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Density Management of Black Spruce on Highly Productive Sites: 9th-Year Results and Implications of Precommercial Thinning

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This file report is an unedited, unpublished report submitted as partial fulfilment of NODA/NFP Project #4048, "Management of black spruce on highly productive sites".

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Density Management of Black Spruce on Highly Productive Sites:

9th-Year Results and Implications of Precommercial Thinning.

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Abstract

Precommercial thinning is commonly viewed as a means of increasing growth rates of individual trees to alleviate medium-term shortfalls in future wood supply. In fall 1985, a precommercial thinning experiment involving cleaning and four levels of black spruce basal area removal (0, 20, 40 and 60%) was established in a dense (6,000 stems ha^{-1}), 24-year-old black spruce plantation on a highly productive site near Beardmore, Ontario. After 9 years, total and merchantable net black spruce stand volume and total net stand volume increment were greatest in the cleaned control, and lowest in the 60% basal area removal treatment. In contrast, there was relatively little treatment response in quadratic mean diameter. Black spruce stand density management diagrams (SDMD) (Newton and Weetman 1994) usually provided better estimates of stand volumes and 9-year stand growth than preliminary variable density yield tables for this species. Projected black spruce net merchantable yields at the physical rotation age (55 years), based on the SDMD, were greater in the cleaned control than in any of the precommercial thinning treatments, while treatment differences in quadratic mean diameter at rotation age were <1 cm. The cost/benefit of precommercial thinning black spruce on highly productive sites should be carefully examined before large programs are undertaken. Silvicultural alternatives to increase merchantable biomass and the production of sawlogs are discussed in terms of stand treatments and species selection.

Introduction

Over the past 20 years harvesting levels and reforestation efforts in Ontario have increased dramatically (Kuhnke 1989, Anon 1996); in 1990, more than 100,000 ha of cutover lands in the province were artificially regenerated by planting and direct seeding (Ghebremichael 1993). There is now a strong impetus to develop site-specific management prescriptions for these developing stands, based on their composition and structure, their response to silvicultural manipulation and broader forest level objectives (Willcocks et al. 1990). One area of particular interest is the use of thinning on more productive sites. In northern Ontario, it is widely hoped that thinning can redress impending wood shortages and saw-timber deficits anticipated in the next 30 years (Willcocks et al. 1990, Atherton 1991).

Precommercial thinning is designed to increase economic yields by concentrating growth on healthy trees and minimizing merchantable volume losses through mortality. Thinning promotes individual tree growth, and as result stands reach merchantable size earlier (Sjolte-Jørgensen 1967). Such stands may produce greater merchantable volumes over short time periods, particularly of higher value-added wood products such as sawlogs (Reed 1991). Earlier suggestions, however, that thinning could also increase total volume production have been refuted, and it is now commonly accepted that thinning may result in some loss of total volume production (Sjolte-Jørgensen 1967, Assmann 1970, Smith

1986). Thinning also increases physical rotation ages (age to maximum mean annual increment and decreases immediate stand volume production, often at a time when stands are most vigorous (cf. Pienaar and Turnbull 1973).

It has also been suggested that, in the boreal forest, thinning might increase total volume increment by improving edaphic conditions. Increased light penetration and reduced canopy interception losses could result in higher growing-season soil temperatures, longer active growing seasons and improved soil water availability (Roberge et al. 1968, Timmer and Weetman 1968, Piene 1978, Van Cleve et al. 1986). This could result in increased soil microbial activity, organic matter decomposition and mineralization rates, foliar nutrient concentrations and hence growth (Weetman 1971, cf. Yarie and Van Cleve 1996). Other factors related to precommercial thinning may, however, counteract many of these effects. Addition of logging slash with high C/N ratios, together with increased drying of surface organic horizons and reduction in feather moss nutrient contents may reduce decomposition rates and N mineralization (Roberge et al. 1968).

Black spruce (Picea marianai [Mill.] B.S.P.) Is the most widely used species for reforestation in northern Ontario, and accounts for over half of the seedlings planted in the province each year (Anon 1991). In natural forests, it typically grows in dense stands of wildfire origin, with normal stocking varying from 2,000 to 3,000 stems ha^{-1} for mature stands on site class I (Plonski 1974). Its narrow, cylindrical crown shape and foliage characteristics make this species well adapted to close spacing and high growing space efficiency (Armson 1975, Van Damme and Parker 1987).

A few older examples of precommercial thinning peatland black spruce exist (Steneker 1969, Whynot and Penner 1990, Erickson 1994, Burns et al. 1996), and recently precommercial thinning experiments in dense, natural upland black spruce stands have been established in Newfoundland (Lavigne et al. 1987, Newton 1988, Karsh et al. 1994) However, while it is suspected that the greatest gains may be realized by thinning this species at an early age on highly productive sites, few rigorous studies have been done under such conditions (Newton and Weetman 1994, cf. McClain et al. 1994). This information is needed to design forest-level crop plans, site-specific stand-level management guidelines, and for economic analyses of forest investment opportunities.

In 1985, we established a precommercial thinning experiment in a dense 23-year-old black spruce plantation as part of a broader investigation of stand response on highly productive sites north of Beardmore, Ontario. The purpose of this report is threefold: to provide information on stand history, site conditions, experimental design and sampling methods pertinent to these studies; 2) to report nine-year black spruce stand level responses to cleaning and different levels of precommercial thinning; and 3) to discuss these results in terms of density management concepts, yield projections and implications for future stand development.

Methods and Materials

Experimental Location

The experimental plots are located within a 210 ha plantation in Meader Township, 15 km north of Beardmore, Ontario (49°37' N, 88°15' W) and 2 km south of Tyrol Lake, at an elevation of 350 m (Fig. 1). This area lies on the border of the Nipigon (B.10) and Central Plateau (B.8) Forest Sections within the Boreal Forest Region (Rowe 1972). The bedrock-controlled topography is rolling with cobbly, coarse loamy ablation till overlying granitic Precambrian (Archaean) bedrock of the Keewatin formation. The area was last glaciated 8,000-10,000 years ago, and, in general, the lithology of the till reflects the composition of the bedrock in the vicinity (Zoltai 1965). The drainage pattern is irregular, and Soil Moisture Regimes (Ontario Institute of Pedology 1985) on the upland sites generally vary from moderately fresh to moist.

The climate of the study area is microthermal and humid, and is characterized by short, warm summers and long, cold winters. Mean daily maxima and minima for July and January are 23 and 11 °C, and -11 and -23 °C, respectively. The mean annual length of the growing season is 155 days and the mean annual frost-free period is 80 days. Mean annual precipitation is 740 mm, while mean growing season (May-September) precipitation is 410 mm (Chapman and Thomas 1968).

Stand History

From the mid 1940s to the early 1950s many of the highly-productive mixed forests occupying the Namewaminekan River basin north of Beardmore, including the study area, were selectively logged (high-graded) for spruce sawlogs and white birch veneer logs. Stand composition at that time consisted of a mixture of white (Picea glauca (Moench) Voss.), and black spruce, jack pine (Pinus banksiana Lamb.) balsam fir (Abies balsamea [L.] Mill.), white birch (Betula papyrifera Marsh) and trembling aspen (Populus tremuloides Michx.) which originated from a large wildfire 120 years before. A large spruce budworm (Choristoneura fumiferana (Chem.)) outbreak in the 1940s (Elliot 1960) had caused extensive mortality to the balsam fir component and substantial damage to the spruce component of these stands prior to logging.

In July and August, 1956, a large portion of these partially cut and insect damaged areas were burned in the 20,000 ha Tyrol Lake wildfire. Following wildfire, salvage operations were conducted to remove the merchantable timber remaining. From the late 1950s to the mid 1960s, extensive tracts of conifers were planted in this area under the supervision of George Marek of the Ontario Department of Lands and Forests. By 1968, over 20,000 ha of black and white spruce, and jack, red and white pine stands, at various spacings and with different species combinations, had been established.

The black spruce stands used for the present study were part of a 210 ha plantation established on burned-over land dominated by bracken fern (Pteridium aquilinum (L.)

Kuhn), beaked hazel (Corylus cornuta Marsh.) and trembling aspen. In 1962, 416,000 2+2 bare root black spruce stock and 58,000 2+1 bare root jack pine stock were planted between May 14 and June 11 at nominal 1.5 x 1.5 m to 1.8 x 1.8 m spacing. In late summer of 1962, a grasshopper infestation caused extensive damage, and many of the seedlings were completely defoliated. As a result, large portions of the plantation were replanted with 2+2 black spruce stock, 2+2 white spruce stock, or 2+1 jack pine stock in May, 1963, at similar spacings, between the rows of defoliated seedlings planted the previous year. Subsequent survival and growth of both plantings were good. The developing stands were subsequently hand cleaned to remove competing hardwoods in 1965,1972 and 1976, and aerially sprayed with 2,4 D (3.4 kg ha^{-1}) to kill trembling aspen in 1979 (see Karsh (1986) for further details).

This combination of treatments resulted in very dense, even-aged and relatively evenly-spaced black spruce dominated-stands on highly productive, loamy upland sites. Gordon and Morrow (1979) described an adjacent vigorous black spruce stand planted in fall 1961 at 1.8 x 1.5 m spacing that attained a height of 5.2 m and a basal area of 9.4 m^3 ha^{-1} 17 years after planting.

From the late 1940s to the early 1980s, spruce budworm populations remained at endemic levels in the Lake Nipigon region (Thompson et al. 1988). The mid 1980's, however, marked the beginning of a large spruce budworm infestation, which moved eastward from Poshkokagan Lake in Thunder Bay district to Lake Nipigon. Moderate budworm defoliation was recorded on white spruce and balsam fir in the Tyrol Lake area from 1985 to 1989, with severe defoliation from 1990 to 1994 (G. M. Howse, Canadian Forest Service, Sault Ste. Marie, unpublished data). During this period black spruce in the study plantation were also heavily attacked. The epidemic collapsed in 1995 (Biggs et al. 1996).

Experimental Design

In fall 1985, 21 25x25 m plots were set out in areas planted solely to black spruce with relative uniform stand cover and site conditions within the plantation (Fig. 2). A randomized design was used involving four replicates of each of four treatments: cleaning plus removal of 0, 20, 40 or 60% of the existing black spruce basal area per plot. In addition, three uncleaned control plots and two cleaned control plots in more widely-spaced stands were also set out[1]. This approach provided a range of residual black spruce basal areas for examining tree and stand response. The high densities (3400-8900 stems ha^{-1}) and uniform spacing of black spruce at the time the experiment was established permitted examination of a range of spacing treatments and the possibility of growth reductions in very dense stands.

Cleaning was carried out in the 18 plots in late September, 1985 to remove competing trees of other species (largely trembling aspen, with some white birch and a few jack pine "wolf trees"). Larger trees (>5 cm ground level diameter) were girdled 1.0-1.5 m above

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[1]Plots were also established at this time in inter-planted black spruce-jack pine and pure jack pine stands to examine the comparative growth, development, productivity and stand structure of combinations of the two species (Karsh 1986). These plots were also remeasured in 1994, but results are reported elsewhere.

ground level with axes or brush hooks, while smaller stems were cut at ground level with a brush saw. In the thinned plots, a combination of geometric and low thinning was conducted (Smith 1986), using brush saws and axes. Priority was given to the removal of trees which had broken or damaged crowns, were diseased or suppressed, or were of small diameter, while at the same time maintaining fairly uniform spacing of the remaining trees. All felled stems and branches were left in-situ. In fall 1994, three additional unthinned and uncleaned permanent plots were established in similar conditions.

Each plot consists of a 15 x 15 m study block in which all trees were tagged and measured for diameter at breast height (dbh - 1.37 m above ground), and a 5 m surround on all sides of the plot, which was cleaned and thinned to the same basal area, but not measured. At this time, total heights of all tagged trees in the thinned plots and of every second tree in the control plots were measured to the nearest 0.1 m using telescoping height poles.

Soil pits were dug to a depth of 1 m in each plot to examine pedological characteristics including soil horizon type, thickness, texture and structure, humus form, rooting and total soil depth, Soil Moisture Regime, Soil Great Group (Canada Soil Survey Committee 1978) and NWO FEC soil type (Sims et al. 1990). Additional soil and foliar samples were collected to examine nutrient status and tree response, but will be reported elsewhere. Similarly, percent cover and temporal change of lesser vegetation and surface conditions were recorded in 15 permanent 1 x 2 m quadrats per plot, but are not discussed here.

Plots were remeasured in fall, 1994. This involved dbh measurements of all trees, height measurements of every second tree in the thinned plots and every fourth tree in the control plots, as well as determination of percent cover of lesser vegetation, nutrient analysis of tree foliage, and measurement of overstorey leaf area index with a LAI-2000 Plant Canopy Analyzer (LI-COR, inc., Lincoln, Nebraska). and understorey light levels with a Sunfleck Ceptometer (Decagon Devices Inc., Pullman, WA).

Data Analysis

Height-diameter curves were developed using all trees for which both height and diameter were measured at a given time, according to:

$$H=1.37+a(1-\exp^{-bD})^{c}$$

where H is tree height, D is tree diameter breast height outside bark and a, b and c are estimated parameters. Equations of the form

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$$H=1.37+(a+a_{z}Z)(1-\exp^{-(b+b_{z}Z)D})^{(c+c_{z}Z)}$$

were used to examine whether height-diameter relationships determined with equation 1 were significantly different for the various treatments or years of measurement. Equation 2 represents eq. 1 with indicator variables (Draper and Smith 1981, Fleming and Piene 1992) added to distinguish between treatments or measurement years (e.g., in each comparison Z=0 for one group of treatments or one measurement year, and Z=1 for the other). The coefficients a_z, b_z and c_z estimate the differences between groupings in their estimated parameters (a, b and c in eq.1). For a given measurement year, the plots were divided into four thinning levels.

This analysis indicated that height-diameter relationships were similar (i.e., a_z, b_z and c_z were not significantly different ($p \geq 0.10$) from zero) for different density groupings in both 1985 and 1994, but that differences exited between the two measurement years (i.e., a_z and b_z were greater than and less than ($p<0.05$) zero, respectively). Thus a separate height-diameter equation was used for the 1985 and 1994 measurements, but in each case was applied to all plots regardless of tree density (Table 1).

Net total and merchantable stand volumes (living trees at the time of measurement) for black spruce and where appropriate, all species combined, were determined by summing stem volumes of individual trees on a plot basis, calculated using equations and appropriate parameter values provided by Honer et al. (1983)(eq. 14 and 22). Merchantable volume was calculated using the adjusted squared diameter ratio method, assuming a minimum merchantable top diameter of 4 cm and a stump height of 15 cm.

Four relative size-density indices were also calculated: mean stand volume-density (P_{rV})(Weller 1987), mean tree volume-density (P_{rv})(Drew and Flewelling 1979, Newton and Weetman 1993), quadratic mean diameter-density (P_{rD}) (Reineke 1933, Day 1985), and dominant height-density (Spacing Factor-*SF*)(Wilson 1979, Day 1985). For these relative density measures, size-density relationships for self-thinning stands (Drew and Flewelling 1977) were first derived using only the 1994 data for the cleaned control plots (n=6). For volume-density calculations, data were fitted to the following equation using linear regression:

$$\log V = \beta \log N + \log K$$

Results indicated *V* and *N* were strongly negatively correlated (r=-0.912; p=0.011) with a thinning exponent of -0.3575. Transforming this equation gives:

$$V = 10^{3.566} N^{-0.357}$$

These parameter estimates were then transformed to a mean tree volume (dm^3) - density (stems ha^{-1}) basis, giving:

$$v = 10^{6.566} N^{-1.357}$$

Fitting *V* rather than *v* follows the suggestion of Weller (1987). In contrast to Mohler et al. (1978) and Weller (1987), however, we fitted this relationship using linear regression rather than Principal Components Analysis. All trees were sequentially numbered and tagged in 1985, and thus there was little error in estimating *N* in 1994. In contrast, the error in the estimation of V was likely an order of magnitude larger because of errors associated with measurement of D, measurement or estimation of H, and estimation of v from dbh and H. Use of Principal Components Analysis to determine these relationships assumes residual variances are equal for N and v, and would likely produce greater relative errors than assuming N was known without error.

Quadratic mean diameter-density relationships were determined by multiple regression using:

$$LogD = \beta \log N + \log K$$

This is consistent with the stand density index of Reineke (1933). Results showed that D and N were strongly negatively correlated (r=-0.994) with a thinning exponent of -0.553 (s.e.± 0.0310). Transforming this equation yields:

$$D = 10^{3.033} N^{-0.553}$$

Using the above formulae, relative size-density indices (P_r) were then calculated for each plot as N_0 / N where N_0 is the actual plot density and N is determined by rearranging the above equations. For the density indices above, this yields:

$$P_{rV} = N_0 / (10^{9.961} * V^{-2.797})$$

for total volume (m^3 ha $^{-1}$),

$$P_{rv}=N_0/(10^{4.839}*v^{-0.737})$$

for individual tree volume (dm^3), and

$$P_{rD}=N_0/(10^{5.484}*D^{-1.808})$$

for quadratic mean diameter (cm).

Spacing factors (*SF*) were calculated as:

$$SF=\sqrt{(10,000/N)}*H_d^{-1}*100$$

where H_d is the mean height of dominant trees. This assumes square spacing among trees.

To examine mortality, P_{rV}, P_{rv}, P_{rD} and *SF* were calculated separately for the 1985 and 1994 data sets and then averaged to provide arithmetic mean values (1985-1994) per plot. This approach implies mortality is a linear function of relative density. In reality, two contrasting processes are probably involved: mortality is likely an exponential function of relative density once some threshold is reached, but current competition-related mortality likely reflects antecedent conditions because tree suppression and death reflect cumulative effects of environmental conditions occurring over substantial periods before mortality actually takes place. Similar reasoning led us to use arithmetic mean values of stand volume, basal area, and tree density when examining relationships with mortality.

Growth and yield responses were analysed using Pearson Product-Moment correlations, analysis of variance (ANOVA), analysis of covariance (ANCOVA) (Wood 1962, McWilliams and Burk 1994) and linear and nonlinear regression techniques (Smith 1959) employing NCSS 6.0 software (Hintze 1995). Orthogonal linear, quadratic and cubic contrasts, as well as Scheffe's and Tukey-Kramer multiple comparison tests, were used to identify trends and differences among individual treatments if ANOVA F-ratios were significant ($p<0.10$). Thinning results and growth and yield projections were also interpreted using the stand density management diagram (SDMD) of Newton and Weetman (1994), the variable density yield tables (VDYT) of Bell et al. (1990), and normal yield tables (Plonski 1974).

Results and Discussion

Soil Characteristics

Soils of the study area are Dystric Brunisols with Ae and Bfj horizons, with the exception of plot 8 which was a Eutric Brunisol with humic accumulations in the B horizon (Btj) (Canada Soil Survey Committee 1978). Soil depths almost always exceeded 1 m; the shallowest soils found in the plots were 75 cm deep (Table 2). Active rooting depths were usually 60-80 cm. Coarse fragments, including gravel, cobbles and some boulders, occupied 10-40% of the mineral soil. Forest humus forms (Ontario Institute of Pedology 1985) were largely fibrimors with some humifibrimors also present. All plots, with the exception of plot 20 (mottles at 42 cm, Soil Moisture Regime 5, NWO FEC S9), were well drained and fell within Soil Moisture Regime 2 and NWO FEC soil types S3 and S4.

Mean values of soil pH, CEC and the concentrations of various nutrients (Table 3) were generally similar to or somewhat higher than those reported for shallow-soiled coarse loamy ablation tills in the Nipigon region (Morrison et al. 1976, Jeglum 1980, Foster and Morrison 1987).

Pre-thinning Stand Conditions

In 1985, before thinning, stand densities averaged 6,100 living black spruce per hectare and 6,900 living stems of all species per hectare. Corresponding basal areas were 19.3 m^2 ha^{-1} for black spruce and 25.2 m^2 ha^{-1} for all species combined, while the mean black spruce height was 7.9 m. Thus at age 23 these stands were still about twice as dense as most black spruce plantations at the time of establishment. Black spruce stand densities, basal areas and heights were comparable to those in normally stocked, natural spruce stands at a similar age on Site Class 1a (Plonski 1974).

Size-Density Relationships in the Control Plots

After crown closure and the onset of vigorous intra-specific competition, pure even-aged stands tend to follow an asymptotic self-thinning trajectory along a maximum size-density line (Yoda et al. 1963, Drew and Flewelling 1977). The strong and statistically significant ($p<0.05$) relationships found for the stand volume-density (adj. $R^2 = 0.788$), mean tree diameter-density (adj. $R^2 = 0.977$) and, to a lesser extent, height-density relationships (adj. $R^2 = 0.563$, $p=0.0526$) for the control plots in 1994 (Fig. 3), together with the marked positive skewness in diameter distributions of dead stems in these plots (Fig. 4), suggest that size-related, density-dependent self-thinning was taking place in a consistent, predictable manner (Weiner and Thomas 1986, Newton and Smith 1990). The slopes (β values) of the asymptotic size-density trajectories determined for these plots were not significantly different ($p \geq 0.05$) than those widely proposed, on theoretical or empirical grounds, for the maximum size-density trajectories for forest stands (-0.50 for stand volume-density (Weller 1987) and -0.60 for mean diameter-density (Drew and Flewelling 1977)). Weller (1987) found that with temperate gymnosperms, more tolerant species had higher (shallower) thinning slopes. Our slope for black spruce and that reported by Mohler et al. (1978) for balsam fir (β=-0.28 to -0.30) are consistent with this.

The *V-N* β value calculated for our stands was, however, somewhat lower ($p<0.05$) than that reported for black spruce by Newton and Smith (1990)(-0.618) and Weller (1987) (-0.83, using Hatcher's (1963) data). This may reflect variation due to differences in locality, age, site quality or genetics (Weller 1987, Zeide 1991), or simply the limited data bases used. As well, Hatcher's (1963) data are for all species in black-spruce dominated stands, but include only stems > 1.5 cm dbh; 15-45% of the volume of these stands consisted of white birch, and the number of conifer stems < 1.5 cm dbh (i.e., those excluded from analysis) was often comparable to the number of conifer stems > 1.5 cm.

The results of these studies, however, contrast sharply with those of Carleton and Wannamaker (1987). The latter reported maximum within-stand volume-density exponents of -2.89 to -1.14, and an among-stand, stand volume-density thinning exponent of 0.036 (i.e., non-compliance with the self-thinning rule) for even-aged black spruce fire-origin stands between the ages of 30 and 50 years

Mortality

1985-1994 black spruce mortality averaged 5.2% for the 21 plots for which data was available. Mortality was greater (MSE=13.921, F-ratio=16.3, p=<0.001, arcsin transformed data) in the control plots than in thinned plots, and in the cleaned control plots than in the uncleaned control plots (Fig. 5). There was, however, no significant difference in mortality among the three different thinning levels.

These results reflect the effects of cleaning and low thinning on subsequent stand development. Greater black spruce mortality in the cleaned control plots than in the undisturbed control plots largely reflected damage from falling hardwood stems which had been girdled and subsequently died. Low thinning from below not only improved resource availability, thus decreasing competition among the remaining trees, but selectively removed the most decadent and suppressed trees (i.e., those most predisposed to mortality). Windfall was not a major factor in tree mortality as evidenced by the low rates of mortality in the thinned plots. There was also no evidence of mortality that could be directly attributed to repeated defoliation by spruce budworm.

There were strong linear or piecewise-linear associations ($p<0.05$) between mortality and various measures of average (1985-1994) stand-level stocking, including total volume (V_{TAve}), basal area (BA_{Ave}), tree density (N_{Ave}) and various relative size-density relationships (P_{rVAve}, P_{rvAve}, P_{rDAve} and SF_{Ave})(Table 4). Second-order polynomials did not improve the fit (i.e., result in a substantially higher R^2 or lower mean square error) of these relationships over the linear and piecewise-linear results reported. Relationships were stronger between mortality and relative size-density indices than between mortality and simple measures of stocking (i.e., V_{TAve}, BA_{Ave} and N_{Ave}). With size-density indices, mortality per unit area (stems ha^{-1} yr^{-1}) often provided slightly stronger relationships than percent mortality (% yr^{-1}). Overall, the strongest relationships between relative stocking level and mortality were provided by P_{rvAve} and P_{rDAve} (Fig. 6).

During 1984 surveys of the Tyrol Lake stands (tree age 27 years), stem counts suggested mean black spruce density-related mortality rates (i.e., excluding uprooted trees) of about 3.5%, most of which likely occurred in the previous 10 years. These estimates, together with the 1985-1994 data for the control plots, indicate black spruce mortality rates of ~15% over the first 37 years in unthinned plots on these highly productive sites. In contrast, Carleton and Wannamaker (1987) found no evidence of black spruce mortality in stands < 30 years old This may reflect differences in growth rates and thus the onset of competition-related mortality on different site types.

The strong piecewise-linear relationships found between $P_{rDAve,}$ P_{rVAve} and $P_{rvAve,}$ and mortality attest to the existence of a threshold P_r (lower limit of the zone of imminent competition-mortality (Drew and Flewelling 1979)) above which self-thinning becomes increasingly important. These piecewise-linear functions also provide a ready means for determining the location of this zone. Threshold values for density-dependent mortality, interpreted as the inflection point in these piecewise-linear relationships, were: BA_{Ave}, 26 m^2 ha^{-1}; $P_{rvAve,}$ 0.67; P_{rDAve} 0.70; and SF_{Ave}, 17.0%. The threshold value for P_{rv} considerably exceeded that derived by Newton and Weetman (1993)(P_{rv} = 0.50) for natural black spruce stands with clumped spacing.

Tree Height

Mean heights of dominant and codominant black spruce were 8.69 m (±0.392 s.d.) in 1985 (H_{DAve}) and 10.88 m (±0.588 s.d.) in 1994 (H_{DAve}). These values place the stands very close to average heights given by Plonski (1974) for Black Spruce Site Class 1A natural stands at corresponding ages of 28 and 37 years, respectively (the trees were 4 years old at the time of planting). The 1986-1994 periodic annual height increment of dominant and codominant trees (H_{DAve}) (24.3 cm) was, however, 10-15% less than that ascribed to this site class by Plonski (1974). We attribute this to defoliation by spruce budworm. Spruce budworm preferentially feed on flowers, vegetative buds and new shoots in the upper crowns of black spruce, and can cause large reductions in shoot elongation (Schooley 1980) and radial increment in the upper stem (Mott et al. 1957).

H_{Dincr} was negatively correlated with 1985 hardwood basal area (R=-0.601, p=0.008), but showed little relationship to any of the stand-level stocking measures, including P_{rvAve} (R=0.034), P_{rDAve} (R=0.013), SF_{Ave} (R=0.112), and BA_{85} (R=0.096) or BA_{94} (R=0.102). Similarly, ANCOVA of H_{Dincr}, using H_{D85} as a covariant, showed no significant differences (F=0.25, p=0.859) among thinning intensities. As with many species (Sjolte-Jørgensen 1967, Lanner 1985), but unlike lodgepole pine (Cieszewski and Bella 1993) and perhaps balsam fir (Piene and Anderson 1987), H_{Dincr} of black spruce in these dense, evenly-spaced, highly productive stands was largely independent of N. These findings are consistent with those of Lavigne et al. (1987) but contrast with 37-year results from a black spruce spacing trial on a highly-productive old-field glaciolacustrine site southwest of Thunder Bay (McClain et al. 1994). In that study, decreased black spruce H_D was associated with N values of 700-800 stems ha^{-1} in comparison with N exceeding 1250 stems ha^{-1}. In the present study N_{94} exceeded 2000 stems ha^{-1} in all plots. Black spruce H_{Dincr} may also be reduced by very high densities on poor sites (e.g., ombrotrophic bogs) where nutrients and/or water, rather than light, are the principal factors limiting growth (Burns et al. 1996, cf. Sjolte-Jørgensen 1967, Nilsson 1994).

Mean 1985 black spruce heights per plot were directly correlated with SF_{85} (R=0.509, p=0.031), and inversely correlated with N_{85} (R=-0.757, p=<0.001). These correlations reflect the influence of interspecific competition and suppression on mean height. Mean black spruce 1986-1994 periodic height increment was also negatively correlated with 1985 hardwood basal area (R=-0.706, p=0.001), probably because of mechanical damage to black spruce crowns by girdled hardwoods which fell to the ground after dying.

Thinning often increases stem taper in many coniferous species (Larson 1963, Assmann 1970), including black spruce (Meng 1981). The lack of significant differences in 1994 height-diameter relationships among stands thinned to varying degrees may reflect insufficient time for these trends to become statistically demonstrable, given the inherent variability in tree and stand conditions, the relatively minor changes in stem taper that may accompany such thinning (Sjolte-Jørgensen 1967, Meng 1980), or the influence of budworm defoliation in the upper crowns on increasing stem taper, regardless of tree density (Mott et al. 1957).

Quadratic Mean Diameter

Immediately after thinning, D_{Q85} was smaller in the undisturbed control plots than in any of the thinned plots (F=7.26, p=0.002, EMS = 0.385, n=19) (Fig. 7a). Orthogonal contrast revealed significant linear (T=5.966, p<0.001) and quadratic (T=2.696, p=0.017) trends in D_{Q85}. In contrast, periodic (1986-1994) quadratic mean diameter increment (D_{Qinc}) was not significantly different (p≥0.10) among any of the treatments, either on its own or once D_{Q85}

was accounted for as a covariate.

The limited response in D_{Qincr} to thinning, together with the relatively high D_{Qincr} response in the undisturbed control plots, may reflect the influence of defoliation by spruce budworm. Newton (1988) reported limited growth responses in precommercially thinned black spruce in Newfoundland following a spruce budworm epidemic. Increases in the composition of overstorey hardwoods, including trembling aspen and white birch (I.e., in the undisturbed controls), have been shown to reduce defoliation by spruce budworm (Batzer 1969, Reams et al. 1988, Su et al. 1995).

For the 18 cleaned plots, there were significant linear correlations ($p<0.05$) between D_{Qincr} and a number of stand parameters, including D_{Q85} (R=0.752), H_{d94} (R=0.524*), SF_{Ave}* (R=0.573), *and* N_{Ave} (R=-0.734). These correlations, while not particularly strong, are consistent with results of most thinning studies; larger trees tend to grow more quickly in absolute terms, and greater D_{Q85} was associated with greater H_{D85} (i.e., with more productive sites). Also, for a given site, trees in less-dense stands (higher *SF,* lower *N*) tend to have greater D_{Qincr} than those in more-dense stands (Sjolte-Jørgensen 1967, Weetman et al. 1980). Finally, $N_{ave,}$ $SF_{Ave,}$ and D_{Q85} were all strongly influenced by thinning regime; lower N_{ave} values were associated with more intense thinning regimes, and these regimes selectively removed smaller diameter trees, thus increasing both SF_{ave} and D_{Q85}.

Basal Area

As expected, BA_{85} was highest in the control plots and decreased in linear fashion with nominal thinning intensity (Fig. 8a). In comparison with the cleaned controls, thinning resulted in actual reductions in basal area of 25%, 32% and 45% in the nominal 20%, 40% and 60% basal area removal plots, respectively. Black spruce BA_{85} in the undisturbed controls was similar to that in the 20% basal area removal plots, while mean basal area of other species (largely trembling aspen) in these undisturbed controls in 1985 averaged 9.9 $m^2\ ha^{-1}$, or 35% of the total basal area.

Among cleaned plots, black spruce BA_{incr} exhibited a strong linear decline with increasing level of basal area removal (ANOVA: F=5.66, p=0.009, MSE= 0.019, n=18)(linear orthogonal contrast: T=3.45, p=0.004)(Fig. 8b). BA_{incr} was not significantly different ($p \geq 0.10$), however, in the undisturbed control, cleaned control and 20% basal area removal plots. For all species combined, the only significant differences ($p<0.10$) found in BA_{incr} were between the cleaned and undisturbed control plots, and the cleaned 60% basal area removal plots (Fig. 8b). When BA_{85} was used as a covariate there were no significant differences among treatments in BA_{incr} for black spruce (F=1.33, p=0.315) or for all species combined (F=1.10, p=0.393).

When the plots were considered individually, significant curvilinear (quadratic) relationships were found between BA_{incr} and several size-density indices including P_{rv} ($R^2 = 0.731$,

BA_{incmax} = 0.74); P_{rV} (R^2 = 0.768, BA_{incmax} = 0.47); P_{rD} (R^2 = 0.735, BA_{incmax} = 0.772); and *SF* (R^2 = 0.564, BA_{incmax} = 15.1); as well as with BA_{85} (R^2 = 0.720, BA_{incmax} = 23.4 m^2 ha^{-1})(Fig. 9). The greatest response (BA_{incmax}) over the range of values for a particular stocking measure occurred at P_{rV} and P_{rD} values of about 0.75, slightly above the threshold for density-dependent mortality. A similar trend was evident for P_{rV} *and SF* in relation to threshold values for density-dependent mortality, although in the latter case relationships were not as strong. These results are consistent with Assmann's (1970) contention that maximum net basal area and volume increment occurs in conifer stands which contain a relative stocking of about 70-80% of that of fully stocked stands. Net increment in stands with higher relative densities than this is offset to an increasing degree by mortality. This is also consistent with the implications of the stand density management diagrams; as stands grow into the zone of competition-imminent mortality, net stand growth will be reduced through mortality as total stand yield asymptotically approaches the self-thinning line (Drew and Flewelling 1979).

Total Stem Volume

V_{T85} was greatest in the undisturbed controls and decreased with cleaning and thinning intensity. In comparison with the cleaned controls, thinning resulted in reductions in V_{T85} of 18%, 26% and 40%, respectively, for the nominal 20%, 40% and 60% basal area removal treatments (Fig. 10a). In the undisturbed controls, black spruce V_{T85} was comparable with that in the nominal 40% basal area removal plots, while V_{T85} of other species averaged 38.7 m^3 ha^{-1} or 37% of the total V_{T85}.

Significant differences in black spruce V_{Tincr} occurred among basal area removal treatments (ANOVA: F=4.54, p=0.020, MSE=1.298, n=18)(Fig. 10b). Unlike BA_{incr}, however, V_{Tincr} exhibited a non-significant linear trend (linear orthogonal contrast T=0.737, p=0.474) but a significant quadratic trend (quadratic orthogonal contrast T=3.248, p=0.006) with increasing levels of nominal basal area removal. Black spruce V_{Tincr} was not significantly different ($p \geq 0.10$) in the undisturbed control plots than in any of the other treatments, with the exception of the 60% basal area removal treatment. When V_{Tincr} for all species was considered, however, significant differences (F=7.68, p=0.001, MSE = 1.262, n=21) were found between the undisturbed control and the cleaned 40% and 60% basal area removal plots.

When V_{T85} was used as a covariate, there were no significant differences in V_{Tincr} amongst any of the treatments for black spruce only (F=0.78, p=0.554), or for all species combined (F=1.50, p=0.252). When the plots were considered individually, linear or curvilinear relationships were evident between black spruce V_{Tincr} and such size-density measures as V_{T85} (R^2 = 0.627), BA_{85} (R^2 = 0.567), P_{rD} (R^2 = 0.657, $V_{Tincrmax}$ = 0.835), P_{rv} (R^2 = 0.651, $V_{Tincrmax}$ = 0.806); P_{rV} (R^2 = 0.703, $V_{Tincrmax}$= 0.515), and SF (R^2 = 0.454, $V_{Tincrmax}$ = 16.1%). Most of these relationships were substantially weaker than those between BA_{incr} and the various size-density measures. In most cases, the greatest responses ($V_{Tincrmax}$) were obtained at size-density index values somewhat greater than those for $BA_{Incrmax}$.

Strong linear relationships existed between V_{T94} and $BA_{94,}$ $P_{rD94,}$ and P_{rv94}, but the linear association between V_{T94} and SF_{94} was much weaker (Fig. 11). Poorer relationships between both stand growth (V_{Tincr} and BA_{incr}) and mortality, and SF, as opposed to either P_{rD} or P_{rv} suggest that the latter measures are more appropriate for determining spacing regimes and projecting future yields than the former. This is at least partially attributable to the fact that SF is based only on values for the largest trees per plot, while P_{rv} and P_{rD} are based on mean values for all trees per plot. As with site index, SF values are contingent upon which tree classes (dominants, or dominants and codominants), and what numbers of trees to include in determining H_D (cf., Plonksi 1974, Wilson 1979, Schmidt and Carmean 1988, Bell et al. 1990).

1994 Merchantable Volume

There were significant differences (ANOVA F=5.55, p=0.005, MSE = 156.3, n=21) in black spruce V_{M94} among treatments, and these trends parallelled those in V_{T94}; greater black spruce V_{M94} was found in the cleaned control plots than in the uncleaned control plots or the 40% and 60% basal area removal plots (Fig. 12). Like $V_{T94,}$ V_{M94} exhibited a non-significant linear trend (linear orthogonal contrast T=0.684, p=0.505) but some indication of a significant quadratic trend (quadratic orthogonal contrast T=2.016, p=0.063) with increasing levels of nominal basal area removal. When all species were considered, however, larger V_{M94} values were found in the uncleaned control plots than in any of the cleaned treatments, and in the cleaned control plots than in the 60% basal area removal plots.

Growth and Yield Comparisons

Black spruce BA_{94} and V_{T94} in the cleaned control plots at Tyrol Lake were within 3% of the values given by Plonski (1974) for Site Class 1a stands of similar age. Plonski's normal yield tables for black spruce Site Class 1a, however, refer to all species; he recognized that these highly productive sites usually support mixed stands as opposed to pure stands of black spruce, and that, on average, the spruce component represents about 65% of the total stand volume. When all species are considered in the undisturbed control plots, BA_{94} and V_{T94} were 8-12% higher than the values given by Plonski.

Using Plonski's (1974) yield tables, at stand age 55 (the physical rotation age) the black spruce cleaned controls should carry a basal area of about 45 m^2 ha^{-1} and a gross total stem volume of about 295 m^3 ha^{-1}. At this time, the undisturbed control plots should carry a total basal area of about 52 m^2 ha^{-1} and a gross total stem volume of about 335 m^3 ha^{-1} if they maintained the same relative yield advantage over the cleaned plots as in 1994.

H_{D94}, D_{Q94} and V_{T94} at Tyrol Lake were also compared with those derived for Site Class 1a at similar stand densities using the black spruce VDYT of Bell et al. (1994). H_{D94} was 0.6 m larger than that predicted by the VDYT, while D_{Q94} was similar to that predicted at most densities, but lower than that predicted at the lowest densities (i.e., the heaviest thinning regime)(Fig. 13). V_{T94} values were consistently lower than predicted for all treatments (usually by 15-20%).

Differences between H_{D94} and predicted values reflect the approach of Bell et al. (1990) in defining site index and stand age. Site index values were taken directly from Plonski (1974) and refer to the mean height of dominant and codominant trees in relation to total tree age. In contrast, Bell et al. (1990) defined age in terms of time since plantation establishment. Since the black spruce at Tyrol Lake were nursery-grown, 4-year-old stock at the time of planting, they likely reached 1 m in height about 5 years earlier than new black spruce germinants established at the same time (Mullin 1978, Fleming and Mossa 1995). Recalculation of average heights in this fashion indicates the Tyrol Lake stands were about 0.6 m shorter in 1994 than predicted for Plonski's Site Class 1a.

Lower D_{Q94} at Tyrol Lake in the thinned plots, particularly at wider spacings, than predicted by the VDYT, may reflect incomplete response to increased growing space following cleaning and thinning. The consistent differences in V_T between the Tyrol Lake stands and those predicted by Bell et al. (1990) are of greater significance. These may reflect incomplete site utilization by black spruce, defoliation by spruce budworm or they be an artifact of the methodology used in developing yield projections. V_{T94} for all species in the undisturbed controls was within 4% of that predicted by Bell et al. (1990), although black spruce mortality rates in the cleaned controls suggest these plots were also fully occupied. With regard to yield table formulation, Bell et al. (1990) used mathematical relationships developed between black spruce and white spruce at the Thunder Bay spacing trials to infer black spruce yields at different densities from Berry's (1987) white spruce variable density yield tables for old fields at the Petawawa National Forestry Institute. Relationships between yields of pure stands of different species are highly site and age dependent; and can readily lead to bias in yield projections for the species of interest under different conditions (Matheson and Stewart 1986, Buse and LeBlanc 1990, cf. Sims et al. 1996).

Finally, 1994 yields at Tyrol Lake were compared with those derived from the black spruce SDMD of Newton and Weetman (1994) using mean values of N_{94} and H_{D94} for the different cleaned treatments. Derived values of D_{Q94} and V_{T94} from the SDMD were very similar (usually within 3%) to the actual values for both thinned and control plots (Fig. 13). Most discrepancies were well within the limits of accuracy, both in terms of visual interpolation of the SDMD, and the accuracy of measurements and calculations for the Tyrol Lake plots.

Growth and Yield Projections

Projections of V_{Tincr} and V_{T94} for the different treatments at Tyrol Lake were calculated from the SDMD, using N_{85} and H_{D85} as inputs. Although the SDMD consistently overestimated V_{T94}, in three of the four cases actual and estimated values were within 5% of one another (Fig. 14a). V_{Tincr} projections were within 4% of those actual measured, and within 7% in the other case (Fig. 14b). Unlike $V_{T94,}$ V_{Tincr} was not consistently over or underestimated. The small but consistent overestimation of V_{T94} is largely a result of overestimations of V_{T85}. The latter may reflect the fact that 25-35% of the total basal area, consisting of hardwoods, had just been removed from the plots.

Given the close agreement between the SDMD yield projections for Tyrol Lake and the actual 1994 yields obtained, yield projections to age 55 (the physical rotation age) were calculated for the different treatments from the SDMD (Table 5). V_{T85} was greatest in the control plots, and declined linearly with basal area removal. Based on merchantable volume specifications of 15 cm stump height, 7.6 cm top diameter and 9.5 cm minimum dbh (Newton and Weetman 1993), V_{M55} was also highest in the control plots. Considering V_{M55} rather than V_{T55} reduced the difference in expected yields among treatments by about 5%. In reality, however, relative gains in V_{M55} of this magnitude with more widely spaced black spruce could easily be offset by reductions in specific gravity (Shepard and Shottafer 1990, Yang and Hazenburg 1994), when considering yield on a mass basis.

At the individual tree level, the heaviest thinnings increased projected values of D_{Q55} from 15.4 to 16.1 cm, and mean individual tree volumes (v_{55}) from 110 to 130 dm^{-3}. None of the thinning treatments were projected to produce a substantial number of trees of sawlog size (minimum D_{Q55} of 20 cm (McClain et al. 1994)) over the 55 year rotation period.

Silvicultural Implications

Taken together, these results suggest a cautious approach to widespread application of precommercial thinning black spruce on highly productive sites. Goals, objectives and cost/benefits of thinning need to be carefully considered in light of the following biological responses of this species to density management:

1) Greatest total and merchantable stem volume yields at physical rotation age (55 years) were projected for the control treatments, despite their high densities (~6000 stems ha^{-1} at plantation age 24). This is consistent with the analyses of Sjolte-Jørgensen and the observations of Smith (1986) that V_T is usually decreased by thinning, and that greater relative decreases occur on more productive than on less productive sites. It contrasts, however, with earlier generalizations that V_T on a given site is constant and optimum over a wide range of densities (Mar:Moller 1947, Smith 1962, Willcocks and Bell 1995). Differences in merchantable pulpwood production among stands of different densities is highly dependent on stand age and merchantability criteria. On highly productive sites, precommercial thinning will produce merchantable black spruce pulpwood stands at an earlier age, but only at great sacrifice of the productive potential of the site. On these sites, denser stands may overtake less dense stands in V_M at least 10-15 years before the physical rotation age is reached, and may remain greater for many years (Whynot and Penner 1992). McClain et al. (1994) reported that black spruce V_M with trees spaced at 1.8 x 1.8 m already exceeded that with trees spaced at 2.7 x 2.7 m by 57% 37 years after planting.

Furthermore, when considered on a mass basis (Yang and Hazenburg 1994), relative merchantable yields (kg ha^{-1}) are even greater at narrower spacings. Armson's (1975) recommendation that black spruce be established at high planting densities (2400-3700 trees ha^{-1}) to maximize fibre yields over short rotations is consistent with these results.

2) Individual tree size at rotation age can only be augmented substantially through reductions in total stand volume production on these sites. This is implicit in the projections of the SDMD. If precommercially thinned stands are allowed to approach the asymptotic mean volume-density line for self-thinning before harvest (i.e., through lighter thinning intensities and/or longer rotation ages), stand yields will approach those of unthinned stands (i.e., they will be maximized), but differences in mean tree size between treated and untreated plots will be small (Lavigne et al. 1987). This is implicit in the observation that growth response of potential crop trees to various thinning levels is often limited, especially in comparison with the mean response of all trees (Adams and Chapman 1942). Maximizing individual tree growth rates and size implies reducing stand volume growth rates and yields substantially. In comparison with white spruce and red pine, black spruce shows the smallest increase in individual tree size, and concomittently the largest percentage decline in total stand volume yield, with increased spacing (Matheson and Stewart 1986, McClain et al. 1994). In terms of crown shape, branching characteristics and foliage longevity, black spruce is well adapted to growing in dense stands but poorly adapted for lateral crown expansion to take advantage of large increases in growing space.

3) Observations from many trials suggest that V_{Tincr} and V_{Mincr} of precommercially thinned or spaced stands increases more slowly with age and reaches a lower peak than that for unthinned stands, but subsequently does not fall as rapidly as that of unthinned stands (Clutter et al. 1983). As a result, physical rotation ages for thinned stands are longer than for unthinned stands, although individual tree size at rotation age is greater (cf. Van Nostrand 1973). This implies that precommercial thinning black spruce on highly productive sites may not be a biologically efficient means of increasing medium -term fibre yield or offsetting shortfalls in allowable pulpwood cuts due to age class imbalances (cf. Willcocks et al. 1990).

4) At physical rotation age on these highly productive sites, black spruce produces substantial pulpwood merchantable volumes, but little sawlog merchantable volume. As improved technology and increased demand lower pulpwood merchantability standards, the shortfall in pulpwood yield from precommercially thinned stands, compared with unthinned stands, will increase. Despite Reed's (1991) optimism, it is unlikely one can increase both black spruce pulpwood and sawlog yields on highly productive sites through precommercial thinning. In contrast, merchantability limits for sawlogs are constrained by the specifications of dimension lumber, and thus technological innovations are unlikely to reduce such limits to the same degree as for pulpwood.

This has major implications for timber supply since shortfalls are anticipated in allowable cuts for both sawlogs and pulpwood. Great reliance has been placed on black spruce as a source of sawlogs in northern Ontario because sustained black spruce growth rates at older ages (Plonski 1974), together with an abundance of overmature stands (>100 years old) (Callaghan 1994), has resulted in the availability of large quantities of sawlog-sized material. Such stands, however, are well past their physical rotation ages. In the coming decades, Ontario's second growth forests will not be capable of providing sustained, historical levels of black spruce sawlog material and at the same time meet increasing industrial demands for black spruce pulpwood (Callaghan 1994).

5) Competition from hardwoods such as trembling aspen is severe on many of these highly productive sites, and some form of competition control is necessary both at establishment and periodically thereafter if black spruce-dominated stands are to be produced (Hearnden et al. 1992). The Tyrol Lake stands were manually cleaned three times before age 15, and chemically cleaned at age 17; yet 24 years after planting, competing hardwoods, principally trembling aspen, composed 30% of the stand basal area. Based on the projections of Newton and Weetman (1994), we estimate crown closure in these stands, initially established at densities of 6500-7,000 stems ha^{-1}, occurred 8-10 years after planting. Ingress of competing aspen continued at least until the stands reached 6-7 m in height and were approaching the lower limit of the zone of imminent competition and mortality.

These results have important implications for competition control strategies and free-to-grow standards; simple crown closure of black spruce on such sites is unlikely to prevent ingress or regrowth of vigorous competitors like trembling aspen. The fall manual cleaning in 1985, at a time when the black spruce had attained mean heights of 6-8 m, and in which the larger aspen were girdled, has so far been effective in preventing further aspen ingress. Plots cleaned four times prior to 1980, but not cleaned in 1985, supported about 23% less black spruce V_{T94} than those cleaned in 1985 as well as on the four previous occasions. The former stands did, however, produce 12% more gross total V_{T94} (all species combined) than the latter stands. Carefully considered, stand-level objectives, prescriptions and cost/benefit analyses will be necessary to optimize use of these sites. Precommercial thinning costs should be compared with cleaning costs when investigating different silvicultural alternatives.

6) The above scenario with regard to thinning black spruce primarily addresses opportunities to grow pulpwood on highly productive sites, and the tradeoffs of volume production versus shorter rotations. If the objectives include growing black spruce sawlogs on longer rotations, the preceding cautions may or may not apply. Given the short time frame since the establishment of these trials, and the lack of tested longer rotation growth projection systems for black spruce plantations on such sites, few definitive statements can be made at this time.

The reservations expressed regarding thinning black spruce on highly productive sites may (Steneker 1969, van Nostrand 1973, Whynot and Penner 1994) or may not (Weetman et al. 1980, Burns et al. 1996) apply to black spruce on less productive sites. On less productive sites, total volume production tends to be more similar over a range of stand densities than on more productive sites (Smith 1986), creating greater opportunities for increasing individual tree size without unduly hampering stand-level production. This may reflect the importance of multiple resource limitations (e.g., nutrient, moisture and temperature, as well as light limitations) and the ability of more widely spaced trees to take advantage of greater soil resources as they become available, without first developing larger assimilating structures (crowns or roots) (Nilsson 1994).

Increased height as well as diameter increment has been reported after thinning very dense black spruce stands on some poor quality sites (Burns et al. 1996), but not on others (Steneker 1969), suggesting thinning may improve site quality, perhaps through enhanced nutrient cycling stimulated by higher soil temperatures. Furthermore, the slow growth rates and high stem densities often associated with poor sites render them inoperable for many years because of small piece size, despite considerable total biomass production. Thinning on such sites could enhance operability and reduce rotation ages considerably, without detracting substantially from V_M for a number of years (Steneker 1969, Erickson 1994, Karsh et al. 1994). The profitability and cost/benefit of thinning such stands, however, should also be addressed.

Use of SDMDs

Some caveats should accompany the use of SDMDs for black spruce growth projection despite the good relationships demonstrated here. These diagrams assume tree form remains unchanged and density-dependent mortality continues to be the major form of mortality throughout the projection period. Tree form of black spruce, and consequent allometric relationships, may indeed change with age as the trees grow in height and develop the deep, narrow, spire-like crowns, with short, upturned branches characteristic of older, larger black spruce (Zeide 1991, Farrar 1995). In addition, with increased age, other factors such as nutrient relations (Carleton and Wannamaker 1987), mechanical damage to adjacent stems by crown clash during tree sway, and windthrow can influence tree form and mortality, and cause actual thinning lines to fall below the upper boundary (Zeide 1987). For instance, in maturing stands, trees grown at lower densities should have greater stem taper and may be more resistant to tree sway. This could reduce crown clash, breakage of small twigs and narrowing of crown width, and consequently result in relatively more complete site utilization (higher P_r values) than in denser stands. In this scenario, equivelant total volume production may be achieved at later stages with trees of greater diameter in the more widely spaced stands. It is noteworthy that the largest overestimates of Douglas-fir yields derived from SDMDs, as reported by Cameron (1988), were for stands > 20 m tall.

Four areas of concern with the use of SDMDs to project future growth and yield are: 1) the rigid relationships between N, v, D and H_D, regardless of stand age, size or density, as portrayed in the bivariate graphs; 2) the accuracy of projected asymptotic mortality functions; 3) the influence of mortality not related to competition for light; and 4) the veracity of the underlying assumptions regarding mortality, stand yield and tree allometry (Weller 1987, Zeide 1987, 1991, and Cameron 1988). In this study, good projections were aided by selecting: 1) young, vigorous plantations established at regular spacing and in which most mortality was related to competition for light, 2) plots with fully-closed canopies and uniform stand conditions, and 3) a combination of low and geometric thinning that probably best reflected natural patterns of density-dependent mortality in such stands (Ford 1975, Kenkel 1988). In addition, comparisons of estimated versus measured growth and yield covered only a 9-year period, over which there was little change in stand composition or tree allometry.

Silvicultural Alternatives

A variety of silvicultural alternatives exist for highly productive sites such as those at Tyrol Lake. Establishing pure plantations of white spruce or red pine could produce substantial pulpwood yields at an early age through commercial thinnings, and large sawlog yields later at final harvest (cf. McClain et al. 1994). Vigorous plantations of these two species are found in the Tyrol Lake area, although most white spruce plantings have suffered severe growth reductions and some mortality as a result of the spruce budworm epidemic. Another alternative is the establishment of mixed conifer-dominated stands using various combinations of jack pine, red pine, white pine, white spruce and black spruce. Through proper species selection, it should be possible to optimize biomass and sawlog production (Wierman and Oliver 1979, Kelty 1989, Brown 1992, Morgan et al. 1992, Pukkala et al. 1994), improve forest stability (Orians 1974, Van Miegroet 1979, Harrison 1979) , and satisfy amenity values for other uses. Many such combinations have been established in the Tyrol Lake area throughout the 1950s and 1960s, and now offer excellent examples for management practices, and opportunities for research on productivity and stand dynamics.

Silvicultural procedures to introduce and maintain a white birch component in these stands should also be investigated. Prior to logging, many of these highly productive sites supported mixed conifer-dominated stands with a sizeable component of white birch. Second growth stands on such sites, however, are often characterized by much higher components of aspen and much lower components of white birch. There is much speculation and some evidence that birch species play important roles in nutrient cycling and the maintenance of stand productivity, and offer less competition to developing conifers than trembling aspen (Frivold and Mielikäinen 1989, Perala and Alm 1990, Longpré et al. 1994).

In the absence of specific silvicultural planning and initiatives at the time of harvest, these sites are likely to become aspen-dominated. This may result in high biomass production at the least cost in the shortest period of time (Perala and Alban 1982). However, this may also reduce opportunities to grow high quality sawlogs or high value-added products in the current and in succeeding rotations (because of the persistence of aspen suckering). In addition, widespread conversion of highly-productive virgin spruce-pine dominated stands to second-growth aspen-balsam fir dominated stands following logging has been pervasive throughout this region, and is one of the most serious threats to maintaining biodiversity at the landscape level (Hunter 1990, G. Racey, personal communication).

Black spruce presents a unique challenge to the silviculturist. This species dominates much of the North American boreal forest and forms the largest and most valuable resource of the Canadian forest products industry. It often forms dense, pure or mixed conifer stands which are characterized by some of the highest stand volume production rates of any boreal species on specific sites. Yet, as individual trees, black spruce are characterized by conservative growth rates and high tolerance of resource scarcity (Chapin 1980, Brumelis and Carleton 1988). They show limited individual tree response to increased resource availability, compared with many faster-growing companion species, and are not highly responsive to silvicultural manipulations such as fertilization (Foster and Morrison 1983, 1986) or thinning. Good stand growth rates are maintained by high tree densities. Emphasis in black spruce silvicultural programs should be placed on obtaining high initial stand densities, rapid canopy closure and freedom from continued vigorous competition from faster-growing species.

Conclusions

After 9 years, precommercial thinning dense, 24-year-old planted black spruce stands on a highly productive site resulted in little response in quadratic mean diameter but sizeable decreases in total stand volume. Mean height growth of dominant and codominant trees was not affected by thinning treatment. Removal of hardwood (mainly trembling aspen) competition resulted in an increase in black spruce periodic stand volume increment of about 1 m^3 ha^{-1} yr^{-1}, but a decrease in total stand volume increment of about 1.8 m^3 ha^{-1} yr^{-1}. Projected yields at age 55 (the physical rotation age) suggest precommercial thinning could increase quadratic mean diameter from 15.4 to 16.1 cm, but concomitantly would decrease net merchantable stand volume from 267 to 227 m^3 ha^{-1}. There was a consistent increase in quadratic mean diameter and a consistent decrease in net merchantable stand volume with increasing intensity of precommercial thinning. Substantial intraspecific competition-related black spruce mortality likely began in these dense stands within 20 years of planting.

These results suggest that total black spruce fibre yield will be maximized in unthinned stands. Cleaning and competition control in young stands may offer greater benefits for black spruce fibre production than precommercial thinning. Individual tree growth and response to silvicultural treatment is more limited in black spruce on highly productive sites than that of common associates white spruce, jack pine and red pine. The latter species offer greater potential for sawlog production than black spruce, and mixtures of these species with black spruce may optimize use of these sites for a variety of products and amenity values.

Stand density management diagrams provided good estimates of stand response to various thinning regimes over this 9-year period. These diagrams have great utility for investigating the response of young stands to density management treatments. Further research is required to investigate the accuracy of SDMDs in forecasting stand growth and mortality in older stands.

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Table 1. Parameter values and goodness-of-fit for Equation 1.

Sampling Year	Sample Size (n)	*a*	*b*	*c*	Mean Square Error	Adjusted R^2
1985	1247	11.011 (0.828)	0.1208 (0.0230)	1.1123 (0.1084)	0.5473	0.701
1994	607	18.266 (3.329)	0.0581 (0.0229)	0.9462 (0.1131)	0.8838	0.759

Asymptotic standard errors are shown in brackets below parameter values for *a, b* and *c.*

Table 2. Some pedological characteristics of the study plots. Shown are soil textures (Text.0 and thicknesses (Thick) of the different horizons, as well as rooting depths and NWO FEC soil types.

Plot	LFH Thick (cm)	Ae Thick (cm)	B_1 Thick (cm)	B_1 Text.	B_2 Thick (cm)	B_2 Text.	C Thick (cm)	C Text.	Root Depth (cm)	NWO FEC Type
1	7	5	18	SivfS 10%	36	LmS 40%	41+	SivfS 40%	55	S3
2	8	6	15	SiL 10%	28	SifS 30%	51+	SivfS 40%	60	S3
3	9	4	48	SiL 5%	n/a		48+	LfS 45%	65	S4
4	6	3	47	SiL 35%	11 (C_1)	SiL 35%	39+	SivfS 35%	79	S4
5	8	5	28	SivfS 25%	37	LfS 40%	30+	SivfS 40%	60	S3
6	9	6	42	SiL 5%	16	LmS 50%	36+	SivfS	50	S4
7	5	7	57	SivfS 20%	n/a		36+	SivfS 30%	80	S3
8	8	0	55	SiL 25%	28 (C_1)	LfS 50%	17+	SifS 30%	60	S4

9	6	6	44	SiL 5%	15	SifS 25%	35+	SifS 20%	75	S4
10	5	8	46	SivfS 25%	n/a		26	SivfS 15%	80	S3
11	6	4	36	SiL 15%	12	LmS 40%	47+	SivfS 20%	70	S3
12	6	6	55	SiL 10%	n/a		39+	SivfS 25%	70	S4
13	4	5	50	SiL 10%	n/a		45+	SivfS 15%	70	S4
14	6	6	50	SivfS 15%	n/a		44+	SivfS 15%	75	S3
15	5	6	45	SivfS 15%	n/a		49+	SivfS 15%	70	S3
16	4	5	45	SiL 15%	n/a		50+	SiL 10%	70	S4
17	5	5	45	SiL 15%	n/a		50+	SiL 10%	70	S4
18	5	5	50	SiL 15%	n/a		45+	SivfS 10%	80	S4
19	5	7	57	SivfS 20%	n/a		36+	SivfS 30%	80	S3
20	9	4	45	SiL 15%	n/a		51+	SivfS 5%	65	S9

21	5	6	50	SiL 25%	n/a		44+	SivfS 20%	75	S4
22	4	6	45	SiL 10%	n/a		44	SifS 30%	80	S4
23	4	5	45	SiL 15%	n/a		28	SifS 30%	70	S4
24	6	3	50	SiL 10%	n/a		47+	SiL 30%	80	S4

Table 3. Mean soil macronutrient concentrations, pH and cation exchange capacities (CEC) in the study plots. Macronutrient concentrations are given in percent (%) or parts per million (ppm), pH is with 0.01 M calcium chloride, and CEC is expressed in milli equivalents per 100 g.

	Macronutrient						
Soil Horizon	N (%)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	pH (CaCl)	CEC (mE/100 g)
B_1	0.056 (0.017)	20.8 (25.6)	27.4 (9.56)	221.2 (208.1)	17.2 (13.8)	4.78 (0.38)	11.1 (1.65)
C	0.015 (0.005)	13.65 (7.15)	19.3 (8.04)	187.3 (221.2)	18.04 (24.5)	5.08 (0.61)	7.07 (1.21)

Table 4. Correlation (R value) between periodic annual black spruce tree mortality (1985-1994) and various measures of stand-level stocking.

Stocking Measure[2]	Mortality (% yr^{-1})	Mortality (stems ha^{-1} yr^{-1})
	R value (relationship)	R value (relationship)
Total Stand Volume (m^3 ha^{-1})	0.745 (linear)	0.658 (linear)
Stand Basal Area (m^2 ha^{-1})	0.926 (piecewise-linear)	0.864 (piecewise linear)
Stand Density (stems ha^{-1})	0.681 (linear)	0.841 (linear)
P_{rvAve}	0.944 (piecewise-linear)	0.948 (piecewise-linear)
P_{rVAve}	0.934 (piecewise-linear)	0.941 (piecewise-linear)
P_{rDAve}	0.938 (piecewise-linear)	0.947 (piecewise-linear)
SF_{Ave}	-0.697 (linear)	-0.893 (piecewise-linear)

[2]Values represent arithmetic averages of the 1985 and 1994 values for a particular stocking measure. The type of relationship (linear or piecewise-linear) between stocking and mortality is indicated in brackets.

Table 5. Tyrol Lake black spruce yield projections at plantation age 55, by thinning treatment, based on the SDMD of Newton and Weetman (1994).

Nominal Basal Area Removed (%)	Current and Projected Density (Trees ha^{-1})	Projected Mean Stem Volume (dm^3) and D_Q(cm)	Projected Total Stand Volume ($m^{-3} ha^{-1}$)	Projected Merch. Stand Volume ($m^{-3} ha^{-1}$)
0	5010 - 3000	110 - 15.4	330	267
20	3620 - 2600	120 - 15.6	312	256
40	3310 - 2400	125 - 15.8	300	249
60	2390 - 2050	130 -16.1	267	227

Figure Captions

Fig. 1. Location of the study area in relation to northwestern Ontario and the Lake Nipigon region.

Fig. 2. Plot layout at the Tyrol Lake plantation, indicating species composition and stand treatment.

Fig. 3. Black spruce relative size-density relationships for the cleaned control plots in 1994: a) log of stand volume(LogV_{T94}) - density (LogN_{94}), and b) log of quadratic mean diameter (LogD_{Q94}) -density(LogN_{94}).

Fig. 4 Diameter distribution (relative frequency) of living black spruce, and 1985-1994 periodic tree mortality in two cleaned control plots: a) plot 5, and b) plot 15.

Fig. 5. Periodic mean annual black spruce mortality (1985-1994), by stand treatment. Values with the same lower case letter are not significantly different at p=0.05 using Scheffe's multiple comparison test. Numbers refer to nominal black spruce basal area removal, while lower case subscript letters refer to cleaned (c) or undisturbed (u) plots. Vertical lines above mean values indicate standard errors of the mean.

Fig. 6. Piecewise-linear relationships between mean annual black spruce mortality (by % and number of stems), and two black spruce size-density indices: a) average (1985-1994) stem volume-density (P_{rvAve}), and b) average (1985-1994) quadratic mean diameter-density (P_{rDAve}).

Fig. 7. Relationship between a) black spruce 1985 quadratic mean diameter (Q_{D85}), and b) black spruce 1986-1994 periodic quadratic mean diameter increment (Q_{Dincr}), and stand treatment. Values with the same lower case letter are not significantly different at p=0.05 using Scheffe's multiple comparison test. Numbers refer to nominal black spruce basal area removal, while lower case subscript letters refer to cleaned (c) or undisturbed (u) plots. Vertical lines above Q_{D85} values indicate standard deviations while vertical lines above Q_{Dincr} values indicate standard errors of the mean.

Fig. 8. Relationship between a) 1985 basal area (BA_{85}), and b) 1986-1994 basal area increment (BA_{incr}), and stand treatment. Values with the same lower case letter are not significantly different at p=0.05 using Scheffe's multiple comparison test. Numbers refer to nominal black spruce basal area removal, while lower case subscript letters refer to cleaned (c) or undisturbed (u) plots. Vertical lines above BA_{85} values indicate standard deviations while vertical lines above BA_{incr} values indicate standard errors of the mean.

Fig. 9. Relationship between 1986 -1994 basal area increment (BA_{incr}) and a) average (1985-1994) relative stem volume-density (P_{rvAve}), b) average (1985-1994) relative

quadratic mean diameter-density (P_{rDAve}), and c) 1985 basal area (BA_{85}).

Fig. 10. Relationship between a) 1985 total stand volume (V_{T85}), and b) 1986-1994 periodic mean stand volume increment (V_{Tincr}), and stand treatment. Values with the same lower case letter are not significantly different at p=0.05 using Scheffe's multiple comparison test. Numbers refer to nominal black spruce basal area removal, while lower case subscript letters refer to cleaned (c) or undisturbed (u) plots. Vertical lines above V_{T85} values indicate standard deviations while vertical lines above V_{Tincr} values indicate standard errors of the mean.

Fig. 11. Linear relationships between 1994 black spruce total net stand volume (V_{T94}) and a) 1994 basal area (BA_{94}), b) 1994 relative stem volume-density (P_{rv94}), c) 1994 relative quadratic mean diameter-density (P_{rD94}), and d) 1994 spacing factor (SF_{94}).

Fig. 12. Relationship between 1994 merchantable stand volume (V_{M94}) and stand treatment. Values with the same lower case letter are not significantly different at p=0.05 using Scheffe's multiple comparison test. Numbers refer to nominal black spruce basal area removal, while lower case subscript letters refer to cleaned (c) or undisturbed (u) plots. Vertical lines above V_{M94} values indicate standard deviations.

Fig. 13. Comparison of a) 1994 quadratic mean diameter (D_{Q94}), and b) 1994 total net stand volume (V_{T94}) measured at Tyrol Lake with values calculated from the the variable

density yield tables (VDYT) of Bell et al. (1990) and the stand density management diagram (SDMD) of Newton and Weetman (1994), using 1994 dominant tree height (H_{D94}) and stand density (N_{94}) as inputs. Vertical lines above measured D_{Q94} and V_{T94} values indicate standard errors.

Fig. 14. Comparison of a) 1994 total net stand volume (V_{T94}), and b)1986-1994 periodic net total stand volume increment (V_{Tincr}) at Tyrol Lake with projected values calculated from the stand density management diagram (SDMD) of Newton and Weetman (1994), using 1985 dominant tree height (H_{D85}) and stand density (N_{85}) as inputs. Vertical lines above V_{T94} and V_{Tincr} values indicate standard errors.

Fig 1

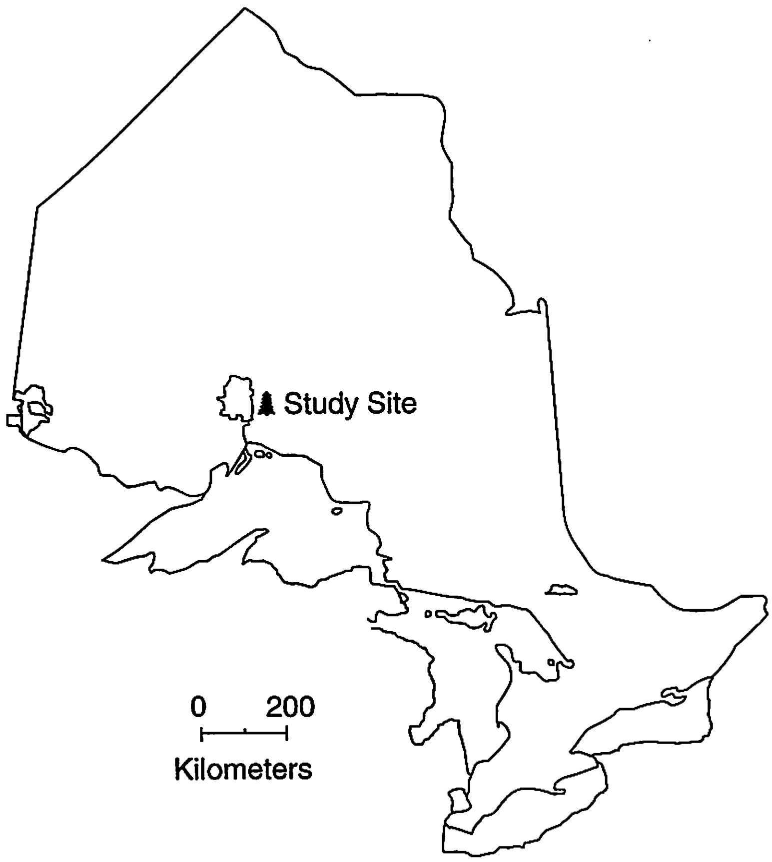
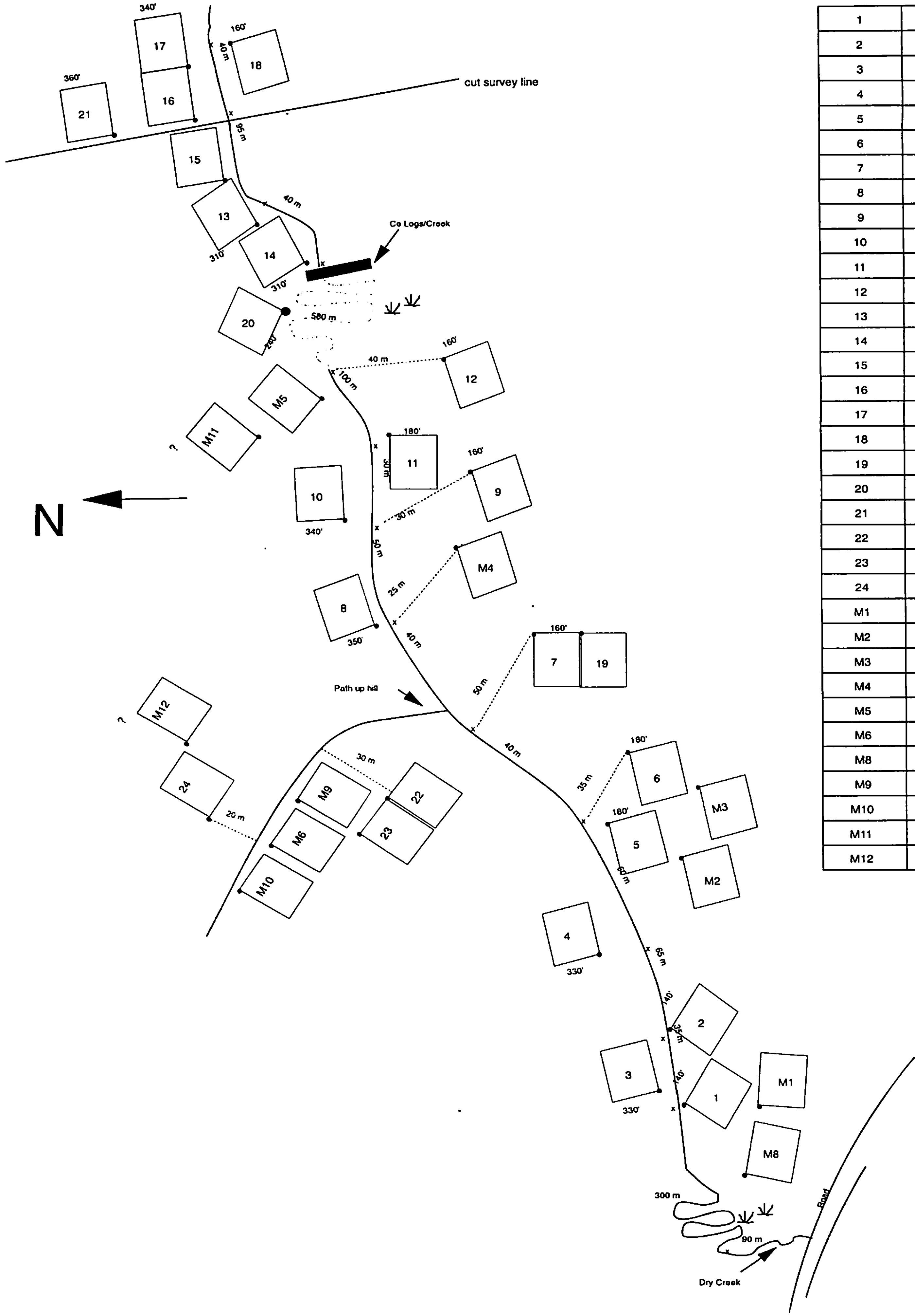


Fig 2



1	0%
2	20%
3	60%
4	40%
5	0%
6	0%
7	20%
8	60%
9	60%
10	20%
11	40%
12	40%
13	20%
14	40%
15	0%
16	CC
17	60%
18	CC
19	Ctrl
20	Ctrl
21	Ctrl
22	Ctrl
23	Ctrl
24	Ctrl
M1	Sb-Pj
M2	Sb-Pj
M3	Sb-Pj
M4	Pj
M5	Sb-Pj
M6	Pj
M8	Sb-Pj
M9	Pj
M10	Pj
M11	Ctrl
M12	Ctrl

Fig. 3 (50% reduction**tygrow-reg20.axg) Nov. 29, 1996

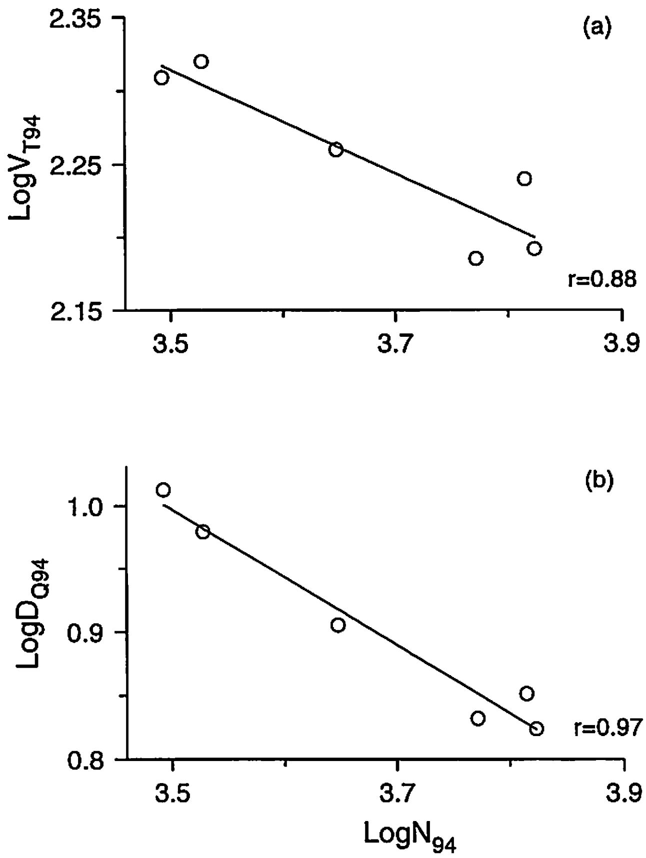


Fig 4 (50% reduction**tybar-bar2) Nov. 29, 1996

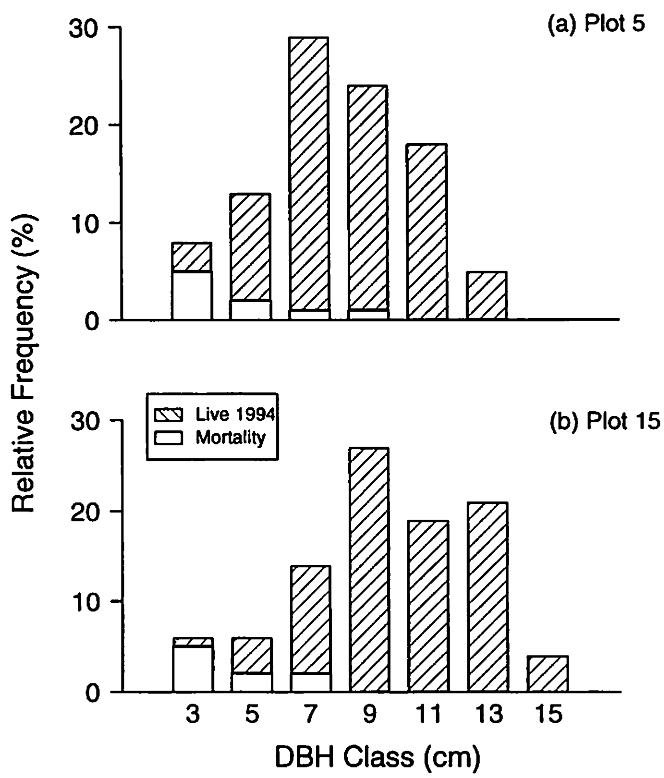
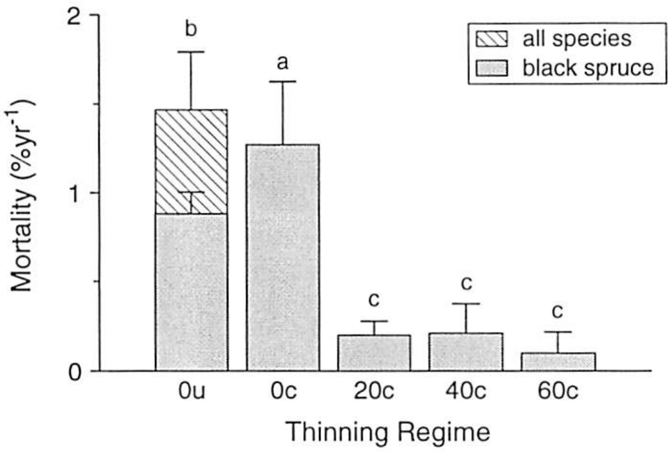


Fig. 5 (60% reduction**tybar-bar8) Nov. 29, 1996



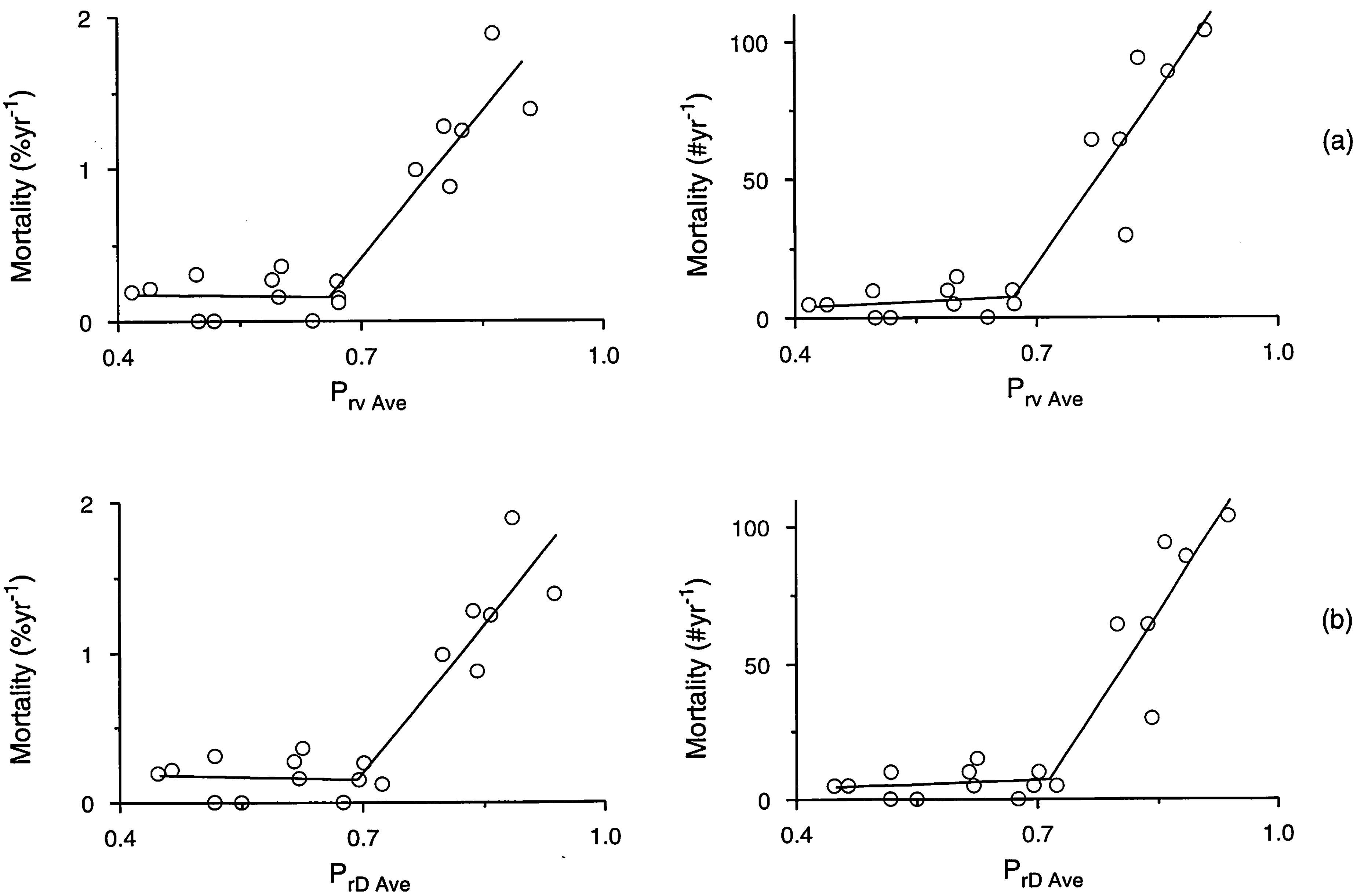

Mortality (%yr-1)
0
1
2
0.4
0.7
1.0
P rv Ave
Mortality (#yr-1)
0
50
100
0.4
0.7
1.0
P rv Ave
(a)
Mortality (%yr-1)
0
1
2
0.4
0.7
1.0
P rD Ave
Mortality (#yr-1)
0
50
100
0.4
0.7
1.0
P rD Ave
(b)

Fig. 7 (50% reduction**tybar-bar1) Nov. 29, 1996

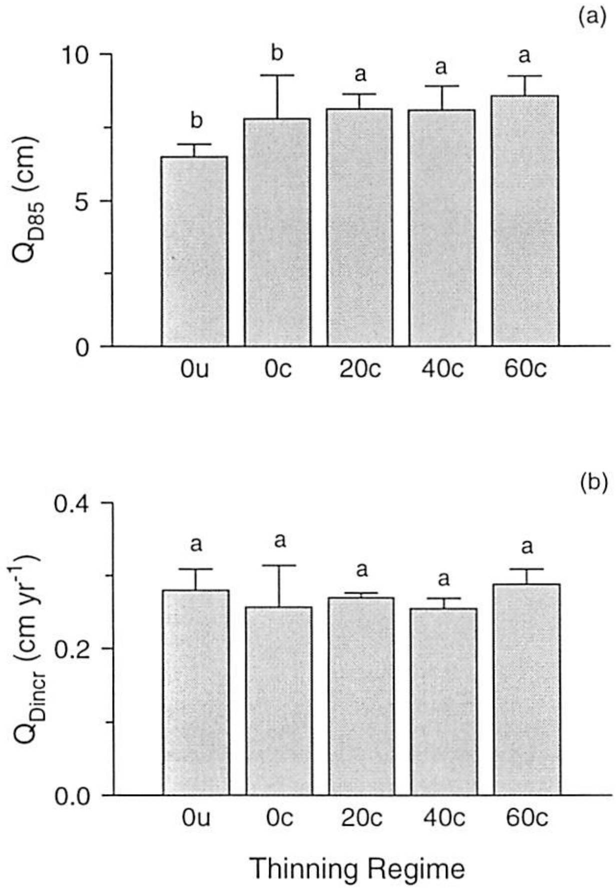
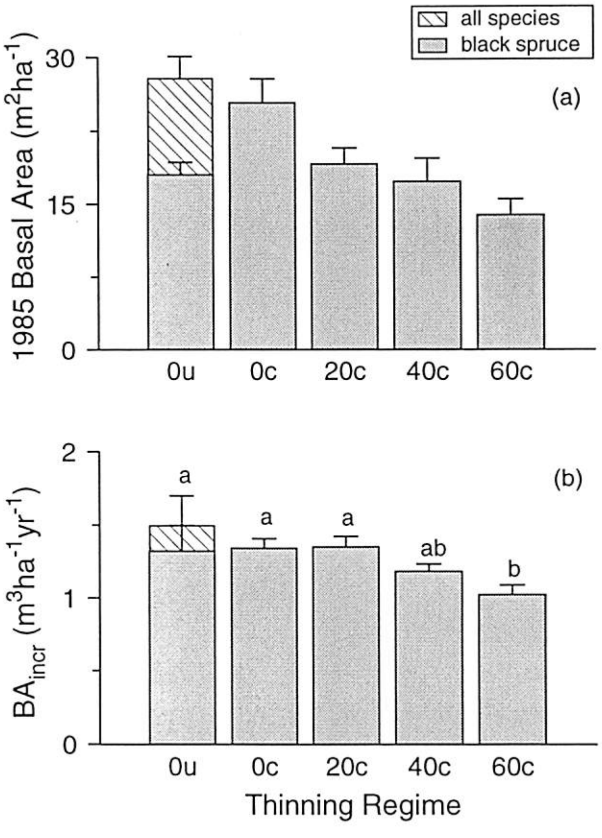
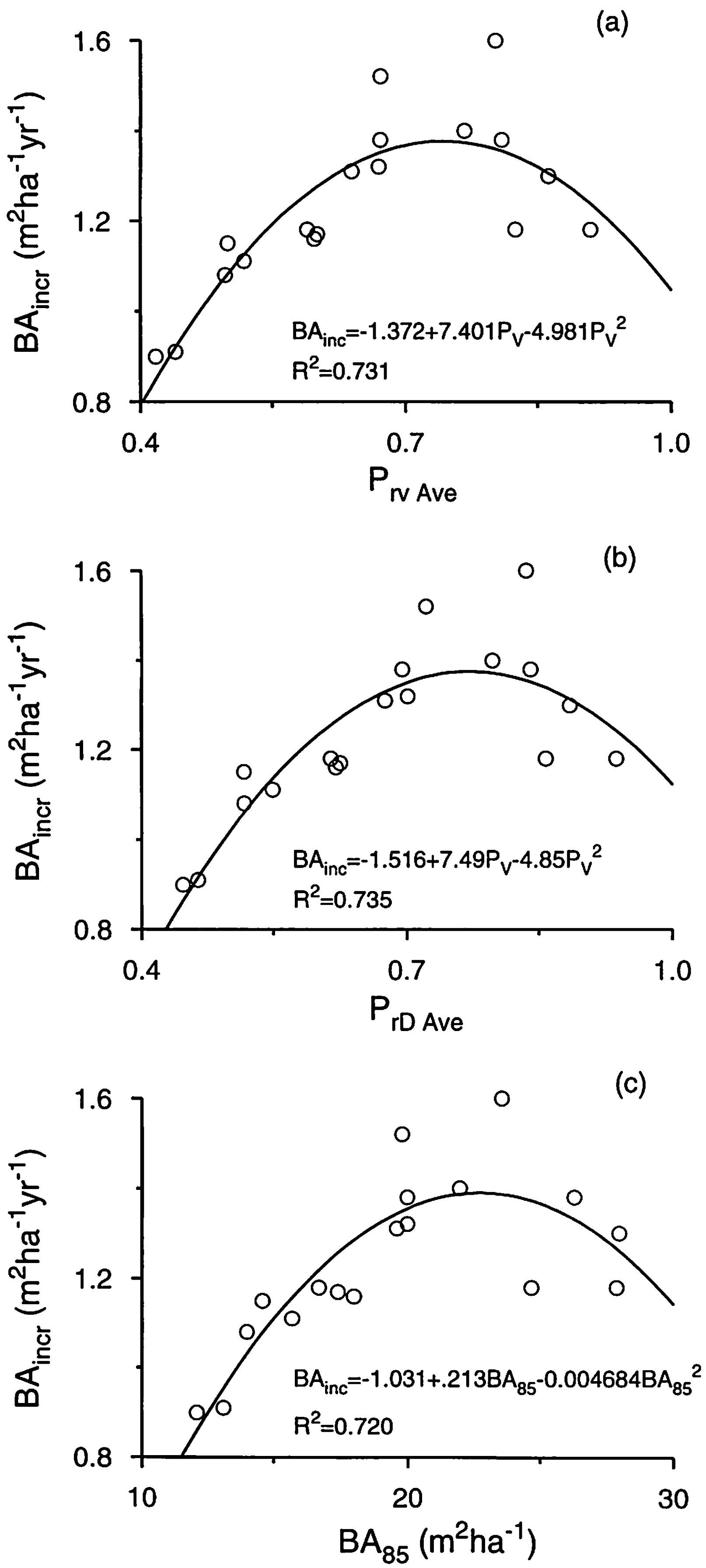


Fig. 8 (50% reduction**tybar-bar4) Nov. 29, 1996




(a)
1.6
1.2
0.8
BA_{incr} $(m^2ha^{-1}yr^{-1})$
BA_{inc}=-1.372+7.401P_V-4.981P_V^2
R^2=0.731
0.4
0.7
1.0
$P_{rv\ Ave}$
(b)
1.6
1.2
0.8
BA_{incr} $(m^2ha^{-1}yr^{-1})$
BA_{inc}=-1.516+7.49P_V-4.85P_V^2
R^2=0.735
0.4
0.7
1.0
$P_{rD\ Ave}$
(c)
1.6
1.2
0.8
BA_{incr} $(m^2ha^{-1}yr^{-1})$
BA_{inc}=-1.031+.213BA_{85}-0.004684BA_{85}^2
R^2=0.720
10
20
30
BA_{85} (m^2ha^{-1})

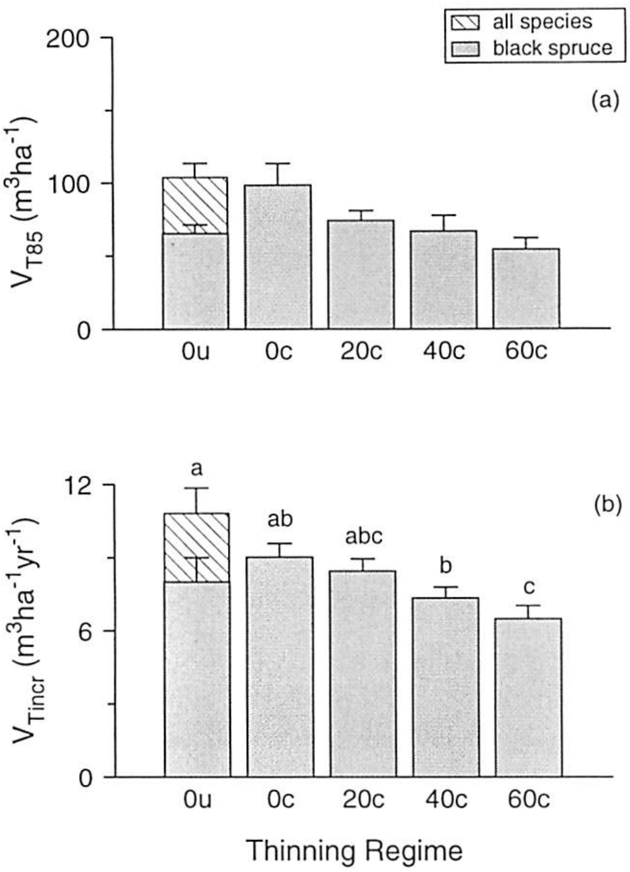

all species
black spruce
(a)
200
100
0
V_{T85} (m^3ha^{-1})
0u
0c
20c
40c
60c
a
ab
abc
b
c
(b)
12
6
0
V_{Tincr} ($m^3ha^{-1}yr^{-1}$)
0u
0c
20c
40c
60c
Thinning Regime

Fig. 11 (tygrow-reg1_4b.axg) Nov. 29, 1996

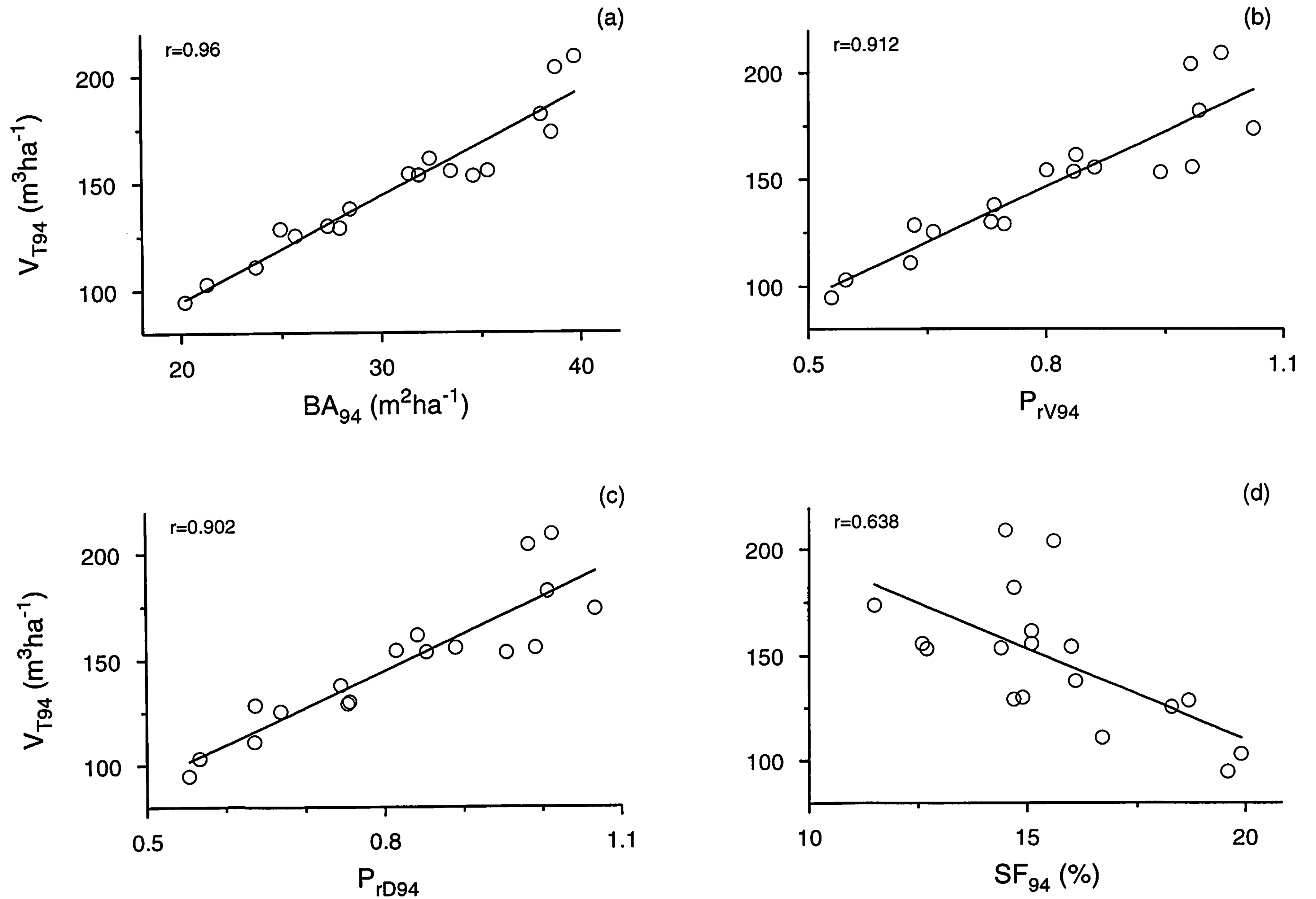


Fig 12 (60% reduction**tybar-bar3) Nov. 29, 1996

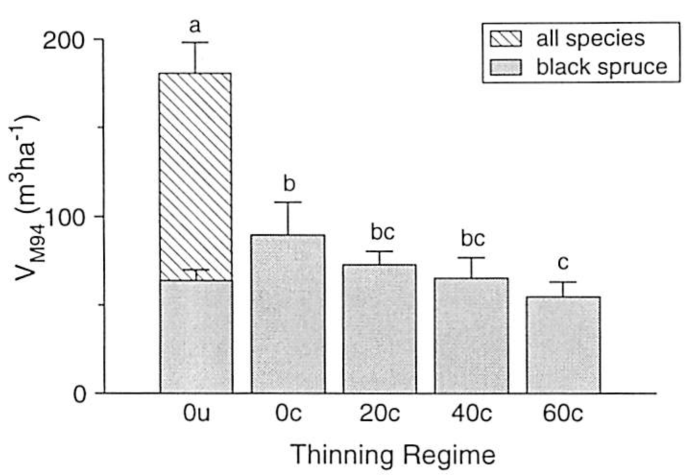


Fig. 13 (50% reduction**tybar-bar7) Nov. 29, 1996

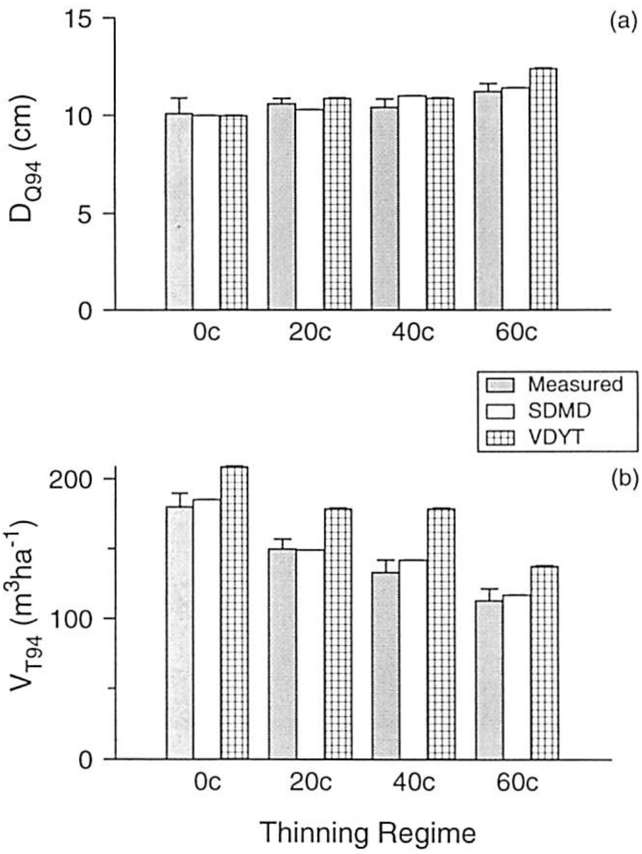


Fig. 14 (50% reduction**tybar-bar5) Nov. 29, 1996