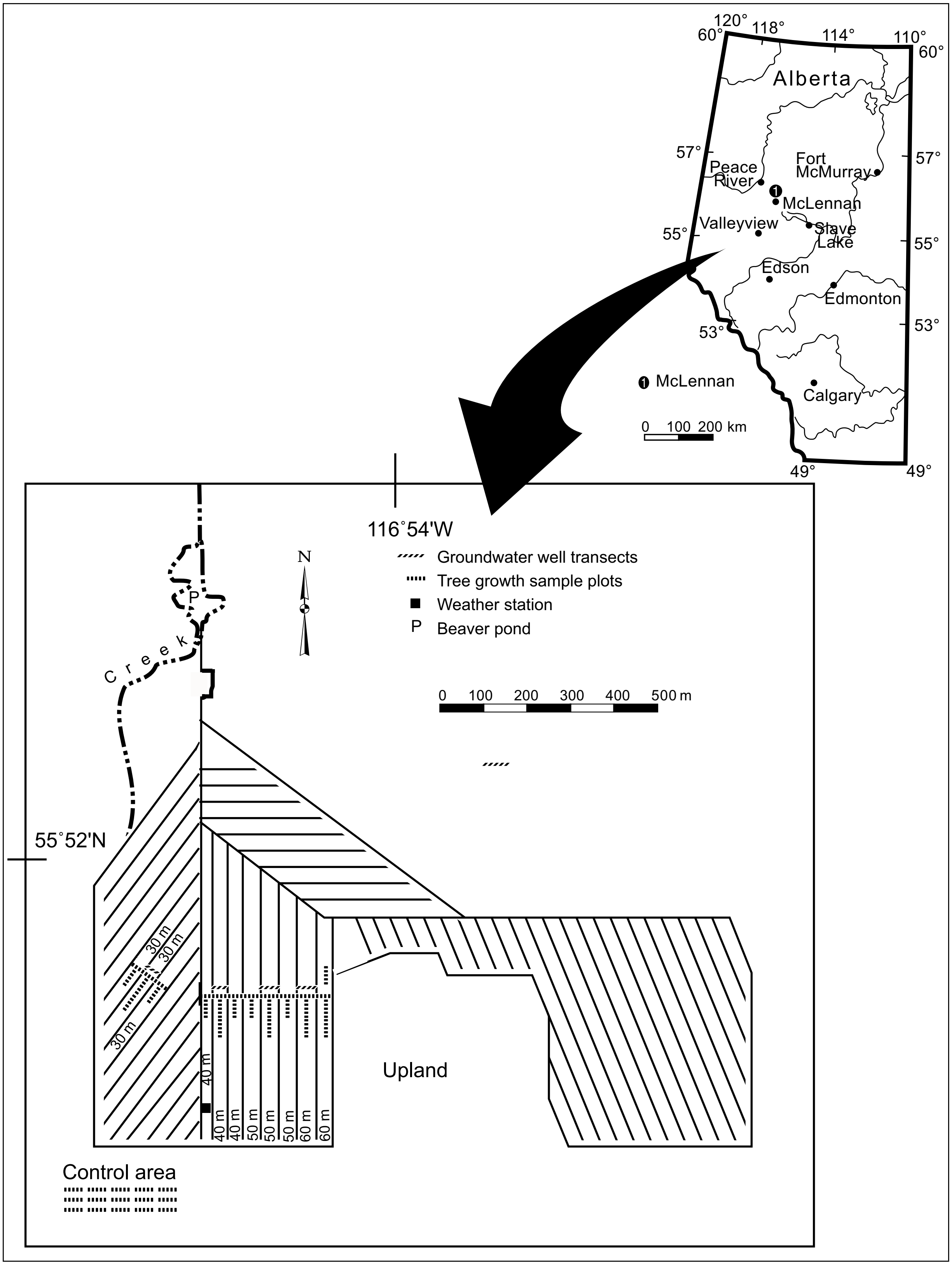

Figure 1. McLennan ditch network plan, showing locations of instrumented transects and sample plots.

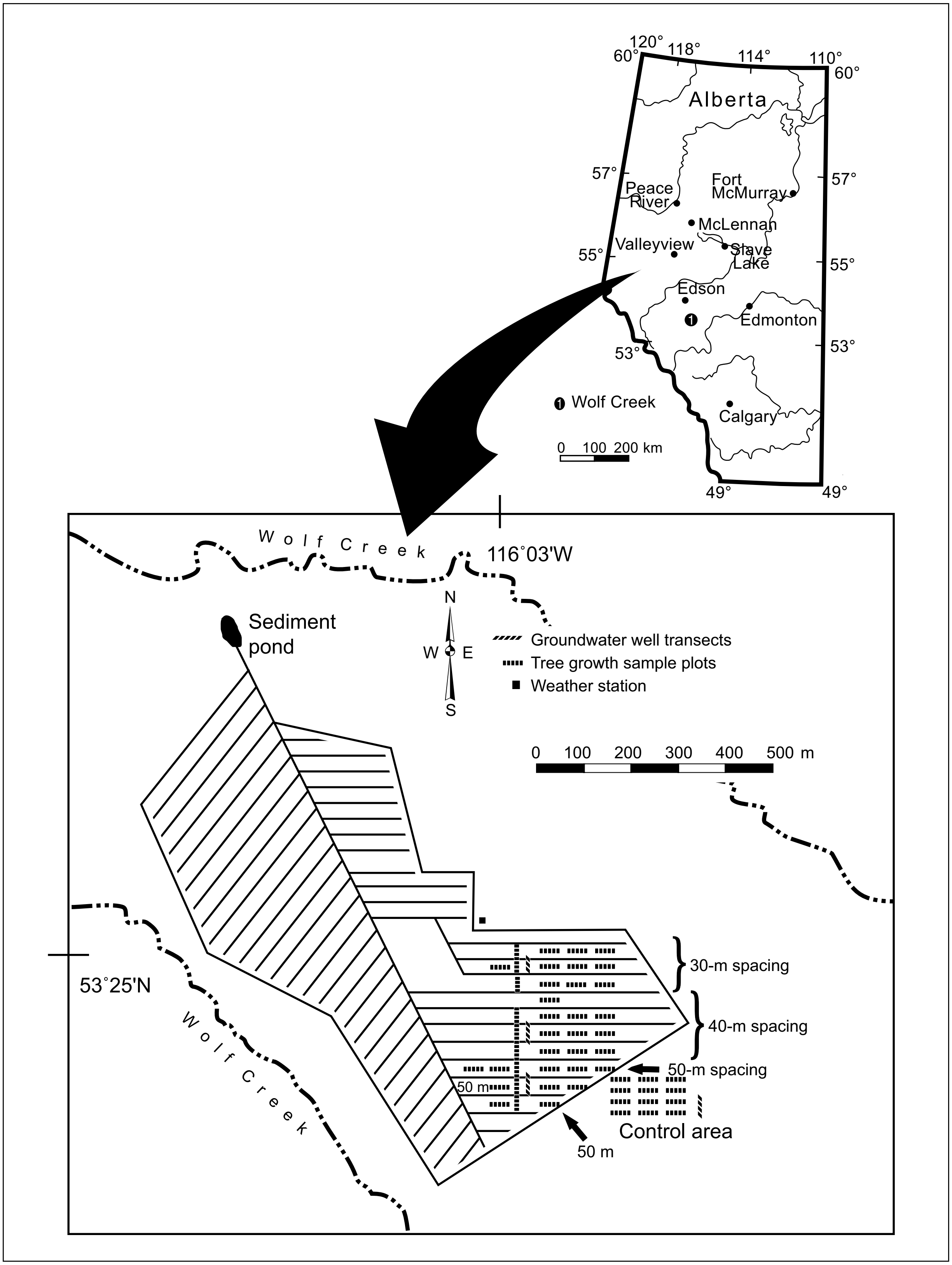

Figure 2. Wolf Creek ditch network plan, showing locations of instrumented transects and sample plots.

areas, the vegetation on the site originated after fire. Tamarack and black spruce, both open growing and both 50 to 60 years old at the beginning of the study, are the predominant tree species on the fen with stem densities of 1 300 and 800 ha^{-1}, respectively. The area was subjected to intense geophysical exploration for oil and gas, and, as a result, the forest is now characterized by a network of intersecting seismic lines, each about 7 m wide. Detailed descriptions of soil profiles, soil properties, and vegetation on the peatland have been provided by Mugasha et al. (1993) and Hillman (1996).

Water Table Control

The method used to lower and monitor the water table levels was the same at both locations. A drainage ditch network was designed, and lines of trees were cut to provide access for the digging machine. Transects were established, instrumented, sampled, and surveyed to determine initial predrainage conditions and to measure the effects of drainage on groundwater levels, peat subsidence, and other variables. A Lannen S-10 digger was then used to excavate the drainage ditches. Groundwater table measurements were taken before, during, and after ditching. Full details of the groundwater studies have been provided by Hillman (1992, 1996).

McLennan

The design of the drainage ditch network (Fig. 1) was based on 30-m ditch spacings in the water track area and 40-m spacings in the remaining area. Different ditch spacings were evaluated in the southwestern portion of the network. In 1986, before ditching, five transects were established, one at a location outside and about 400 m north of the ditch network and four at different ditch spacings (30, 40, 50, and 60 m) perpendicular to ditch lines in the designated drained area.

Construction of the ditch network commenced in the fall of 1986, before the ground was frozen, but construction was suspended during the winter months. Most of the ditching was done in June 1987, and all work was completed in July 1987. In total, 30 km of ditches on 90 ha was excavated, resulting in a drainage ditch density of 333 m•ha^{-1}. At the down-slope end of the main ditch, a C-shaped sediment collector ditch was constructed to capture the sediment issuing from the ditches.

Wolf Creek

In 1986, a network of drainage ditches 35 m apart was marked out on the selected area, with accommodation for a control area and 30-, 40- and 50-m ditch spacings on the southeast portion of the area (Fig. 2). It should be noted from this layout that the areas containing the 30-, 40-, and 50-m spacings were not hydrologically independent, because there were nine lateral ditches upstream from the 30-m spacing area intercepting groundwater flow, five ditches upstream from the 40-m spacing area, and two ditches upstream from the 50-m spacing area. This means that less groundwater may have reached the 30-m spacing area than the 50-m spacing area, which might affect tree growth response. Groundwater well transects were established on each of the three ditch spacings perpendicular to the ditch lines. In May 1987, a control area was established south of and upstream from the proposed ditch network. Groundwater table configurations were monitored from May through October, 1986 to 1991.

In fall 1987, the ditch network was constructed in unfrozen ground and a sediment pond created at the down-slope end of the main ditch to capture sediment. An undisturbed buffer strip separated the sediment pond from the watercourse by 130 m. Its purpose was to trap sediment particles that escaped the sediment pond. A total of 20 km of ditches was dug on 60 ha resulting in a drainage ditch density of 333 m•ha^{-1}. The entire network was completed on 28 October 1987.

Sample Plots

Two types of sample plots were used to measure tree growth response to drainage (Figs. 1 and 2). In the first, 5 m x 40 m sample plots were established in a control area and in each ditch spacing area. In the drained areas, the long axes of the plots were placed parallel to the ditches, centered at the midpoints between ditches; these are referred to as parallel plots. The second set of plots was oriented perpendicular to ditches in the drained areas to determine tree growth response in relation to distance of trees from the nearest ditch. These plots, with dimensions 5 m x x m (where x equals the distance between ditches), are called perpendicular plots.

On all plots, live trees with diameter at breast height (dbh) ≥ 1.1 cm were tagged with sequentially numbered aluminum tags, and the tree number, species, dbh, tree height, and condition (defect) codes recorded (Alberta Forest Service 1991). On the perpendicular plots, the distance of each tree to the center of the nearest ditch was also measured. For each tree, dbh was measured to the nearest 0.1 cm with a standard diameter tape, and tree height was measured to the nearest 0.1 m with an 8.22-m telescoping height-measuring pole. Height and dbh were used to determine gross total volumes from individual tree volume tables for black spruce and tamarack (Huang 1994a, 1994b). The gross total volume (m^3) used in this report is defined as the volume of wood from 0.00 m stump height to 0.0 cm top diameter inside bark (Huang 1994a, 1994b). Ingrowth, consisting of those trees with dbh ≥ 1.1 cm during the current remeasurement but dbh < 1.1 cm during the previous measurement, was also tagged and measured.

A regenerated tree was defined as any tree stem 0.16 m or taller to a maximum dbh of 1.0 cm (Alberta Forest Service 1991). A regeneration tally was done on a 5 m x 10 m regeneration subplot nested within each main plot, where each regeneration subplot was located at one end of each main plot. Within each subplot, all trees with dbh < 1.1 cm were identified and tallied by species, according to the following height classes: 0.16–0.30 m, 0.31–0.60 m, 0.61–0.90 m, 0.91–1.20 m, and > 1.20 m.

McLennan

The 28 plots on the drained area were established and trees were first measured in August 1988 (Fig. 1). Trees in the 15 control plots were measured in summer 1989. Although the trees in the drained and control plots were measured in different years, the control trees were measured before significant growth occurred in 1989. Thus, from a tree growth perspective, both plot types were effectively measured in 1988. All plots and associated regeneration subplots were remeasured in fall 1994 and fall 1997. The results of the McLennan study are based on incremental growth (diameter, height, basal area, and volume) between 1988 and 1997, i.e., the response 10 years after drainage is based on 9 years of growth. Only those trees that were measured in 1988 or 1989 and in 1997 are included in the incremental growth analyses.

Wolf Creek

The 39 plots on the drained area were established and trees were first measured in October 1986 (Fig. 2). During the first measurement of trees on the drained area, the height of every third tree was measured and recorded. Subsequently, the height of all trees on the plots was measured. Tree heights that were not measured the first time were estimated on the basis of dbh. Trees on the 12 control plots were measured in July 1987. Measurements were repeated in the fall of 1993 and 1996. The results for Wolf Creek are reported as incremental growth between 1986 and 1996, i.e., the response 9 years after drainage is based on 10 years of growth.

Tree Ring and Stem Analyses

After selected trees were felled and sectioned, disks were obtained at heights of 0.0, 0.3, 0.8, and 1.3 m and at height increments of 0.5 or 0.75 m thereafter. Age and ring widths were determined from two radii on each disk using a Holman digimicrometer and television camera. The computer programs DUFFNO and STEM, developed by Kavanagh (1983), were used to process the resulting data sets. The STEM program was used to carry out stem analyses and generated tables showing average annual and periodic annual increments for dbh, height, basal area, and volume. Paired and nonpaired t-tests were run to test the hypothesis that there were no differences in diameter growth between trees from the drained areas and trees from the undrained areas, before and after ditching.

McLennan

In October 1994, seven growing seasons after ditching, one black spruce tree near each control plot and one near each of the 28 drained plots were felled and sectioned for tree ring and stem analyses. Also in October 1994, the ages of 12 black spruce trees in the control area and 12 black spruce trees in the 50-m spacing area were estimated from standing tree height. The trees were subsequently felled, sectioned, and measured so that their ages could be precisely determined through ring analyses.

Wolf Creek

Twenty-four trees, consisting of three tamarack and three black spruce trees from the control area and from each of the three ditch spacing areas but outside the plots, were felled and sectioned in mid-October 1993, six growing seasons after ditching.

Statistical Analyses

For both sites, the two species were assessed separately because of the large difference in population sizes. They also grew at different rates and responded differently to drainage. The nature of this experiment and the fact that it was conducted on such a large scale made it logistically impossible to randomly assign areas within the forest to a specific ditch-spacing treatment. Therefore, for analytical purposes we assumed that the experiment was based on a completely randomized design and conducted one-way analyses of variance (Delwiche and Slaughter 1998) on all variables, comparing the treatment means with Scheffé's test. Effects were considered significant if $p \leq 0.05$.

RESULTS

Change in Groundwater Table Levels

At McLennan, the average depths from the ground surface to the water table before ditching (1986–1987) were 7, 17, 27, and 18 cm for the 30-, 40-, 50-, and 60-m ditch spacing areas, respectively. After ditching (1987–1989), the average depths were 86, 83, 83, and 91 cm, respectively. The changes in water table levels on the control plots were negligible compared with the changes that occurred in the drained area.

At Wolf Creek, the average depths to the water table before ditching (1986–1987) were 17, 16, 6, and 9 cm for the control and the 30-, 40-, and 50-m ditch spacing areas, respectively. After ditching (1988–1991), the average depths were 24, 77, 52, and 58 cm, respectively.

A more detailed description of the results from the groundwater studies was provided by Hillman (1992, 1996).

Stand Statistics

A summary of stand statistics for black spruce and tamarack at McLennan, at the beginning and end of the measuring period, based on data from all 43 plots (Table 1), shows that there were about 10 times as many black spruce trees as there were tamarack. This difference in numbers explains the greater per hectare increments in basal area and volume for black spruce on the drained area, even though diameter and height increments for tamarack on the drained area were 1.7 and 2.1 times, respectively, those of black spruce. Although in 1997 the trees were still small, drainage had considerably increased the diameter, height, basal area, and volume of both species. Volume increases on the drained area were 4.1 and 10.7 times that on the control for black spruce and tamarack, respectively.

At Wolf Creek, about two-thirds of the stand consisted of tamarack trees (Table 2). Growth after ditching was greater on the drained areas than on the control, and greater for tamarack than black spruce. Basal area and volume increases for tamarack on the drained area were 4–6 times that of tamarack growth on the control, and 3–5 times that of black spruce on the drained area.

Diameter and Height Growth

At both sites, diameter growth of black spruce and tamarack on the drained area was significantly greater ($p \leq 0.0005$) than on the control area (Fig. 3A). There was no difference in diameter growth of tamarack among the different ditch spacings, but for black spruce, the greatest diameter growth tended to occur with 40-m spacing. Diameter growth of black spruce on the drained areas was 1.6–2.1 times that on the control areas, whereas diameter growth of tamarack on the drained areas was 2.2–2.3 times that on the control areas.

As mentioned earlier, the height of only one in three trees on the drained area at Wolf Creek were measured initially in 1986. Tree heights not measured the first time were estimated on the basis of dbh. The r^2 values obtained for black spruce and tamarack (0.9243 and 0.7365, respectively) suggest a close relationship between height and dbh in both species, and that the use of predicted values of height in the analyses did not unduly affect the results.

Height growth of black spruce and tamarack was significantly greater ($p \leq 0.0001$) on the drained area at McLennan and Wolf Creek (Fig. 3B). With the exception of black spruce at McLennan, there was no difference in height growth among the different ditch spacings. For both sites, average black spruce height growth on the drained area was 2.7–3.3 times that on the control area. Tamarack height growth on the drained areas was 3.0–3.5 times that on the control areas. At Wolf Creek, for all treatments, the height of black spruce increased by less than 1 m over the period 1986–1996.

Height and diameter growth was greatest for tamarack at McLennan and least for black spruce at Wolf Creek.

Basal Area and Volume Growth

Basal area growth of black spruce and tamarack was significantly greater ($p \leq 0.0001$) on drained sites at both McLennan and Wolf Creek (Fig. 3C). There were also differences in basal area growth of tamarack among the different ditch spacings at both sites and of black spruce at McLennan. At both sites, the average basal area growth of black spruce on the drained area was 2.4–3.7 times that on the control area. For tamarack, the average basal area growth on the drained areas was 4.3–7.1 times that on the control areas.

Volume growth of black spruce and tamarack on the drained areas at both sites was significantly greater ($p < 0.0001$) than on the control areas (Fig. 3D). There were differences in volume growth among ditch spacings at McLennan, but not at Wolf Creek. Average volume growth of black spruce on the drained areas was 4.4–5.5 times that of black spruce on the control areas. For tamarack, volume growth on the drained areas was 5.0–9.7 times that on the control areas.

Comparison of Growth on Drained Plots with Growth on a Better Site

The mean annual increments for diameter, height, basal area, and total volume for black spruce on drained plots at McLennan and Wolf Creek were compared with growth of similar-aged black spruce on a good, undrained site (Alberta Energy and Natural Resources 1985). No data were available to make similar comparisons for tamarack, so tamarack growth at McLennan and Wolf Creek was also compared with black spruce growth on the good site.

The diameter growth of black spruce on drained plots compared favorably with or exceeded that of black spruce on the good site (Table 3). In contrast, height growth of black spruce at McLennan was slightly less and at Wolf Creek was less than half

Table 1. Characteristics (as mean and standard error) of black spruce and tamarack on the McLennan peatland 1 year after (1988) and 10 years after (1997) drainage

	Black spruce				Tamarack			
	1988		1997		1988		1997	
Characteristic	Control	Drained	Control	Drained	Control	Drained	Control	Drained
Dbh (cm)	2.4 (0.1)	3.0 (0.1)	3.4 (0.1)	5.1 (0.1)	3.6 (0.4)	4.0 (0.3)	5.2 (0.5)	7.5 (0.4)
Height (m)	2.5 (0.1)	2.9 (0.1)	3.0 (0.04)	4.4 (0.1)	3.6 (0.2)	3.8 (0.2)	4.5 (0.3)	6.9 (0.3)
Basal area ($m^2 \cdot ha^{-1}$)	2.12 (0.46)	2.63 (0.39)	3.57 (0.57)	6.08 (0.63)	0.30 (0.10)	0.63 (0.14)	0.49 (0.14)	1.97 (0.41)
Volume ($m^3 \cdot ha^{-1}$)	2.58 (0.81)	4.55 (0.27)	4.87 (1.00)	14.05 (0.47)	0.56 (0.19)	1.39 (0.38)	1.11 (0.34)	7.26 (1.60)
Stem density[a] (ha^{-1})	3387 (479)	2702 (235)	3387 (479)	2702 (235)	235 (74)	347 (62)	235 (74)	347 (62)

[a]Only trees measured in both 1988 and 1997 are included in these totals. Dead trees, ingrowth, and stems with dbh < 1.1 cm are not included.

Table 2. Characteristics (as mean and standard error) of black spruce and tamarack on the Wolf Creek peatland before (1987) and 9 years after (1996) drainage

	Tamarack				Black spruce			
	1987		1996		1987		1996	
Characteristic	Control	Drained	Control	Drained	Control	Drained	Control	Drained
Dbh (cm)	5.2 (0.3)	4.5 (0.1)	6.2 (0.3)	6.6 (0.1)	3.4 (0.2)	4.4 (0.1)	4.4 (0.2)	5.8 (0.1)
Height (m)	4.1 (0.1)	3.9 (0.1)	4.7 (0.1)	5.5 (0.1)	2.8 (0.1)	3.5 (0.1)	3.2 (0.1)	4.3 (0.1)
Basal area ($m^2 \cdot ha^{-1}$)	2.54 (0.23)	3.31 (0.24)	3.26 (0.28)	6.37 (0.45)	0.46 (0.08)	1.91 (0.22)	0.69 (0.13)	2.76 (0.26)
Volume ($m^3 \cdot ha^{-1}$)	6.93 (0.77)	8.72 (0.70)	8.91 (0.92)	20.27 (1.32)	0.71 (0.14)	4.34 (0.64)	0.88 (0.25)	6.57 (0.80)
Stem density[a] (ha^{-1})	821 (77)	1432 (193)	821 (77)	1432 (193)	396 (65)	895 (67)	396 (65)	895 (67)

[a]Only trees measured in both 1987 and 1996 are included in these totals. Dead trees, ingrowth, and stems with dbh < 1.1 cm are not included.

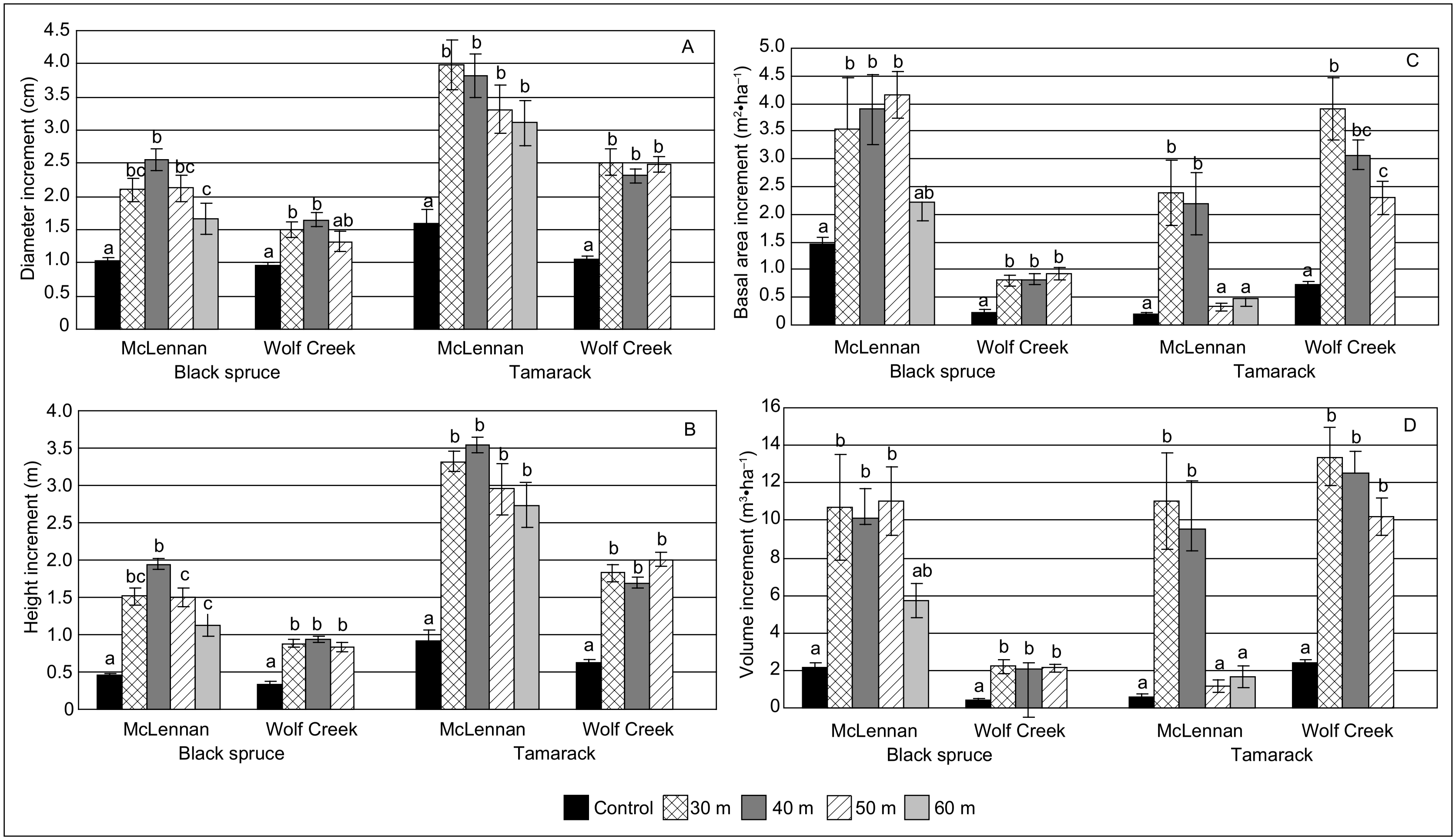

Figure 3. Incremental diameter (A), height (B), basal area (C), and volume (D) of black spruce and tamarack (as mean and standard error). The growth periods for McLennan and Wolf Creek were 1988–1997 and 1987–1996, respectively. Means identified with the same letter do not differ significantly at $\alpha = 0.05$.

that of black spruce on the good site. Basal area growth of black spruce at Wolf Creek was 21% of that of black spruce on the good site, whereas at McLennan it was 84%. The corresponding values for volume growth of black spruce at Wolf Creek and McLennan were 6% and 27%, respectively.

The diameter and height growth of tamarack either exceeded or was comparable to that of black spruce on the good site. Basal area growth of tamarack at McLennan was 33% of that of black spruce on the good site, whereas at Wolf Creek it was 75%. The corresponding values for tamarack volume growth at McLennan and Wolf Creek were 17% and 34%, respectively. The noticeable difference in basal area and volume growth between the upland site and the two drained sites may be attributed, in part, to the greater density of stems on the good site. There were nearly twice as many trees on the good site as there were black spruce trees at McLennan, and three times as many as there were tamarack trees at Wolf Creek.

Tree Ring and Stem Analyses

The summary for trees destructively sampled at McLennan and Wolf Creek (Table 4) shows that the average tree age ranged from 50 to 70 years and that tamarack growth was faster than that of black spruce. At McLennan, ring growth of black spruce during the period 1979–1994 was greater on the drained area than on the control area (Fig. 4A) 8 years before ($p < 0.001$) and 8 years after ($p < 0.001$) ditching. On the control area, diameter growth was significantly less ($p = 0.003$) during the postdrainage period than during the predrainage period. On the drained area, the difference between pre- and post-drainage diameter growth was not statistically significant ($p = 0.077$), although there was a definite tendency for diameter to increase with time during the last 5 years of record.

Growth trends for the drained and control areas at McLennan were initially similar, maintaining a difference of about 0.4 mm in ring width, up until 2 years after drainage, beyond which time they became noticeably different. Growth rate for ring width on the control areas remained static between 1989 and 1994 at about 0.38 mm•year^{-1}. During the same period, the growth rate on the drained area increased by 0.15 mm•year^{-1} so that by 1994 the difference in ring width between the areas had increased to 1.16 mm. A scan of the 1994 ring widths at different locations along the stems revealed that, in nearly all cases, the widest rings occurred near ground level (Fig. 4B). In about one-third of the trees, ring widths were greater in the upper portion of the stem than elsewhere, with the exception of the base (Fig. 4B).

At Wolf Creek, the mean ring widths at breast height for the 6 years before and the 6 years after ditching (Fig. 4C) indicate that tamarack and black spruce trees responded to ditching during the third and fourth growing seasons after ditching, respectively. On the drained area, postdrainage ring widths were significantly greater than predrainage ring widths for tamarack ($p < 0.001$) and black spruce ($p = 0.003$). There were also differences in postdrainage ring widths between tamarack and black spruce ($p = 0.054$). On the control area, there was no difference between the pre- and post-drainage growth rings for either tamarack or black spruce ($p = 0.322$ and 0.246, respectively). For black spruce at McLennan and both species at Wolf Creek, ring widths increased with time after drainage and showed no sign of leveling off. Further studies are necessary to determine how long these increasing trends continue.

Additional comparisons were made using 6-year pre- and post-drainage averages (Table 5) calculated by the computer program STEM. For the control areas, there were no differences in growth of diameter, height, basal area, or volume before and after drainage, with one exception: at McLennan, predrainage diameter growth of black spruce was greater than postdrainage diameter growth ($p = 0.0032$). For black spruce on the drained area at McLennan, postdrainage growth in diameter, height, basal area, and volume were significantly greater ($p \leq 0.004$) than predrainage growth. On the drained area at Wolf Creek, diameter and volume growth of black spruce were greater after drainage than before ($p \leq 0.0013$). Similarly, diameter, basal area, and volume growth of tamarack on the drained area at Wolf Creek was greater after drainage than before ($p < 0.0001$).

Table 3. **Growth of tamarack and black spruce on drained plots at McLennan and Wolf Creek compared with growth of black spruce on a good, undrained site**

Species and site	Dbh ($cm•yr^{-1}$)	Height ($m•yr^{-1}$)	Basal area ($m^2•ha^{-1}•yr^{-1}$)	Total volume ($m^3•ha^{-1}•yr^{-1}$)
Black spruce				
Good, undrained site[a]	0.16	0.19	0.410	3.520
McLennan	0.21	0.15	0.345	0.940
Wolf Creek	0.15	0.09	0.085	0.213
Tamarack				
McLennan	0.36	0.31	0.134	0.584
Wolf Creek	0.24	0.18	0.309	1.204

[a]Height = 13.00 m at 50 years breast height age.

Table 4. **Characteristics (as mean and standard error) of black spruce trees cut at McLennan in October 1994 and black spruce and tamarack trees cut at Wolf Creek in October 1993**

Species and site	*n*	Age (years)		Dbh (cm)		Height (m)		Basal area ($m^2•tree^{-1}$)		Gross volume ($m^3•tree^{-1}$)	
Black spruce											
McLennan	38	50.7	(3.4)	4.6	(0.4)	3.9	(0.2)	0.00145	(0.0002)	0.0051	(0.0008)
Wolf Creek	12	67.9	(8.0)	6.7	(0.8)	4.8	(0.4)	0.0041	(0.0012)	0.0104	(0.0041)
Tamarack											
Wolf Creek	12	55.0	(0.8)	8.8	(0.6)	6.9	(0.3)	0.0063	(0.0008)	0.0194	(0.0032)

Table 5. **Mean periodic annual increments, before and after drainage, calculated by the computer program STEM for the destructively sampled trees on the control and drained plots at McLennan and Wolf Creek**

	Dbh ($cm•yr^{-1}$)		Height ($m•yr^{-1}$)		Basal area ($dm^2•tree^{-1}•yr^{-1}$)		Volume ($dm^3•tree^{-1}•yr^{-1}$)	
Treatment	Before	After	Before	After	Before	After	Before	After
McLennan, black spruce								
Control	0.0986	0.0712	0.0600	0.0536	0.0029	0.0027	0.0957	0.0881
Drained	0.1797	0.2252	0.1298	0.1663	0.0074	0.0138	0.2542	0.5075
Wolf Creek, black spruce								
Control	0.1270	0.0987	0.0771	0.0755	0.0078	0.0086	0.3153	0.4043
Drained	0.1353	0.1952	0.0865	0.0988	0.0289	0.0143	0.2385	0.4832
Wolf Creek, tamarack								
Control	0.1101	0.1148	0.0979	0.0949	0.0098	0.0116	0.4846	0.6053
Drained	0.1043	0.2376	0.1440	0.1953	0.0095	0.0283	0.4281	1.5352

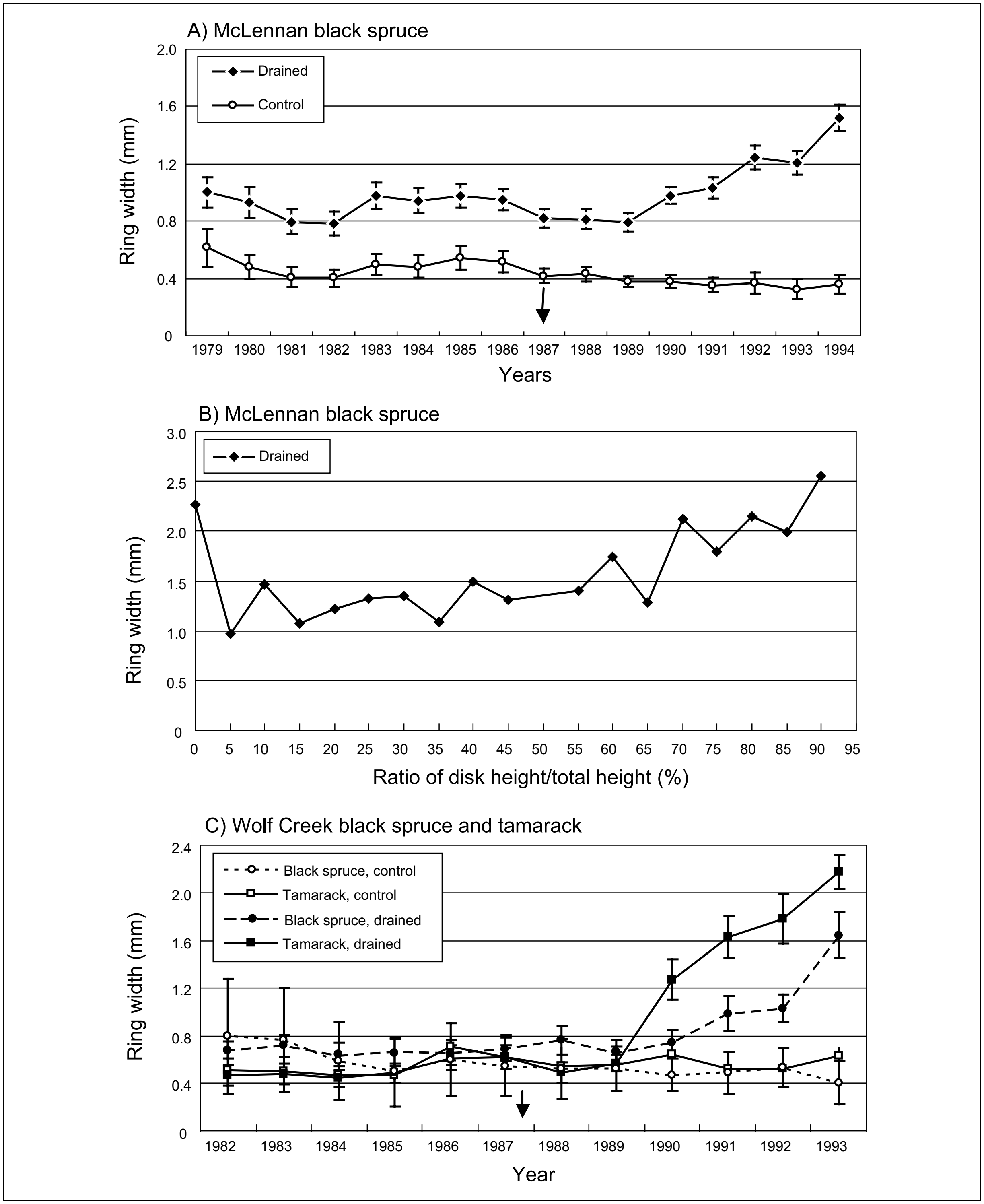

Figure 4. Growth response to drainage. (A) Ring width at breast height of black spruce at McLennan, before and after drainage (as mean and standard error). n = 15 in the control area and n = 23 in the drained area. The vertical arrow indicates time of ditching. **(B)** Mean ring widths in 1994 at different locations on the stems of 14 black spruce trees from the drained area at McLennan. **(C)** Ring width at breast height of black spruce and tamarack at Wolf Creek before and after drainage. n = 3 in the control area and n = 9 in the drained area for each species. The vertical arrow indicates time of ditching.

Tree Age and Response to Drainage

The ability of trees to respond positively to drainage is governed by age, among other factors. It is assumed that young, vigorous trees will respond better than older, mature trees. This seemed to be the case for black spruce at McLennan, where current-year (1994) height growth decreased from 36 cm in a 22-year-old tree to 12 cm in trees 88 years and older (Fig. 5). On the undrained control area, the 1994 height growth was consistently 3 cm or less regardless of age.

Ingrowth

Drainage had no effect ($p \geq 0.073$) on ingrowth (trees ≥ 1.1 cm dbh between the first and current measurement) diameter at Wolf Creek, but significant differences ($p \leq 0.0032$) in diameter between the drainage treatments and the control were detected at McLennan (Fig. 6A). There were also differences in diameter among the different ditch spacings. Overall, average ingrowth diameter was 1.9 and 2.4 cm for the control and drained areas, respectively. Diameter on the drained areas ranged from 1.2 to 1.4 times that on the control areas.

The average height of ingrowth was significantly greater on the drained area than on the control area ($p \leq 0.0004$), for both sites and for the two species (Fig. 6B). At Wolf Creek, ditch spacing had no effect on ingrowth height, whereas some differences were detected among ditch spacings at McLennan. Overall, average ingrowth height was 2.2 and 2.7 m for the control and drained areas, respectively. Height on the drained areas ranged from 1.1 to 1.4 times that on the control areas.

There was significantly greater basal area ($p \leq 0.0014$) for black spruce ingrowth on the drained areas at both locations and for tamarack ingrowth at McLennan than occurred on the control area (Fig. 6C). At Wolf Creek, the pattern of basal area was similar for both species, with no difference in basal area across the different ditch spacings. Some differences in basal area among ditch spacings were observed at McLennan, notably for black spruce, for which basal area on the 40- and 50-m spacings was 4.7 times that on the control. Although ingrowth diameter was relatively uniform across the treatments and species at the two sites (Fig. 6A), this was not the case for ingrowth basal area. At McLennan, average basal area of black spruce ingrowth was 3.4–8.7 times that of tamarack at both locations and that of black spruce at Wolf Creek.

The wide disparity in basal area per hectare of ingrowth can be attributed to the difference in ingrowth density across the different treatments at the two locations (Fig. 6D). The patterns of basal area and density of ingrowth were similar, indicating that sites with a greater number of ingrowth stems per hectare will produce a greater basal area per hectare than sites with fewer stems. At McLennan, ingrowth between 1988 and 1997 raised the stand density of black spruce to 4 860 and 5 260 stems•ha^{-1} on the control and drained areas, respectively. The stand density of tamarack increased to 435 and 1 078 stems•ha^{-1}, respectively. At Wolf Creek, the additional stems increased tamarack densities to 944 and 1 849 stems•ha^{-1} on the control and drained areas, respectively. Black spruce densities increased to 546 and 1 318 stems•ha^{-1}, respectively.

Regeneration

The number of stems < 1.1 cm dbh recorded for both species at the two locations during the final measurement session varied considerably (700–12 067 stems•ha^{-1}), with the dominant species at each location producing the greatest number of stems per hectare (Fig. 7). Tamarack regeneration at both locations and black spruce regeneration at Wolf Creek showed the same general trends detected for the other growth variables, i.e., production on the drained areas was greater than on the control areas. Thus, average regeneration on the drained areas was 2.2–3.0 times that on the controls. At McLennan, however, black spruce regeneration on the control area was 70% greater than on the drained area.

Noticeable differences in regeneration were also recorded between the perpendicular and parallel plots. On all tamarack plots (with the exception of tamarack on the area with 60-m spacing at McLennan) and on the black spruce plots at Wolf Creek, the ratio of regeneration on the perpendicular plots to regeneration on the parallel plots ranged from 1.2 to 6.6. At McLennan, the ratio for black spruce ranged from 0.7 to 0.9. Thus black spruce regeneration at McLennan was greater on the parallel plots for all ditch spacings. The standard errors for tamarack regeneration at Wolf Creek were large (Fig. 7), indicating that there was great variation among plots within a particular treatment.

Distance of Trees from the Nearest Ditch

Attempts to find significant correlations between distance of trees from the nearest ditch and the various growth variables using linear, log, polynomial, and exponential functions were generally unsuccessful. At McLennan, for example, the correlations of diameter increments versus distance from the nearest ditch for black spruce (Fig. 8A) were significant ($p < 0.01$), but the regressions accounted for only 0.9% to 28% of the variation. Similar regressions were run for tamarack, but the results were questionable, because of the small number of tamarack trees in the perpendicular plots.

At Wolf Creek, the best correlation for height increment of black spruce was obtained with a second-order polynomial for the 40-m spacing, where distance of trees from a ditch accounted for 13% of the variation (Fig. 8B). For the 30- and 50-m spacings, distance of trees from a ditch accounted for 3% and 6% of the variation, respectively. Polynomials derived for diameter increment of black spruce indicated that, on the 30-m spacing, 35% of the variation was associated with distance of trees from a ditch, whereas on the 40-and 50-m spacing, distance of trees from a ditch accounted for 4% and 10% of the variation, respectively.

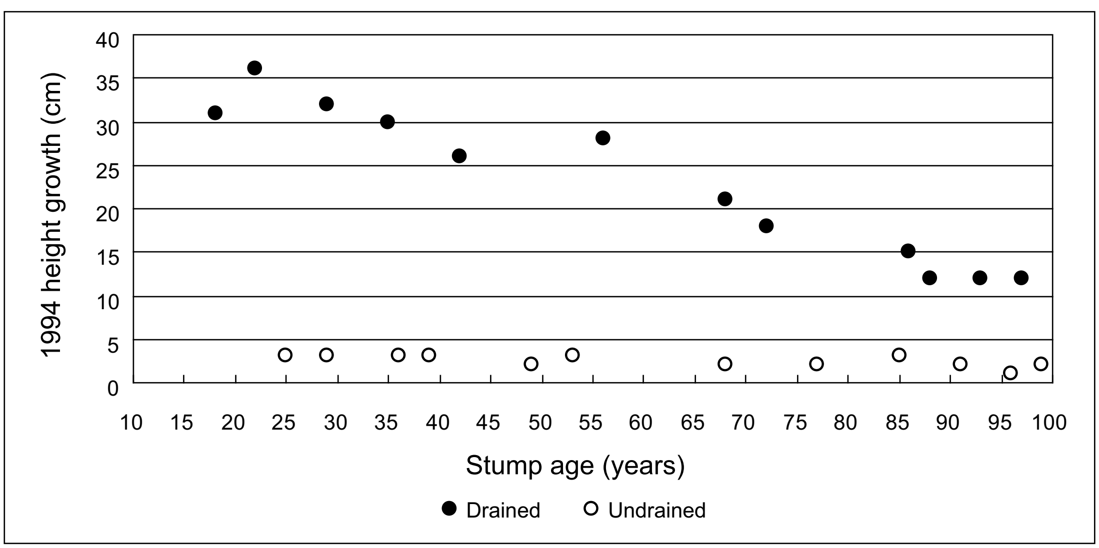

Figure 5. Current-year (1994) height growth of black spruce at McLennan, showing age response to drainage for 12 trees from the control area (undrained) and 12 trees from the 50-m spacing area (drained).

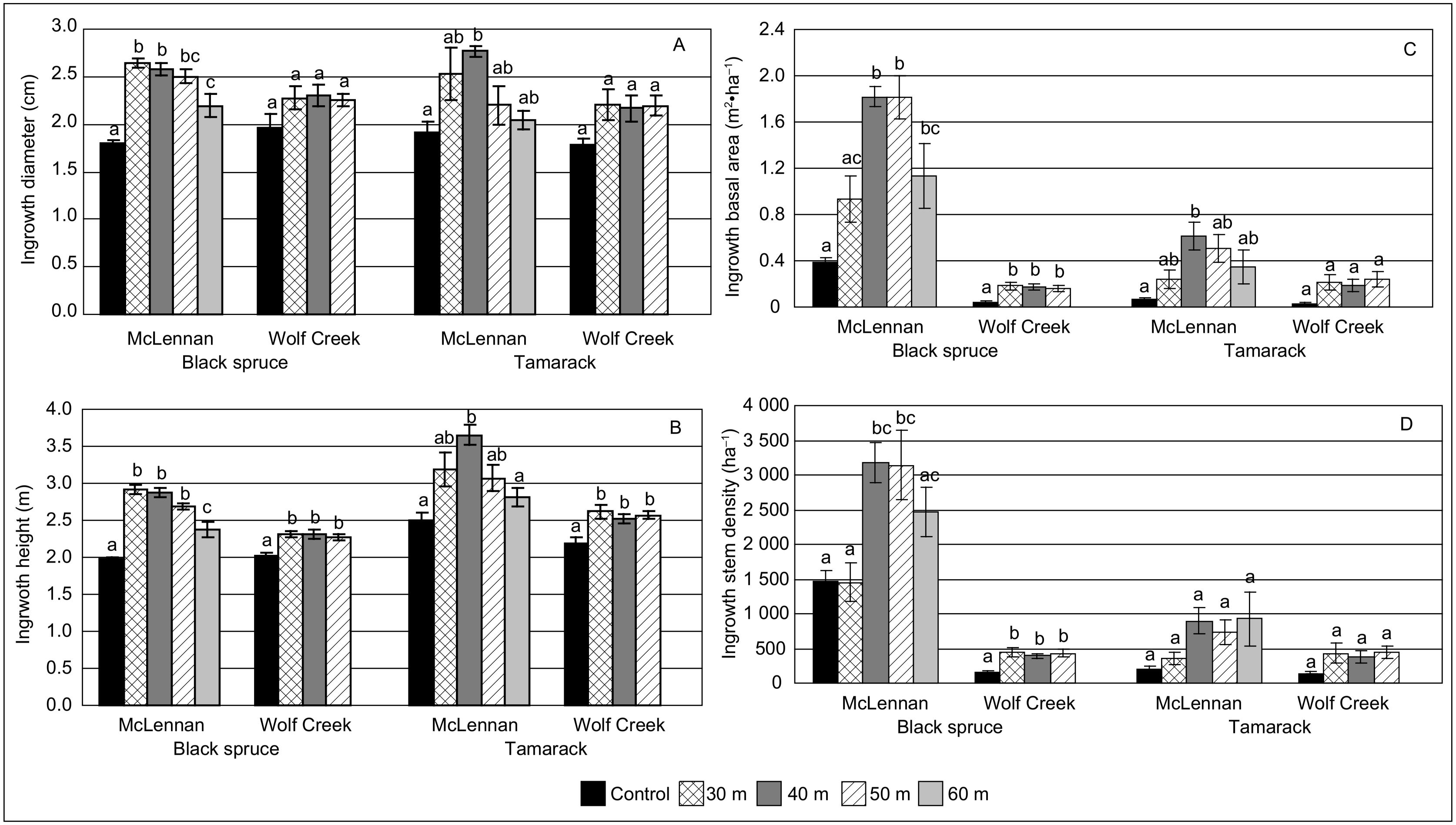

Figure 6. Diameter (A), height (B), basal area (C), and stem density (D) of black spruce and tamarack ingrowth (as mean and standard error). Ingrowth consists of stems (dbh ≥ 1.1 cm) that grew into the plots between 1988 and 1997 at McLennan and between 1986 and 1996 at Wolf Creek. Means identified with the same letter do not differ significantly at $\alpha = 0.05$.

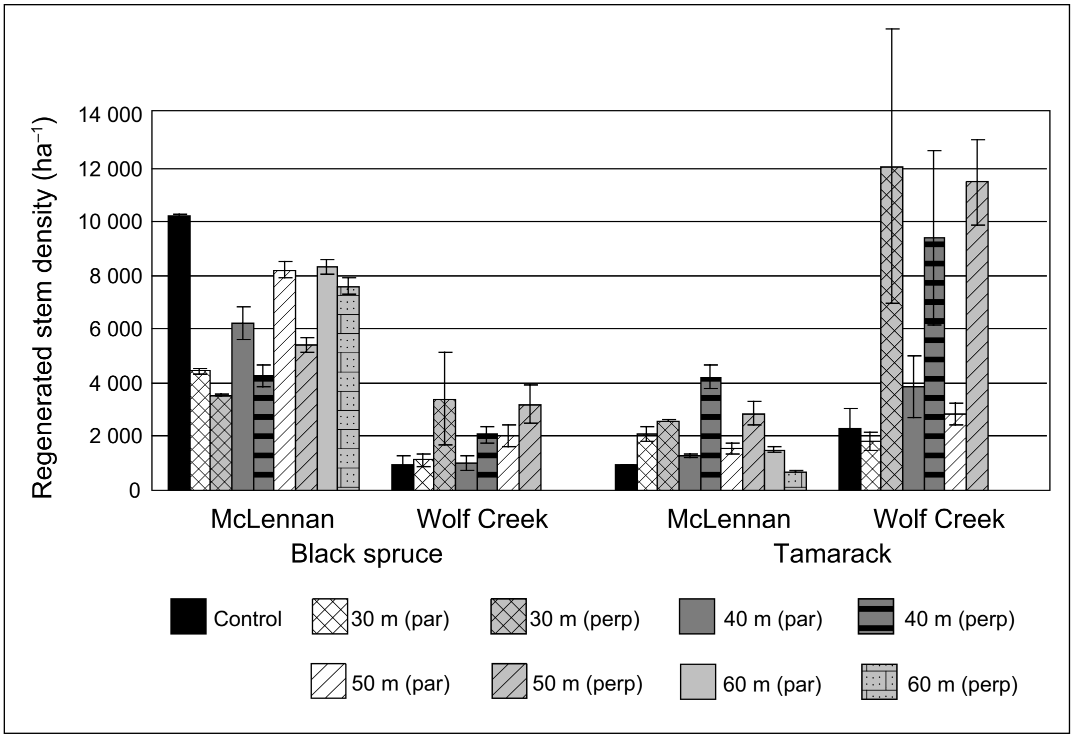

Figure 7. Black spruce and tamarack regeneration (stems with dbh < 1.1 cm) on 0.005-ha sample plots (as mean and standard error). Par = parallel plots, perp = perpendicular plots.

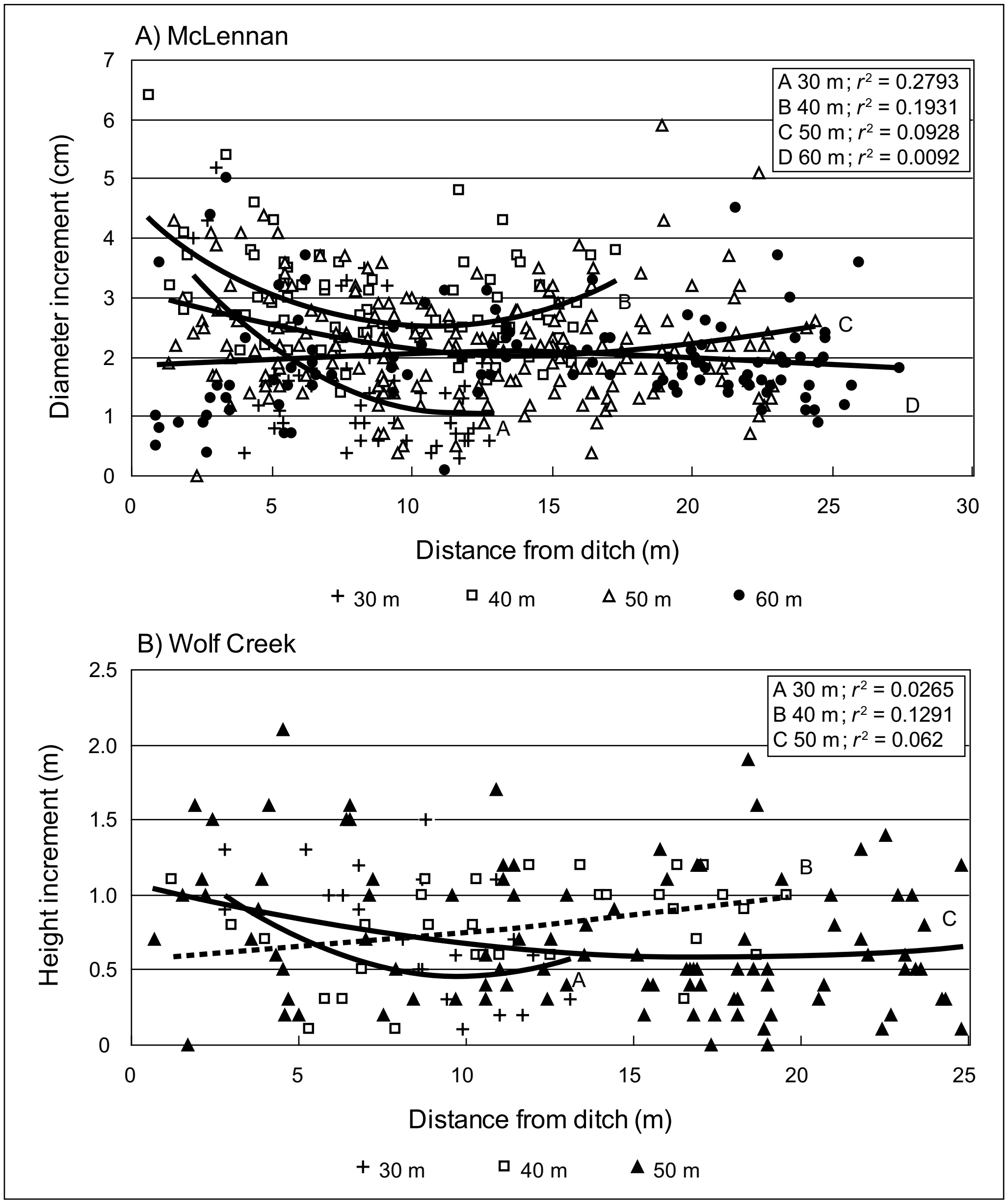

Figure 8. Black spruce diameter increment at McLennan (A) and black spruce height increment at Wolf Creek (B), as second-order polynomial functions of distance from the nearest ditch.

DISCUSSION

The results reported here show that, in black spruce and tamarack, diameter increments of up to 4.0 cm and height increments of up to 3.5 m can be achieved 9–10 years after treatment when peatland drainage is used as a means of promoting forest growth. Basal area of 4 $m^2 \bullet ha^{-1}$ and gross total volume exceeding 10 $m^3 \bullet ha^{-1}$ were attained for both species. Generally, tamarack tended to grow faster than black spruce. These results were compared with those of other Canadian peatland drainage studies. For this purpose, the results from all studies are summarized as periodic annual increments (Table 6). In some of the studies, the effects of fertilization were investigated as well. Table 6, however, records only data from drained and unfertilized plots. The growth periods for the studies shown ranged from 5 to 40 years.

Growth in diameter, height, and basal area for black spruce at McLennan and Wolf Creek compared favorably with growth observed in the other Canadian studies, but volume growth in the current study was 0.53 times or less than that recorded elsewhere (Table 6). Black spruce volume increases (per tree) in Alberta, however, can reach up to 28 times the predrainage volume, especially in very young trees (Wang and Micko 1985; Wang et al. 1985). Differences between results obtained at McLennan and Wolf Creek and those obtained in eastern Canada are to be expected because the climates of the two regions are different. In general, the trees in the eastern Canada studies were older and larger than those in the current study. Differences in stand densities may also be a contributing factor when comparing differences in growth in basal area or total volume.

Tamarack is not fully utilized by the forest industry in Canada, and consequently, growth data for this species are scarce; for tamarack on drained sites, available data are even more limited. Two studies, one in Quebec and one in Alberta, provide some information about tamarack growth on drained sites (Table 6). In an evaluation of different ditch spacings (20, 40, 60, and 80) on a tall-sedge and tamarack swamp near Québec City, conducted 5 years after ditching, Trottier (1991) found that the increases in diameter and height growth were proportional to drainage intensity. Increases in diameter ranged from 36% to 84%, and increases in height from 36% to 68%. The increase on the control plot was 15% and 10% for diameter and height, respectively. In Alberta, stem analyses of very young tamarack showed that per-tree volume increases 14–16 years after drainage may exceed 80 times the predrainage volume (Wang and Micko 1985).

Height and diameter growth of black spruce and tamarack in the current study were generally as good as or better than the corresponding growth of black spruce on a good upland, undrained site (Table 3). Basal area and total volume growth were better on the upland site. The greater stand density on the good site probably contributed to the greater values recorded there.

The increases in total volume growth for black spruce and tamarack reported in this study are considered to be primarily the result of increasing the depth of the soil aeration zone through drainage and, to a lesser extent, opening up the stand for the drainage ditches. The latter effect may become more important at narrower (10 to 20 m) ditch spacing, when even more trees would be removed to accommodate the ditches. Bella (1986) reported that cutting 7.3-m-wide seismic lines (for oil and gas exploration purposes) in Alberta resulted in increases in radial increment of 15% to 20% in white spruce (*Picea glauca* (Moench) Voss) and black spruce, within a distance of one-half dominant height from the stand edge after 10 years, where the dominant height is defined as the average height of trees with crowns extending above the general level of the canopy and receiving full light from above and partly from the sides. The improved tree growth was attributed to the greater availability of nutrients, moisture, space, and sunshine.

Other, indirect effects of drainage may contribute to increased growth rates of black spruce and tamarack. Lieffers and MacDonald (1990) reported that trees with greater depth to the water table had high concentrations of foliar nitrogen and sulfur and greater basal area increment. The improvement in nitrogen relations was associated with high rates of net carbon dioxide assimilation; together, these variables were positively correlated with leader growth (MacDonald and Lieffers 1990).

Although in this study there was a significant difference in tree growth between the control areas and the drained areas, no clear relationship was found between the growth variables and ditch spacing (Fig. 3). This may be attributed, in part, to the effects of low tree densities at some locations—notably on basal area and volume increments for the 50- and 60-m spacings at McLennan. Generally, the water table drawdown (or depth to water table) increases as the drainage density increases (i.e., closer ditch spacings), and better growth would be expected in trees on areas with narrow ditch spacing (e.g., Trottier 1991). At McLennan and Wolf Creek, most of the plots on the drained area run parallel to the ditches and are concentrated on lines running through the midpoints between ditches (Figs. 1 and 2). These locations are the farthest away from the ditches and therefore the least affected by drainage. Consequently, the effects on tree growth are likely to be minimal as well. Arguably, it would have been better to orient all plots perpendicular to the ditches.

Table 6. Periodic annual increments for black spruce and tamarack on drained areas, as reported in Canadian studies

Location	Diameter (cm•yr^{-1})	Height (m•yr^{-1})	Basal area (m^2•ha^{-1}•yr^{-1})	Volume (m^3•ha^{-1}•yr^{-1})	Reference
Black spruce					
Central Alberta	0.184	0.125	0.234	0.629	This report
Central Alberta	0.106	NA	NA	NA	Wang and Micko 1985
Southeastern					
Manitoba	0.093[a]	NA	NA	NA	Woons 1988
Northern Ontario					
Cochrane	0.345	0.095	NA	NA	Stanek 1968
Cochrane	0.109	0.115	0.279	1.198	Payandeh 1982
Iroquois Falls	0.146	0.104	0.219	1.830	Payandeh 1973
Wally Creek	0.078	0.137	NA	2.118	Sundström 1992
Wally Creek	0.111	0.114	NA	NA	Sundström and Jeglum 1992
Quebec (Valcartier)	0.220	0.080	NA	2.16	Stanek 1976
Tamarack					
Central Alberta	0.307	0.258	0.209	0.850	This report
Central Alberta	0.348	NA	NA	NA	Wang and Micko 1985
Quebec (Beauséjour forest)	0.540	0.435	NA	NA	Trottier 1991

Note: NA = not available.
[a]Diameter at 30-cm height.

In studies relating tree growth to distance from either a single agricultural or roadside ditch (Päivänen and Wells 1978; Trottier 1986) or multiple ditches (Trottier 1991), good correlations were reported, with tree growth rates reaching a maximum near a ditch and decreasing with distance from that ditch. At McLennan and Wolf Creek, however, with data from only the perpendicular plots, significant relationships between tree growth and distance of trees from the nearest ditch could not be established (Fig. 8). Therefore, it must be concluded that the water table drawdown on these drained sites was sufficient to create unsaturated aeration zones that facilitated equitable tree growth rates across the strips between the ditches. The water table at McLennan was lowered to an average depth of between 80 and 90 cm with all ditch spacings (Hillman 1992), whereas at Wolf Creek the average postdrainage depth ranged between 52 and 77 cm (Hillman 1996). Consequently, on average, there were no near-surface water table conditions anywhere between ditches such as existed before drainage. The main factor previously limiting tree growth—excess water—had been removed.

The difference between the two species in their response to drainage may be attributed to the difference in their growth habit: tamarack is a fast-growing species that can outgrow co-occurring evergreen conifers. There are a number of reasons for this rapid growth: tamarack is a deciduous species, which, unlike evergreen conifers, does not have to contend with winter desiccation; the specific leaf area (amount of leaf area constructed per unit leaf mass) is 2–3 times greater for larches than for evergreen conifers; and leaf nitrogen concentrations are generally greater for deciduous than for evergreen species. The greater specific leaf area and leaf nitrogen concentrations of larches relative to evergreen conifers are related to the greater net photosynthetic rates (weight basis) reported for larches (Gower et al. 1995). Rapid growth in tamarack can be achieved through drainage, but Wang et al. (1985) cautioned that too-rapid growth may be accompanied by decreases in relative wood density and tracheid length—conditions that may affect the end use of the trees.

The ring width and stem analyses of trees taken from McLennan and Wolf Creek confirmed that growth in diameter, height, basal area, and volume were greater after drainage than before. They also showed that black spruce and tamarack respond to drainage 3–4 years after treatment. In contrast, other researchers have reported no response to drainage 5–6 years after treatment (Dang and Lieffers 1989; Sundström 1992; Sundström and Jeglum 1992). In the first 6 years after drainage, Dang and Lieffers (1989) found no increase in tree ring growth of 33- to 107-year-old black spruce near Slave Lake, Alberta, but between 6 and 19 years after drainage the maximum net increase in tree ring growth ranged from 76% to 766% of projected tree ring growth if the sites had not been drained. The data from the current study indicate that, 6–7 years after drainage, ring width was increasing with time and showed no signs of leveling off (Figs. 4A, 4C). The results of Dang and Leiffers (1989) suggest that maximum ring growth at McLennan and Wolf Creek may be achieved by 2007.

The new diameter growth formed in 1994 in black spruce at McLennan was distributed unevenly along the stem, the widest rings occurring at the base and in the upper portion of the stem (Fig. 4B). Concentration of new growth at the base is understandable because the base of the tree must support an increasing mass of living, moving material above it—a mass that grows taller each year and that is subject to increasing wind sway. Thus, additional wood at the base provides a larger surface area to bear the weight and stresses of the tree. The increase in base size is presumably accompanied by an increase in root size, particularly since, after drainage, there is a greater opportunity for root system development.

The preferential allocation of growth to the upper portion of trees observed in this study has been reported for other forest drainage studies, in Alberta (Wang et al. 1985) and Ontario (Sundström and Jeglum 1992). In Alberta, this tendency was observed for tamarack, black spruce, and white spruce irrespective of drainage treatment (Wang et al. 1985). In his review of the relation between stem form and tree growth, Larson (1963) concluded that the width of a ring at various heights correlated with crown size and length of the branch-free boles. He also stated the general rule that favorable growth conditions tended to shift increment downward, such that trees developed more taper, whereas unfavorable conditions tended to shift increment upward, leading to a more cylindrical bole. On this basis, the greater average ring width observed higher up the stems of the sample trees at McLennan suggests that the trees were growing under unfavorable conditions. It is not clear, however, what unfavorable conditions might have been operating at McLennan after ditching.

The age of the stand must be factored into the selection criteria when deciding which peatlands are best suited for stand development through drainage. The height growth of black spruce in a single year (1994) at McLennan plotted against age (Fig. 5) showed that younger trees respond to drainage more vigorously than older ones. As mentioned earlier, Wang and his colleagues reported that, for black spruce and tamarack, the greatest growth response to drainage occurred in very young trees (Wang and Micko 1985; Wang et al. 1985). In northern Ontario, Payandeh (1973) also found that the greatest growth response to drainage occurred in younger black spruce trees, especially those growing on better sites and having larger crowns.

Ingrowth height and diameter for black spruce and tamarack were greater on the drained plots than on the control plots (Figs. 6A, 6B). The differences, however, were not as marked as the corresponding differences observed in the older trees (Figs. 3A, 3B). This suggests that young trees can initially adapt and grow well under adverse site conditions (i.e., the wetter conditions on the control site), but they eventually become suppressed as their developing root systems encounter increasingly anoxic soil conditions. In general, with the exception of basal area and density of black spruce ingrowth at McLennan, there were no discernible differences in growth response among the ditch spacings (Fig. 6). This lack of real differences tends to support the suggestion that the water table was lowered sufficiently to promote equitable tree growth rates across the strips between the ditches.

The noticeable difference in numbers between black spruce and tamarack regeneration at McLennan (Fig. 7) can be attributed, in part, to the difference in numbers of potential seed source trees growing on the McLennan peatland, where there are 10 times as many black spruce trees as there are tamarack (Table 1). Similarly, at Wolf Creek, where tamarack regeneration densities reached 12 000 stems•ha^{-1}, there are more tamarack trees with the potential to produce seed than black spruce trees.

Regeneration density varied considerably, depending on whether the plots were oriented parallel or perpendicular to the ditches (Fig. 7). With the exception of black spruce (all ditch spacings) and tamarack (60-m spacing) at McLennan, regeneration was greater on the perpendicular plots than on the parallel plots, particularly for tamarack at Wolf Creek. The parallel plots are located on the center lines between ditches, where the water table is nearest the ground surface. Perpendicular plots, in contrast, fall entirely within the first 10 m from the ditch edges—areas where the water table is lower than at the center between ditches and which are subjected to the greatest disturbance during ditching.

The greater abundance of regeneration in areas close to a ditch can be attributed to the deposition during ditch construction of spoil, material that provides a relatively good medium for seedling establishment and growth. At McLennan and Wolf Creek, the spoil piles usually consisted almost entirely of peat—a mixture of fibric, mesic, and humified peat that generally possesses better thermal and water-holding characteristics than the fibric peat that occurs naturally on the surface.

Changing conditions in the unsaturated zone after drainage may also be a factor. Rothwell et al. (1996) found that water content in the unsaturated zones on these sites and one other Alberta experimental drainage site was inversely related to the degree of lowering of the water table. Thus, water content was highest near the ditch edges, where water table drawdown was greatest. The high water content at the ditch edges coincided with the highest peat bulk densities and subsidence at these locations. Because subsidence is partly related to increased oxidation and decomposition of peat, with consequent release of nutrients, particularly nitrogen (Lieffers 1988; Laiho and Laine 1994), these locations are likely made more favorable for seedling establishment and growth.

Postdrainage peat temperatures may also promote greater regeneration near the ditches. Seasonal maximum temperatures at the 10-cm depth can be 3.5°C higher at 5 m from the ditch and 1.5°C higher at greater distances than those of undrained peat. This improvement, however, may be offset by later frosts in spring and early summer and lower winter temperatures on drained peat than on undrained peat (Prévost et al. 1997).

At McLennan, black spruce regeneration on the parallel plots was greater than on the perpendicular plots (Fig. 7)—the reverse of the result obtained for tamarack at Wolf Creek. The result at McLennan may be attributed in part to the parallel plots containing about 60% more older black spruce trees (seed sources) than the perpendicular plots. The rights-of-way cleared to allow machine access were 7 m wide at McLennan and only 5 m at Wolf Creek; therefore, more regenerated trees were removed from the McLennan site than from the Wolf Creek site. This factor also contributed to the lower regeneration count in the perpendicular plots than in the parallel plots.

At McLennan, regeneration of species other than black spruce and tamarack was observed on all 11 perpendicular plots but on only 1 parallel plot. Evidently, the spoil piles on the perpendicular plots provided the best seed beds for the establishment of these species. Aspen (*Populus tremuloides* Michx.) was the most common species observed (350–1 133 stems•ha^{-1}), followed by balsam poplar (*Populus balsamifera* L.; 133–667 stems•ha^{-1}), and white birch (*Betula papyrifera* Marsh.; 67–650 stems•ha^{-1}). At Wolf Creek, only two perpendicular plots in the 50-m spacing area contained species other than black spruce and tamarack. Densities of aspen, birch, and balsam poplar in one plot reached 640, 120, and 80 stems•ha^{-1}, respectively.

CONCLUSIONS

Peatland drainage at two central Alberta sites resulted in improved growth rates for black spruce and tamarack 9–10 years after treatment. Diameter, height, basal area, and gross total volume were greater on the drained plots than on the undrained control plots, and tamarack grew faster than black spruce. Generally, there were no clear differences among the various ditch spacings (30-, 40-, 50-, and 60-m), and correlation between the growth variables and distance of trees from a ditch was poor. This lack of differences in growth among different ditch spacings is contrary to the findings from other experimental drainage studies in Canada. It can be attributed to water table drawdown after drainage being low enough to create unsaturated zones that facilitated equitable tree growth across the strips between ditches. On the basis of these results, the widest spacing (50–60 m) should be used in future forest drainage projects on similar sites because the difference in volume growth on the widest and narrowest spacing was relatively slight, fewer trees need to be removed to accommodate ditch lines, operating costs are lower, and environmental disturbance is minimized.

Tree ring analyses revealed that increases in black spruce and tamarack growth could begin 3–4 years after drainage, earlier than reported in other studies. The regeneration rate of black spruce on the control area at McLennan and the size of ingrowth trees on the control area at both sites suggest that black spruce and tamarack can germinate and survive initially on wetter sites. High water tables, however, produce anoxic conditions that prevent tree root systems from developing properly, thereby inhibiting further development. A plot of black spruce height growth in a single year (1994) against age showed that younger trees responded more vigorously than older trees.

In the long term, it is important to maintain the integrity of the drainage ditch networks on the experimental areas at McLennan and Wolf Creek, especially given that plots on other experimental drainage areas in Alberta have been lost to fire (Saulteaux River study, near Slave Lake) and to flooding by beaver (Goose River study, near Valleyview). Several forest drainage studies have been initiated in Alberta, but none of them have provided long-term tree growth data. It is important to continue periodic measurement of the plots at McLennan and Wolf Creek so that long-term growth trends on drained areas can be determined and the financial feasibility of draining peatlands in Alberta properly ascertained. The costs of draining the Goose River, McLennan, and Wolf Creek experimental areas averaged $333/ha in 1987. If adequate tree growth data are obtained, it should be possible to determine whether draining peatlands for forestry could be incorporated into forest management planning or if it would be preferable to use the funds to develop forests on better upland sites.

The improved growth described in this report was the result of drainage only. Small substudies at Goose River (Mugasha et al. 1991; Hillman and Takyi 1998) and Wolf Creek (Mugasha et al. 1993) have shown that further growth benefits accrue when fertilization and thinning treatments are applied to drained areas. These treatments, of course, entail further costs. Special planning is required for harvesting machines to negotiate the intricate network of ditches, to remove the trees, and to maintain the integrity of the drained sites. The effects of water discharge from the ditches into lakes and streams must also be properly evaluated. Much of the information related to these issues can be obtained from Finnish sources (e.g., Heikurainen 1964, Päivänen, 1984, Laine et al. 1995). In Finland, where wet sites predominate, the forest industry has successfully incorporated drainage, fertilization, and thinning practices into forest management planning, which has enabled the industry to achieve a high level of productivity.

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