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Differences in extrinsic tree quality and value of fibre production following alternative vegetation management treatments in northwestern Ontario

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ABSTRACT

We examined differences in stem quality, and volume and value of fibre produced by planted white spruce 16 years after vegetation management treatments in northwestern Ontario. Forest Vegetation Simulator (FVS^{Ontario}) was used to project the total and merchantable volume to age 70 and BUCK-2 was used to optimize the resulting product mix. Projected value was based on 2009 prices for hog fuel, pulpwood and SPF (spruce–pine–fir) eastern green lumber prices. At 16 years post-treatment, gross total volumes in herbicide-treated and mechanically cut plots were significantly higher (120%–165% and 94%–98%, respectively) than that in control plots (14.73 m^3 ha^{-1}). Based on height, diameter, and taper criteria, observed tree quality did not differ among treatments. The projected value of the fibre produced was 36% to 53% higher in herbicide-treated plots and 24% to 37% higher in mechanically cut plots than in control plots ($18 486.76 per ha).

Key words: brush saw, Fallingsnow Ecosystem Project, forest economics, forest vegetation management, glyphosate, herbicides, Silvana Selective, triclopyr

RÉSUMÉ

Nous avons étudié les différences au niveau de la qualité de la tige, du volume et de la valeur des fibres produites par des épinettes blanches plantées 16 ans après des traitements de contrôle de la végétation dans le nord-ouest de l'Ontario. Le Forest Vegetation Simulator (FVSOntario) a été utilisé pour projeter le volume total et le volume marchand à l'âge de 70 ans et le BUCK-2 a été utilisé pour optimiser la gamme des produits obtenus. La valeur projetée a été établie à partir des prix de 2009 pour le bois de feu, le bois à pâte et le bois de sciage (vert) d'EPS (épinette-pin sapin) de l'Est. Seize ans après traitement, le volume brut total des parcelles traitées au moyen de phytocide et coupées mécaniquement était significativement plus élevé (respectivement de 120%-165% et de 94%-98%) par rapport aux parcelles témoins (14,73 m^3 ha-1). En se basant sur la hauteur, le diamètre et le défilement, la qualité des arbres étudiés ne différait pas entre les traitements. La valeur projetée de la fibre produite était de 36% à 53% supérieure dans les parcelles traitées par phytocide et de 24% à 37% plus élevée dans les parcelles traitées mécaniquement par rapport aux parcelles témoins (18 486,76$ par ha).

Mots clés : débroussailleuse, Projet écosystémique de Fallingsnow, économie forestière, contrôle de la végétation forestière, glyphosate, phytocides, Silvana Selective, triclopyr

Introduction

Achieving economic efficiency from forest resources is key for forest companies to remain competitive in the present era of globalization. Canada has been losing its competitive edge in global markets, whereas other countries, especially in Scandinavia and the southern hemisphere, have shown significant growth in the forest products markets (NRCan 2002). This growth is in part attributable to major gains in forest productivity resulting from more intensive silviculture, including major investments in regeneration, release treatments, and other stand tending operations (NRCan 2003). Thus, to maintain Canada's international economic competitiveness and to meet global demand for Canadian wood products, the forest industry has sought to improve forest productivity through more intensive silvicultural practices (NRCan 2009).

Ontario is one of the most forest-rich provinces in Canada, having 32.7 million ha of productive forest area (OMNR 2006a). Most of these forests are in the boreal region, where the goal is to optimize growth rates within the primary objective of sustainable forest management (Hearnden *et al.* 1992). Maintaining overall forest composition is a legal requirement under Ontario's Crown Forest Sustainability Act 1994, which stipulates that "large, healthy, diverse and productive Crown forests and their associated ecological processes and biological diversity should be conserved" (Statutes of Ontario 1995). Ontario Ministry of Natural Resource's directive "Aerial Spraying for Forest Management" states that much of Ontario's forest industry requires coniferous species and that aerial application of herbicides is the most cost-effective way to regenerate conifers (OMNR 2006b). Accordingly, Ontario's forest industry relies heavily on the use of herbicides for forest regeneration, with approximately half of the harvested areas treated (CCFM 2009) once in a 60- to 70-year cycle.

Over the past few decades, a substantial amount of research has been focused on quantifying the gains in wood yield following the management of competing vegetation

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(Wagner *et al.* 2006). The results of about 60 long-term studies in North America, South Africa, South America (Brazil), New Zealand, and Australia have reported 30% to 500% increases in wood volume following effective vegetation treatments (Wagner *et al.* 2006). To ensure that forest management practices on Crown lands are socially acceptable and consistent with the principles of sustainable management, the Vegetation Management Alternatives Program (VMAP) was initiated in Ontario in 1991 to develop and/or refine the use of several alternatives to aerial herbicide application, including motor-manual/mechanical cutting, prescribed burning, biological control, and ground-applied herbicides (Wagner *et al.* 1995). One of the studies initiated under that program was the Fallingsnow Ecosystem Project established near Thunder Bay in northwestern Ontario, where vegetation management treatments were tested for white spruce (*Picea glauca* [Moench] Voss). Tenth-year post-treatment stocking, cost-effectiveness, and stand-level volumes have been reported by Pitt and Bell (2005), Dampier *et al.* (2006), and Bell *et al.* (2011a, this volume), respectively. Bell *et al.* (2011a) assessed stand-level volume responses for 31 combinations of site, species, and treatments from six VMAP studies, including the Fallingsnow Ecosystem Project and reported that 10th-year preferred conifer and gross total volumes ranged from -49% to +556% and -71% to +116%, respectively. However, longer-term effects of different vegetation release treatments on crop tree quality and value have not been quantified. These growth and yield characteristics, in combination with tree geometry and wood characteristics or defects (Steele *et al.* 1994, Guddanti and Chang 1998), affect the quality and value of fibre production and potential future wood products.

Tree diameter at breast height (DBH) and total height are the two most important variables used to determine the yield and quality of lumber, since they affect volume and grade (Houllier *et al.* 1995, Zhang and Chauret 2001). Several studies have shown that value recovery is directly related to tree diameter (Zhang *et al.* 2002, Lei *et al.* 2005, Liu and Zhang 2005). In addition, tree taper influences the value of lumber, as noted for black spruce (*Picea mariana* [Mill.] BSP) by Chuangmin *et al.* (2007). Aubry *et al.* (1998) reported that stem volume was the best single predictor of total value of an individual tree. Cotterill and Jackson (1985) also found significant effects of stem height and diameter on the product value of trees.

The assessment of tree quality has become a crucial issue in the operational value chain as resource managers and the wood processing industry are under increasing pressure to maximize extracted value. Stem quality is an important consideration in quantifying potential lumber recovery and valuing harvested stems and can be classified using measures and observations of standing trees (Stayton *et al.* 1971). Agestam *et al.* (1998) identified ten quality classes for standing trees based on height, stem form, presence of knots, and branch thickness and applied the classification system to assess timber quality in Scots pine. Similarly, Schmidt and Kandler (2009) used six quality classes to grade mature Norway spruce (*Picea abies* [L.] Karst.) trees on the basis of bark characteristics, branch characteristics, stem form, and stem damage. To apply these classification systems to younger trees, some method of projecting future growth and yield is required.

Several simulation models have been developed to project tree growth and quality. Hansen *et al.* (1995) used the ZELIG model to simulate the ecological and economic effects of alternative silviculture regimes for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*). Soalleiro *et al.* (2000) used the PINASTER model to evaluate silvicultural alternatives. The Tree and Stand Simulator (TASS) model has been used for over two decades to generate yield tables for managed stands in British Columbia (Harper and Polsson 2007, Harper *et al.* 2008). Another model, SYLVER is also used in British Columbia to evaluate the effects of silvicultural treatments on yield, lumber value, and economic return (DiLucca 1999). Kabzems *et al.* (2007) used a mixed growth model (MGM) to compare the yield of white spruce in pure vs. mixed stands. In Ontario, Forest Vegetation Simulator (FVS$^{\text{Ontario}}$) has been used to project the growth of forest stands. The model simulates growth and mortality of individual trees within a stand over a specified time period. It can be used to model stands composed of one or several species of any age. Future value of the fibre produced, however, depends on the desired forest product mix. Software such as BUCK-2, a product mix optimization tool (Zakrzewski *et al.* 2010), can be used to optimize the products based on growth and yield projections.

This is one of a series of papers related to forest vegetation management published in the March/April 2011 issue of *The Forestry Chronicle* (see Bell *et al.* 2011b). In this paper, we present results of a study to assess crop tree stem quality and estimate the value of fibre produced following vegetation management treatments in the Fallingsnow Ecosystem Project in northwestern Ontario. The specific objectives were to: (i) compare post-treatment growth and yield characteristics (height, diameter, and gross total volume) of white spruce crop trees, and (ii) estimate stem quality and value of fibre produced 16 years post-treatment, and to use that information to (iii) project expected volume up to age 70 (standard rotation age for white spruce in Ontario) for all treatments, and (iv) generate possible product mixes to compare the projected value of total fibre produced among treatments.

Methods

Study location and design

The Fallingsnow Ecosystem Project (89°49–53′W and 48°8–13′N at 380 m to 550 m above sea level) was established approximately 60 km southwest of Thunder Bay, Ontario (Bell *et al.* 1997) in the transition between the boreal and the Great Lakes – St. Lawrence forests (Rowe 1972). Before harvesting, the site supported three different stand types of 75- to 101-year-old natural forest. The study area was clearcut between 1986 and 1988. Each stand formed one block[4] of 20 or more hectares in a randomized complete block design.

Vegetation management treatments

The original stands were harvested and planted between 1986 and 1989 with 82-cm-tall bareroot white spruce stock (2+2), at 2-m to 2.5-m spacing. White spruce was the preferred crop tree and all analyses reported here are for this species. Within each block, each vegetation management release treatment was applied to a minimum 4-ha plot. Treatments, applied in 1993, were: (i) brush saw (BRU) – motor-manual cutting with

[4] Four blocks were included in the original study design (as per Bell *et al.* 1997) but operational issues resulted in Block 1 being discarded.

brush saws (18 cm above ground line in mid- to late-October), (ii) Silvana (SIL) – mechanical cutting using a Ford tractor mounted with a parallelogram boom attached to a Silvana Selective cutting head (33 cm above ground line in late October to early November), (iii) Vision (VIS) – glyphosate herbicide (trade name Vision®) applied at 1.5-kg acid equivalent (a.e.) per ha delivered aerially via a Bell 206 helicopter in August, (iv) Release (REL) – triclopyr herbicide (trade name Release®) applied at 1.9 kg a.e. per ha delivered aerially via a Bell 206 helicopter in August, and (v) control (CON) – untreated control (for additional details about study establishment see Bell *et al.* 1997).

Data collection and analyses

Tree measurements

Two crop tree plots (approximately 30 m × 40 m) were established in each block/treatment combination before the vegetation management treatments were applied (Bell *et al.* 1997). In each plot, 20 crop trees were permanently marked for periodic remeasurement. The plots were remeasured in 2000 (seven years post-treatment), 2003 (10 years post-treatment), and 2009 (16 years post-treatment). In the summer of 2009, diameter at breast height (DBH), total tree height, average crown width, and height of the lowest living branch were measured. Crop tree mortality estimates were based on the number of living trees in each treatment plot. Previous crop tree measurement data were obtained from MNR's Ontario Forest Research Institute (2000 data – Bell, unpublished data; 2003 data – Bell *et al.* 2011a, this volume). Gross total volume (GTV) was computed using Honer's equation (Honer *et al.* 1983):

$$[1] \quad V_T = \frac{0.0043891 \quad D^2(1 \quad 0.04365 \quad B_2)^2}{(C_1 + 0.3048 \quad C_2/h)}$$

where: V_T = gross total volume (m^3)
D= diameter at breast height (cm)
h = total tree height (m)
B_2, C_1 and C_2 are constants

Volume was not computed from 2000 (i.e., seventh year post harvest) data because the trees were too small for the models used in FVS^{Ontario}. Stem taper was calculated using the ratio of DBH to total height (cm:m) for 2009 data.

Growth projection model

We used FVS^{Ontario}—a non-spatial, individual-tree growth model—to project expected crop tree volumes. The model simulates (projects) changes in diameter increment of individual trees using current size and calibrated values of previous growth. An increment model accumulates periodic increments over successive time intervals (e.g., five or 10 years) (for details about FVS^{Ontario}, see ESSA 2008). For all treatments, we used the same forest region, site quality (Site quality II, Ontario West), crop species, and plantation year. We simulated total volume assuming equal spacing between existing trees and no intermediate silvicultural operations. The existing inventory condition was defined using the 2003 and 2009 tree measurements (height, diameter, and number of trees per ha) for all three blocks combined. To compare the value of fibre produced among treatments, merchantable volume was projected to 70 years. Value was linked to product recovery and stem quality attributes.

Product-mix optimization model

Future value of projected fibre production, which was based on volume estimates obtained using FVS^{Ontario}, depends on the desired forest product mix. We used BUCK-2 software (Zakrzewski *et al.* 2010) to optimize the future forest product mix. Roundwood timber products and desired size limits (length, minimum diameter) and rankings of log categories (e.g., sawlogs, veneer logs) were defined as follows: 2.44 m (8 feet) minimum length and 15 cm minimum diameter for the first category of saw log (Rank I); 1.83 m (6 feet) minimum length and 10 cm minimum diameter for the second category of saw log (Rank II); 1.22 m (4 feet) minimum length and 5 cm minimum diameter for pulp logs (Rank III) and a kerf factor of 1.5 cm (assuming wastage allowance for circular saw). We did not specify or rank products for utility pole or veneer logs.

Stem quality and value

Based on the 2009 assessment, all measured stems were assigned to four quality classes: Q1 to Q4, from highest to lowest (Table 1). Since height, diameter, and taper are the major attributes of tree quality, these simple parameters are often used to assess grades (Agestam *et al.* 1998). In addition to these attributes, we included crown width and height to the lowest living branch to define tree quality grades. An equal weight was assigned to each criterion (measured attribute) to calculate the stem quality classes. We assumed that internal defect levels were consistent among treatments.

As of 2009, the fibre produced in the white spruce plantations was considered juvenile and not appropriate for structural use. Thus, its merchantable value was limited to hog fuel. In Thunder Bay, Ontario, hog fuel value estimates are based on hog fuel prices for mixed conifer species. We estimated a price of CDN $20 per m³ of hog fuel wood, based on local market value (Buchanan Pulp Sales Thunder Bay, 2009, personal communication). After 50 years the trees would be large enough to produce additional products. Wood price statistics for 2009 (December average) (Random Lengths 2009) were used to estimate the value of lumber that could be recovered from the 70-year projected volumes from stems in different treatments. Lumber price was calculated by averaging prices given for SPF eastern green lumber for 2×4s, precision end trim (PET), stud grade, #1 and #2, and random.

Table 1. Criteria for tree quality classes applied in this study, modified from Agestam *et al.* (1998)

	Measured attribute				
Quality class	DBH (cm)	Height (m)	Crown width (m)	Crown height (m)	Taper (cm/m)
1	>9.0	>6.0	>3.0	>1.5	>1.5
2	6.0 to 9.0	4.0 to 6.0	2.0 to 3.0	1.0 to 1.5	1.0 to 1.5
3	3.0 to 6.0	2.0 to 4.0	1.0 to 2.0	0.5 to 1.0	0.5 to 1.0
4	<3.0	<2.0	<1.0	<0.5	<0.5

Stem taper and diameter affect the value of lumber recovered from conifer logs. Generally, 50% to 80% of the wood volume can be recovered (turned into a product) depending on species and age of the crop (Zhang 2003). Accordingly, we used lumber recovery ranges of 50% to 80% in 10% increments linked to the four quality grades. We assumed that the current stem quality grades will remain valid to rotation age and that the effects of other damaging agents, such as fire and insects, would be similar among treatments and quality grades. The value of pulp wood was estimated using the current market price ($31.25 per green ton) for white spruce in the Thunder Bay area (Buchanan Pulp Sales Thunder Bay, 2009, personal communication). Volume that could not be assigned to lumber or pulp was considered hog fuel and valued at $20.00 per m^3.

Statistical analysis

To elucidate the differences in white spruce height, diameter, and gross total volume among treatments, we applied analysis of variance (ANOVA) with a post hoc Duncan's test at 5% significance level using SPSS (SPSS Inc. 2008). ANOVA with planned orthogonal contrasts (SPSS Inc. 2008, Field 2009) was used to compare overall stem quality among treatments and the projected future value of fibre produced (based on 2009 prices). The orthogonal contrast comparisons were: within mechanical cutting treatments (BRU vs. SIL), within herbicide treatments (REL vs. VIS), between herbicides and cutting treatments (BRU + SIL vs. REL + VIS), and between control and all release treatments combined (CON vs. (BRU + SIL + REL + VIS)/4).

The linear model for the ANOVA was:

$$[2] \quad Y_{ij} = \mu + B_i + T_j + \mathring{a}_{ij}$$

where: Y_{ij} is the calculated response from i^{th} block and the j^{th} treatment
μ is the overall mean
B_i is the random effect of the i^{th} block (i = 1, 2, 3)
T_j is the fixed effect of the j^{th} treatment (j = 1, 2, 3, 4, 5)
$\mathring{a}_{ij}$ is the (pooled) interaction effect of the i^{th} block and the j^{th} release treatment with error term to test the treatment effect.

Statistical significance of differences among treatments was tested by pooling the interaction term (B*Tij) with the error term in the model.

Results

Crop tree growth and yield: Observed

Diameter

Fig. 1a shows the average diameter of crop trees from all treatments. In all cases, REL and VIS plots contained stems with the highest average diameters. Sixteenth-year (2009) post-treatment diameter of trees in the control plots differed significantly ($p < 0.001$) from that of trees in the mechanical cutting (BRU and SIL) and herbicide treatment (REL and VIS) plots. However, differences between trees within the mechanically cut (BRU and SIL) and those within the herbicide (REL and VIS) treated plots were not significant ($p = 0.113$). A similar trend was observed for the 10^{th}-year post-treatment (2003) data, but was less apparent in the seventh-year post-treatment (2000) data.

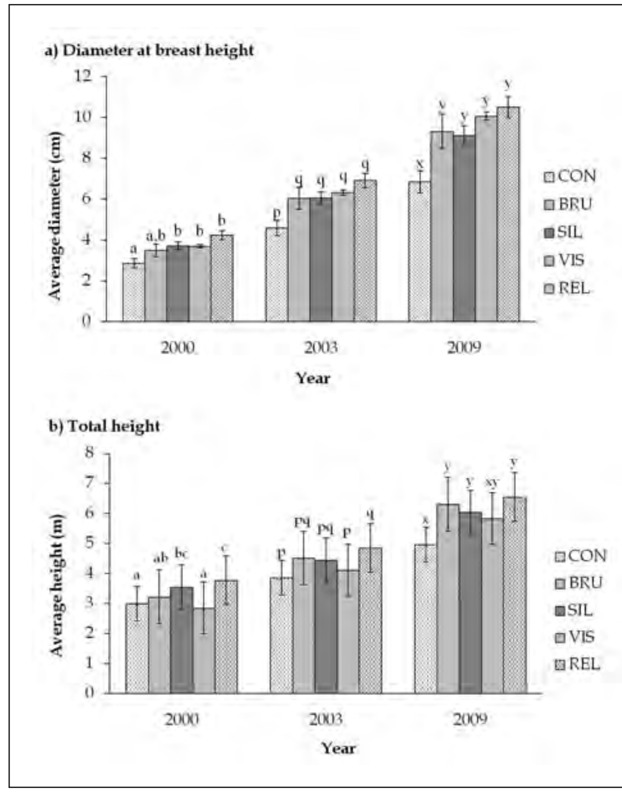

Fig. 1. Average size of white spruce crop trees at 7 (2000), 10 (2003), and 16 (2009) years after vegetation management treatments (CON – control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide) in northwestern Ontario: (a) diameter at breast height, and (b) total height. Letters above each bar show the statistical significance ($p = 0.05$); a, b and c for 2000; p and q for 2003; x and y for 2009; and bars are the standard errors of the mean.

Height

Average crop tree height 16 years post-treatment (2009) was 4.97 m for trees in the control plots compared to 5.83 m in VIS, 6.04 m in SIL, 6.31 m in BRU, and 6.55 m in REL (Fig. 1b). Average height of trees in the control and VIS plots in 2009 differed significantly ($p < 0.001$) from those in BRU, SIL, and REL plots. In 2000 and 2003, REL differed significantly from VIS and control. Effect of treatments on total height of the crop trees is more evident in 2009 than in 2000 and 2003.

Gross total volume

Volume in 2009 was highest for trees in the REL treatment plots (39.01 m^3 ha^{-1}) followed by those in the VIS (32.42 m^3 ha^{-1}), SIL (29.16 m^3 ha^{-1}), BRU (28.56 m^3 ha^{-1}), and control (14.73 m^3 ha^{-1}) plots (Fig. 2). Similarly in the 2003 measurement, the REL treatment produced the highest average volume (14.39 m^3 ha^{-1}), followed by SIL (11.23 m^3 ha^{-1}), VIS (10.53 m^3 ha^{-1}), BRU (9.98 m^3 ha^{-1}), and control (5.86 m^3 ha^{-1}) plots. In 2003, the orthogonal contrast test established that the average volumes of trees in the REL and SIL treatments differed significantly ($p < 0.001$) from those of trees in the VIS, BRU, and control plots but did not differ between trees

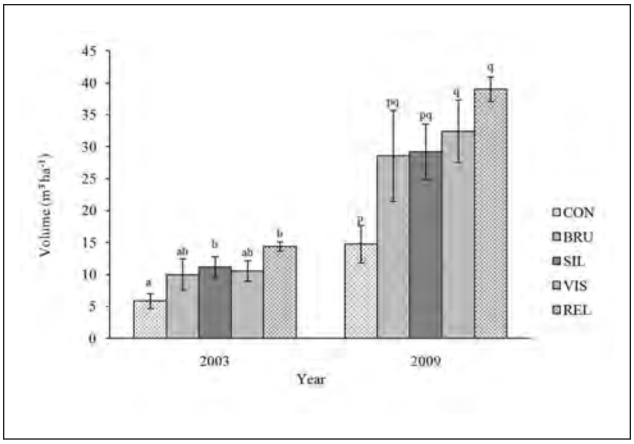

Fig. 2. Average gross total volume of white spruce crop trees at 10 (2003) and 16 (2009) years after vegetation management treatments (CON – Control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide) in northwestern Ontario. Letters above each bar show the significance (p = 0.05); a and b for 2003; p and q for 2009; and bars are the standard errors of the mean.

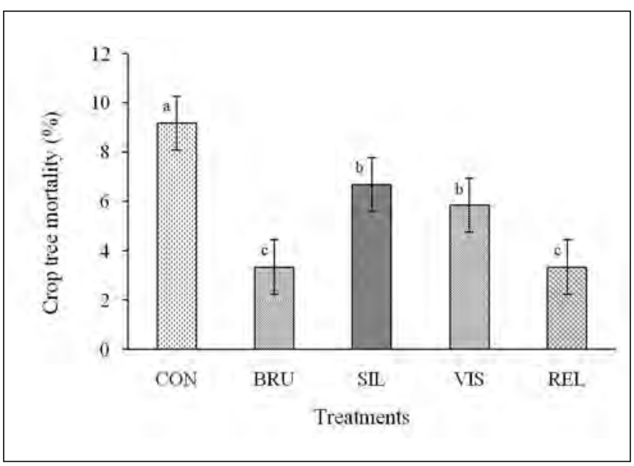

Fig. 3. White spruce mortality occurring between 7 (2000) and 16 (2009) years after vegetation management treatments (CON – Control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide) in northwestern Ontario. Letters above each bar show the significance (p = 0.05); a is significantly different from b and c, b is different from c; and bars are the standard errors of the mean.

in the herbicide (REL + VIS) and mechanically cut (BRU + SIL) plots. By 2009, the gross total volume of trees in the herbicide-treated plots was significantly higher ($p < 0.001$) than those in the mechanically cut and control plots. White spruce mortality was highest in control plots, and differed significantly ($p < 0.001$) from mortality levels in all other treatment plots (Fig. 3). Mortality of trees in REL and BRU plots was significantly lower than that in VIS and SIL ($p = 0.012$) plots but did not differ significantly between the two mechanical cutting and the two herbicide treatments. On average, trees in herbicide-treated plots produced 140% more volume and those in the mechanically cut plots produced about 95% more volume than those in the control plots (Table 3).

Total and merchantable volumes: Projected

Observed and projected gross total white spruce volumes at 10-year intervals are presented in Table 2. For all projection periods, trees in the REL treatment produced more volume than those in the other treatments, with those in the control plots producing the least volume. Fig. 4a shows gross total volumes calculated using Honer's equation (eq. 1) for each treatment for 2009 along with the projected volumes. Merchantable volumes were projected to 70 years using $FVS^{Ontario}$, with the same simulation assumptions as GTV, for trees in all treatments using a minimum top diameter of 10 cm and stump height of 30 cm (Fig. 4b). Trees in the REL treatment had the highest and those in the control plot the lowest merchantable volumes over the projection period.

Stem quality and fibre value: Projected

Crop tree stem quality 16 years (2009) after vegetation management treatments is presented by quality class in Fig. 5. The percentage of trees in the Q1 class was significantly higher in treated ($p = 0.009$) plots than in the control plots, however, differences among treatments were not significant ($p = 0.274$). About 25% of stems were classified as Q1 and 60% were considered Q2. There was no difference in the number of trees in the Q2 class based on treatment. Only 7% of stems were in the Q3 class and only control plots produced stems classified as Q4 (only 1% of all stems).

Average value of fibre produced ($ per ha) from the treatments is presented in Table 3. As of 2009, trees from REL plots produced the highest value (CDN$ 780.28 per ha) – albeit for juvenile fibre valued as hog fuel. This value differed significantly ($p < 0.001$) from that produced by trees in the VIS, SIL, and BRU treated plots, which in turn produced significantly

Table 2. Observed (Honer's Equation) and projected (FVS) gross total volume of white spruce trees following vegetation management treatments (CON – control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide)

	Observed volume (m^3 ha^{-1})		Projected volume (m^3 ha^{-1})					
Treatment	1988–89	2009	2009	2019	2029	2039	2049	2059
CON	0	14.73	19.10	53.27	109.69	145.23	181.31	203.69[a]
BRU	0	28.56	32.00	68.22	133.75	177.09	217.32	248.37[b]
SIL	0	29.16	34.88	74.33	137.34	182.10	224.30	255.04[b]
VIS	0	32.43	36.56	79.34	137.94	185.37	227.04	259.87[b]
REL	0	39.01	40.38	83.26	150.8	205.34	256.53	287.47[c]

Within column, different letters indicate significant differences among treatments ($p = 0.005$).

Table 3. Volume and value of fibre produced by white spruce following vegetation management treatments (CON – control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide) in 2009 (age 20 – measured) and in 2059 (age 70 – projected) compared to that of untreated controls

				Projected					
Treatment	Gross total volume in 2009 (m^3 ha^{-1})	Difference in volume (from control in %)	Value of fibre produced in 2009 ($ per ha)	Merchantable volume in 2059 (m^3 per ha)	Lumber (mbf per ha)	Pulpwood (metric ton per ha)	Hogfuel (metric ton per ha)	Projected value of fibre in 2059 ($ per ha)	Difference in value (from control in %)
CON	14.73	0	294.66 [a]	162.95[a]	74.34	29.17	2.65	18 486.76[a]	0
BRU	28.56	94	571.28[b]	198.70[b]	90.82	43.14	3.99	22 838.99[b]	24
SIL	29.16	98	583.26[b]	204.03 [b,c]	104.58	21.96	3.03	25 392.04[c]	37
VIS	32.43	120	648.60[b]	207.90[b,c]	104.58	24.94	2.89	25 176.52[c]	36
REL	39.01	165	780.28[c]	229.98[c]	116.24	25.31	1.63	28 209.35[d]	53

Within columns, different letters indicate significant differences among treatments ($p = 0.005$).

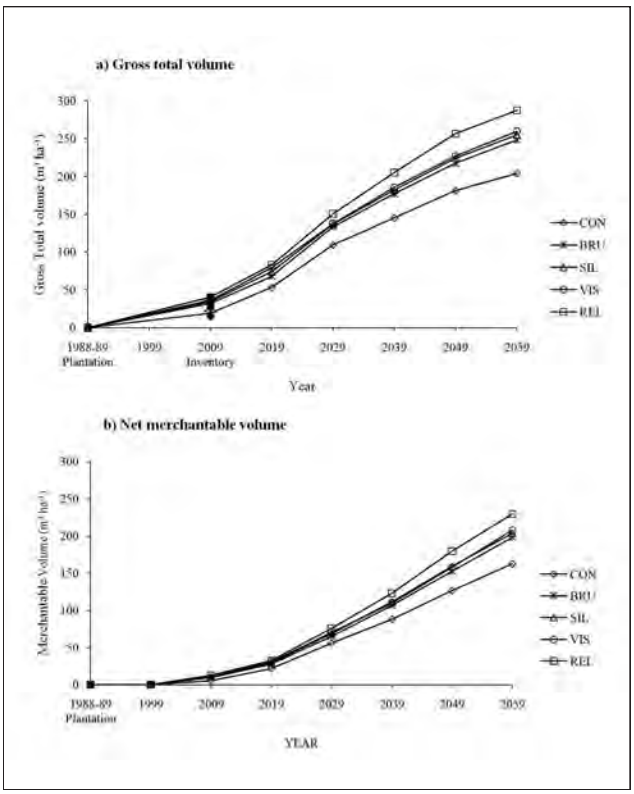

Fig. 4. Projected volumes (1988 to 2059) for planted white spruce in northwestern Ontario following vegetation management treatments (CON – control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide): (a) gross total volume and (b) net merchantable volume. In (a), the mean 2009 measured gross total volumes are indicated using filled symbols.

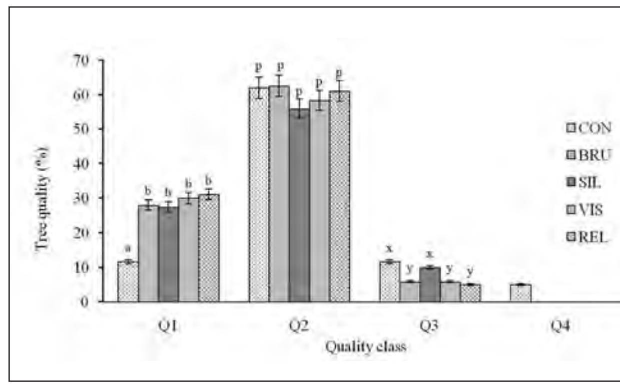

Fig. 5. White spruce tree quality in northwestern Ontario after 16 years (2009) following vegetation management treatments (CON – control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide). Quality grades (Q1 – high quality to Q4 – low quality) were categorized on the basis of visual tree characteristics (height, diameter, taper, crown width, and height to the lowest live branch). Letters above each bar show the significance (p = 0.05); a and b for Q1; p for Q2 and x and y for Q3; and bars are the standard errors of the mean.

($p = 0.002$) more value than trees in the control plots.

Orthogonal contrasts for analysis of variance of future value of fibre produced per ha after 70 years for each treatment group are presented in Table 4. Overall, treatments differed significantly ($p < 0.001$) from one another. Trees in the BRU treatment differed significantly from those in SIL ($p = 0.001$) and those in the REL treatment differed significantly from those in VIS ($p = 0.007$). The value of fibre produced by trees in the cutting treatments differed significantly from those in the herbicide treatments ($p < 0.001$) and all treatments differed significantly from controls ($p = 0.048$). Trees in the herbicide-treated and mechanically cut plots produced significantly more (36%–53% and 24%–37%, respectively) value based on potential wood products at 70 years than those in control plots (Table 3).

Discussion

We discuss our results in terms of: (i) stem mortality, diameter, height, and volume; (ii) stand level gross total and merchantable volumes; (iii) stem quality; and (iv) stand level value of fibre produced. Our results are directly related to how well the treatments suppressed competitive vegetation when the white spruce trees were establishing.

Stem mortality, diameter, height, and volume were all affected by the vegetation management treatments. Stem mortality was significantly lower, and diameter and height of

Table 4. Analysis of variance results with orthogonal contrasts for future (year 70) value of fibre produced ($ per ha) by white spruce following vegetation management treatments (CON – control, BRU – brush saw, SIL – Silvana Selective, VIS – Vision herbicide, REL – Release herbicide)

Source	df	Type III SS	Mean square	F-ratio	F-crit (0.05)	*p*-value
Constant	1	8.66E + 09	8.66E + 09			
Block	2	9.09E + 06	4.55E + 06			
Treatment	4	1.58E + 08	3.96E + 07	43.23	3.84	< 0.001
BRU vs. SIL	1	2.84E + 07	2.84E + 07	31.04	5.32	0.001
REL vs. VIS	1	1.19E + 07	1.19E + 07	13.01	5.32	0.007
Cutting[a] vs. Herbicides[b]	1	1.13E + 08	1.13E + 08	123.45	5.32	< 0.001
CON vs. Treatments[c]	1	5.01E + 06	5.01E + 06	5.47	5.32	0.048
Error (Block×Treatment)	8	7.32E + 06	9.15E + 05			
Total	14	1.75E + 08				

[a]BRU and SIL
[b]REL and VIS
[c]BRU, SIL, REL, VIS

trees in plots treated with vegetation management alternatives were much higher than those of trees in controls, resulting in more gross total volume 16 years after treatment. Our observations that reducing competitive vegetation improves survival, diameter, and height concur with other published results. Sutton (1995) also reported increased survival following control of competitive vegetation. Results from many other studies confirm that white spruce produces more volume following vegetation management treatments (Wagner *et al.* 2006; Boateng *et al.* 2006, 2009.

Although projected gross total volumes calculated using FVS^{Ontario} compare with volumes calculated using Honer's equations (Table 2) and with volumes presented in Bell *et al.* (2011a) they are typically lower than those reported for the few other intensive forest management studies focused on white spruce in Ontario. McClain *et al.* (1994) reported GTV of 208 m^3 ha^{-1} for a 37-year-old plantation near Thunder Bay, Ontario, and Stiell and Berry (1973) reported a GTV of 244 m^3 ha^{-1} in 50 years for trees planted at 2.7 m spacing near Petawawa, Ontario. Similarly, Morgenstern *et al.* (2006) reported maximum volumes of 287 m^3 ha^{-1} and 216.7 m^3 ha^{-1} for white spruce of Thunder Bay and Kakabeka seed origin in 44-year-old provenance trials established at the Petawawa Research Station. Richer site quality could be one of the reasons for higher GTVs in those studies. It is also plausible that stem densities in the Fallingsnow Ecosystem Project are lower than those in other studies. In this study, white spruce densities were approximately 917 to 1722 stems per ha in the control and continuous removal plots respectively. Whereas other studies found stem densities of 1162 trees per ha (McClain *et al.* 1994), 1372 trees per ha (Stiell and Berry 1973), and 2400 trees per ha (Morgenstern *et al.* 2006). The 20-year maximum height in our study was 9 m, which is lower than those reported for the other studies mentioned. The lower projected values in our study could also be the result of our assumption of average site quality (we may have been overly conservative in our estimate of intermediate site quality) and because we included only white spruce in the FVS^{Ontario} simulations although other trees (and thus available volume) were present on site.

Based on external features of individual stems (Table 1), our results suggest that vegetation control improved stem quality. Approximately 80% of trees in all treatments were classified as having good stem quality (i.e., Q1 and Q2) 16 years after treatment. However, the proportion of stems in the Q1 class was significantly lower for the control plots. More tests to compare intrinsic tree characteristics, including wood defects and mechanical properties, may help to determine differences among treatments (Wang *et al.* 2001). The trees are still too immature (20 years from establishment) for destructive sampling for internal wood characteristics, but mechanized non-destructive testing in standing trees could be carried out for basic wood density, ring width, and wood strength.

The average value of fibre produced by trees in herbicide-treated (VIS and REL) and mechanically cut (BRU and SIL) plots were significantly higher ($p = 0.05$) than that of trees in control plots. Our value analysis is based on the FVS^{Ontario} projections for merchantable volume of crop trees at 70 years, tree quality assessed for measured crop trees, and lumber recovery factors for the various quality grades based on December 2009 average wood prices (Random Lengths 2009). McClain *et al.* (1994) reported that the net value of 37-year-old pure white spruce established at 2.7-m spacing was CDN $6891 per ha (at 1994 market price, which is equivalent to about CDN $11 544 per ha at 2009 values compounded at 3.5%). This is the only other boreal Ontario study we could find for which white spruce values were reported. This value is proportionally greater than our estimated average value of CDN $10 155 per ha ($9964 including the controls) per ha at 2009 prices. The difference may be because the McClain *et al.* (1994) study was an intensive spacing trial on a site of relatively better quality.

Conclusion

In our 16th-year post-treatment assessment of a vegetation management study in northwestern Ontario, we found that, although overall average tree quality classes did not differ significantly among treatments, vegetation management treatments produced higher numbers of larger and thus better quality—from a potential wood products perspective—white spruce crop trees. Height and diameter growth, gross total volume, and projected value of fibre produced were higher for trees in herbicide-treated and mechanically cut plots than for those in untreated controls. In general, trees in herbicide-treated (VIS and REL) plots produced more volume with higher future value than those in mechanically cut (BRU and SIL) plots. These results suggest that vegetation management treatments result in more volume 16 years post-treatment and have the potential produce much higher future wood values at age 70.

Prior to extrapolating this conclusion beyond this study, we suggest that since we considered only fibre value the cost of the various treatments and all other costs associated with the production of fibre and wood volume need to be compared more thoroughly. Future research could focus on cost–benefit analysis of fibre production at the stand level, comparing results among vegetation management studies as well as with those from other operational tending studies in boreal Ontario, to determine whether the additional volume produced is economically viable.

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