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ARTICLE

Effects of overtopping on growth of white spruce in Alaska

E.C. Cole, M. Newton, and A. Youngblood

Abstract: Early establishment of competing vegetation often presents an obstacle to the success of planted white spruce (*Picea glauca* (Moench) Voss) seedlings. We followed growth and development of white spruce and associated vegetation for up to 17 years in Alaska's boreal forests to quantify roles of overtopping plant cover in suppressing conifers. The three study areas represented a range of site conditions of varying productivity and species of competing cover, different site preparation and release treatments, and different bare-root and container white spruce stock types. Herbaceous overtopping peaked early after planting and decreased as white spruce were able to outgrow competitors. Overtopping by shrubs and hardwoods, especially aspen (*Populus tremuloides* Michx.) and resin birch (*Betula neoalaskana* Sarg.) peaked somewhat later than herbaceous overtopping and decreased over time for most sites and treatments. In a model that combined all sites, vegetation management treatments, and years, overtopping and previous year's volume explained approximately 85% of the variation in volume growth. Increasing the size of planting stock helped reduce overtopping, hence suppression, even in treatments dominated by hardwood species. Results suggested that control of overtopping was essential for maximum growth and long-term or increasing levels of overtopping severely suppressed white spruce seedling growth.

Résumé : L'établissement précoce de la végétation concurrente compromet souvent le succès des semis plantés d'épicéa blanc (*Picea glauca* (Moench) Voss). Nous avons suivi la croissance et le développement de l'épicéa blanc et de la végétation associée pendant 17 ans dans les forêts boréales de l'Alaska, dans le but de quantifier le rôle que joue le couvert végétal dominé par les espèces concurrentes dans la suppression des conifères. Les trois zones d'études représentaient un éventail de conditions de station incluant différentes productivités et compositions en espèces du couvert formé par la végétation concurrente, différentes préparations de terrain et différents traitements de dégagement, ainsi que différents types de plants d'épicéa blanc, à racines nues ou en récipient. La domination des plantes herbacées a atteint un sommet tôt après la plantation et a diminué par la suite étant donné que l'épicéa a réussi à dépasser les compétiteurs. La domination des arbustes et des feuillus, particulièrement le peuplier faux-tremble (*Populus tremuloides* Michx.) et le bouleau d'Alaska (*Betula neoalaskana* Sarg.), a culminé un peu plus tard que celle des plantes herbacées et a diminué avec le temps dans la plupart des stations et des traitements. Dans un modèle qui combinait toutes les stations, tous les traitements de gestion de la végétation et toutes les années, la domination des espèces concurrentes et le volume de l'année précédente expliquaient approximativement 85 % de la variation de l'accroissement en volume. L'augmentation de la taille des plants a contribué à réduire la domination des espèces concurrentes, et par conséquent la suppression, même dans les traitements dominés par des espèces feuillues. Les résultats indiquent que la maîtrise de la domination des espèces concurrentes est essentielle pour une croissance maximale et que la domination de longue durée ou de forte intensité des espèces concurrentes réduit sérieusement la croissance des semis d'épicéa blanc. [Traduit par la Rédaction]

Introduction

Forests have been identified as critical components to a sustainable future (FAO 2012). Planting trees can be used to establish or restore biodiversity and ecosystem function (Ciccarese et al. 2012; FAO 2012) after deforestation. Large deforestation events have occurred in white spruce (*Picea glauca* (Moench) Voss)[1] forests of interior and south-central Alaska. Bark beetle (*Dendroctonus rufipennis* Kirby) attacks and wildfires in the past two decades have resulted in extensive white and Lutz (*Picea* X *lutzii* Little) spruce mortality (Werner et al. 2006). Restoration of these forests after bark beetle attacks, wildfire, and clear-cut harvesting has been limited. Alaskan forest practice regulations allow 5 years after commercial harvest before reforestation must be completed; white spruce forests must be planted or otherwise be restocked with 1111 trees per hectare that survive more than 2 years (Alaska Forest Resources and Practices Act 2009). Planting with or without site preparation has been shown to be successful for reforesting white spruce in Alaska (Cole et al. 1999; Cole et al. 2003; Youngblood et al. 2011). Natural regeneration in beetle-infested stands is highly dependent upon forest type and degree of spruce mortality within the stands (Boucher and Mead 2006). White spruce regeneration can be limited wherever early seral vegetation occupies stands before natural regeneration can become established (Holsten et al. 1995). Bluejoint grass (*Calamagrostis canadensis* [Michx.] Beauv.), a frequent understory species throughout the boreal forest, inhibits spruce regeneration (Martin-DeMoor et al. 2010). The loss of seed trees reduces the reliability of natural regeneration (Martin-DeMoor et al. 2010).

The effects of competing vegetation on white spruce plantations have been well-documented in Canada (DeLong 1991; Jobidon et al. 2003; MacDonald and Thompson 2003; Boateng et al. 2009; Man et al. 2009; Pitt et al. 2010) and in Alaska (Cole et al. 1999; Cole et al. 2003; Youngblood et al. 2011). Light is considered the primary limiting resource in boreal forests (Newton et al. 1992; Macadam and Kabzems 2006; Man et al. 2008), although competing vegetation can also affect soil temperatures, nutrients, and soil moisture (Brand 1991; Lieffers et al. 1993; Thevathasan et al. 2000; Hangs et al. 2003). Several studies from Canada have quantified the reductions in white spruce growth with competition,

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[1]Plant nomenclature based on United States Department of Agriculture, Natural Resources Conservation Service plant database, plants.usda.gov.

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primarily for light (Comeau et al. 2003; Jobidon et al. 2003; Filipescu and Comeau 2007; Cortini and Comeau 2008), and some studies have suggested that various vegetation management treatments can increase white spruce growth for up to 20 years (Boating et al. 2006; Boateng et al. 2009). Efficacy of treatment for increasing tree growth has varied across sites, resulting in various degrees of competition related to treatments. Some of these studies have presented models to describe the relationship between competition and white spruce growth (Filipescu and Comeau 2007; Cortini and Comeau 2008), and these models can be used to describe the impact of competition independent of mechanisms of treatment. These studies generally considered competing vegetation as ground cover or a single measure of competition in time rather than assessing the shifting effects of overtopping of seedlings over time.

Seedling size and vigor are also important factors in establishing plantations. Jobidon et al. (2003) observed that after outplanting, different sizes of container stock received varying levels of light. The greatest increases in growth occurred between the 110 and 340 cm^3 container stock, and that corresponded to the greatest increases in light energy. Mullin (1963) and Grossnickle (2005) reported growth advantages from large transplant white spruce seedlings, suggesting that competition management with a range of stock sizes may reveal complementary responses of stock size with vegetation management. Grossnickle (2000) and Cole et al. (2003) identified interaction of seedling size and competition, with the observation that either reduction in cover and (or) increase in seedling size and quality would lead to a reduction in overtopping, hence improved longer term growth. While this early work points to a clear linkage among initial seedling size and effects of competing vegetation, as of yet, little attention has been directed at the interaction of overtopping competition with different sizes of seedlings over time.

Comparison of short-term effects of treatment to those from longer time periods has not always yielded consistent results. Seedling growth trends followed for 20 years after treatment at two sites in British Columbia were similar to those reported after 5 years (Boateng et al. 2009). In contrast, vegetation management treatment effects were similar after 20 years on another site, but stock type differences were not maintained (Boating et al. 2006). Man et al. (2008) speculated that differences in vegetation development in later years may impact longer term results, so there is incentive to track vegetation development and influence through time. As of yet, few studies have addressed the long-term implications of treatments that may initially reduce competing vegetation, or followed the development of overtopping vegetation that may impact subsequent stand development.

Developing a model that describes growth losses based on fluctuating levels of competition will allow managers to determine if site preparation or release treatments are warranted and (or) feasible over an extended time interval. However, quantifying the degree of competition that impacts growth can be time-consuming and expensive depending upon the evaluation method. Several studies (Simard 1990; Wagner and Radosevich 1991; Newton et al. 1992; Bell et al. 2000) have indicated that visual estimators of competition are as effective as measured parameters for evaluating growth losses. Visual estimates of percent overtopping have been effective as an indirect measure for light competition (Howard and Newton 1984; Newton et al. 1992; Cole et al. 1999, 2003; Harrington 2006).

To determine the impacts of overtopping on white spruce growth in Alaska, we used data from three long-term studies in two areas where competition and conifer growth were followed for up to 17 years after planting. Our specific objectives were to (1) determine the impacts of different vegetation management treatments on overtopping, (2) determine if onset of overtopping varied with different stock types, and (3) assess the impact of overtopping on white spruce volume over time.

Methods

Research installations and climate

Experiments were installed in areas ranging from very cold to more moderate locations within the range of white spruce in Alaska. The oldest experiment, Bonanza Creek Competition Study (BCCS), is located west of Fairbanks (lat., 64.51°N; long., 148.44°W; elevation 250 m) in and adjacent to the Bonanza Creek Experimental Forest. This area is north of the Tanana River, where thick deposits of micaceous silt loess provide deep soils on relatively warm southern exposures that lack permanent frost. Precipitation in the area averages 280 mm·year^{-1}, peaking in August. The short summers have long days and moderate temperatures; winters are long and severe, but deep snow offers some protection against deep soil freezing. Occasional heavy snow and freezing weather may occur in September. Surrounding stands are dominated by white spruce (35 m at 100 years) with resin birch (*Betula neoalaskana* Sarg.) and aspen (*Populus tremuloides* Michx.) suckers, fireweed (*Chamerion angustifolium* (L.) Holub), and bluejoint grass (*Calamagrostis canadensis* [Michx.] Beauv.) abundant in the understory. This study area was more fully described by Cole et al. 2003.

The other two competition studies, Fort Richardson Competition Study (FRCS) and Fort Richardson Mature Forest Study (FRMF), are at Fort Richardson, Alaska, near Anchorage, (lat., 61.15°N; long., 149.45°W; elevation 30 m). Both are on gently undulating gravelly glacial outwash soils with a surface layer of 15–30 cm of silty loess and volcanic ash. Precipitation averages 400 mm annually, about half occurring as snow. Temperature extremes are similar to Bonanza Creek in summer and less frigid in winter. These studies were described earlier by Cole et al. (1999, 2003).

Study designs

The BCCS experiment was installed at three locations within 8 km of each other, each with a different recent disturbance history:

1. A 3-year-old clearcut (OC) was prepared with a disc trencher. We removed existing seedlings that interfered with our experiment.
2. A new clearcut (NC) was adjacent to the OC and was harvested 1 year before the site was planted.
3. The third site (BU) was an older clearcut that first was treated with a nontranslocated herbicide (bialaphos) to desiccate shrubs and herbs, and then was broadcast burned.

The experimental design at BCCS was completely randomized within each installation with three replications of each of six vegetation management treatments (Table 1). Plot size was 13 m × 16 m, planted in 1991 at a 3 m × 3 m spacing with twenty 1+0 plug seedlings of local seed origin grown in the Alaska State Nursery that had been overwintered close to the study sites.

The FRCS experiment was established at three sites within 12 km of each other:

1. "Firewood" (FW) was a productive site previously occupied by 60-year-old resin birch with an understory dominated by bluejoint grass; the birch had been harvested for firewood 1 year previously by a feller-buncher leaving bluejoint grass and fireweed the dominant cover, with resin birch, willow (*Salix* spp.), and Sitka alder (*Alnus viridis* (Chaix) DC. ssp. *sinuata* [Regel] Á. Löve and D. Löve) seedlings in scarified areas.
2. "Davis" (DA) was a site with intermediate productivity that was occupied by resin birch and aspen, with Sitka alder in the understory. This site was cleared 1 year previously for firewood and for moose habitat enhancement.
3. "Bulldog" (BD) was the poorest site, and was located in a cold-air drainage. This site was dominated by resin birch and aspen, with a considerable presence of Labrador tea (*Ledum* spp.); it was cleared about 3 years previously for moose habitat enhancement.

Table 1. Vegetation management treatments for the Bonanza Creek Competition Study, interior Alaska.

Treatment	Herbicide applied	Date applied
Untreated (UNTR)	None	None
Weed-free (WEED)	Broadcast application of 1.2 kgae·ha^{-1} glyphosate[a]	August 1990
	Broadcast application of 1.6 kgae·ha^{-1} glyphosate[a]	August 1991 (New and Old Clearcut units only; seedlings covered by bags during application)
	Directed application of 2% glyphosate	July 1991, June 1992, May 1993, May 1994, and May 1995
Site preparation (SIPR)	Broadcast application of 1.7 kg·ha^{-1} hexazinone + 1.6 kgae·ha^{-1} glyphosate[a]	August 1990
Year 1 release (Y1RE)	Broadcast application of 1.7 kg·ha^{-1} hexazinone	May 1991
Year 2 release (Y2RE)	Broadcast application of 1.7 kg·ha^{-1} hexazinone	June 1992
Years 1 and 2 release (Y12R)	Broadcast application of 1.7 kg·ha^{-1} hexazinone	May 1991 and June 1992

[a]ae, acid equivalent of glyphosate.

At each FRCS site, a randomized complete block experiment was installed with two replications of the four vegetation management treatments (Table 2). Each plot was planted in 1992 with forty 1+0 containerized seedlings grown at the Alaska State Nursery from local seed.

The FRMF experiment was established in two adjacent 5-ha clearcuts recently dominated by white spruce averaging about 25 m tall, and 60- to 70-year-old resin birch about 20 m tall. The understory was dominated by highbush cranberry (*Viburnum edule* (Michx.) Raf.), alder, Labrador tea, and fireweed. During logging operations, unintended scarification by dozer blade and yarding left swaths of exposed mineral soil even in the untreated plots.

The experimental design at FRMF was a randomized block split-plot repeated on two sites, with four 0.2-ha square plots in each of two blocks on each site. Whole-plot treatment was manipulation of vegetation (Table 2). Three types of white spruce seedlings were planted in randomized rows in May 1993:

1. 1+0 white spruce plugs from local seed grown at the Alaska State Nursery, Eagle River, Alaska (SN); 30 seedlings in each plot.
2. 1+0 white spruce plugs from the same seed source as above, grown at the Dean Creek Nursery, Oregon (DC); 14 seedlings in each plot.
3. Plug+1 (P1) white spruce seedlings grown in raised beds on site, from the same seed source as above; 30 seedlings in each plot.

Measurements

White spruce seedlings in each of the previously mentioned studies were evaluated at time-of-planting, annually in their first 5 years after planting, and at intervals of 2–4 years thereafter through year 15, 16, or 17 (the most recent measurement for each of the experiments). The three experiments began with a total of 3800 white spruce seedlings. Seedling measurements at each visit included total height and height to each node since previous measurement (to obtain yearly height when not measured annually), basal diameter at 15 cm above ground level, and diameter at 137 cm. Root collar diameter was measured for FRCS and FRMF through year 7 or 8. At each measurement through year 5, total plant cover was recorded by species group within a 0.5 m radius of each seedling. Overtopping (maximum 100%) for each seedling was estimated by visual measures of occlusion by leaf area projected within a 60° conical projection above the second node from the top (Howard and Newton 1984). Instances of insect or animal injury or damage, such as loss of bud, top dieback, or becoming lodged under fallen vegetation, were noted during each plantation evaluation.

Analyses

Previous analyses (Cole et al. 1999, 2003) indicated treatment effects varied among the sites, and treatment impacts on growth varied based on treatment efficacy within sites. For work reported here, we first evaluated whether overtopping that developed differed among treatments. Then we asked if overtopping could be used to assess growth impacts on seedlings rather than focus on the impacts of specific treatments. We emphasized overtopping as an indicator of competition and stem volume as the primary response variable.

Initial analyses using analysis of variance (ANOVA) (SAS PROC GLIMMIX or MIXED software) examined whether vegetation treatments affected overtopping within each experiment. Year was included as a continuous regression variable within the multivariate ANOVA, allowing us to test for main effects and to generate equations through time. The shape of the overtopping curves in time could not be linearized, however, leading us to abandon these analyses and analyze overtopping individually for years 1, 2, and the most recent measurement for each of the experiments. Although constructed as a randomized complete block design, we were unable to analyze BCCS as such because of site by treatment interactions. Sites were therefore analyzed individually as completely randomized designs. FRCS was analyzed as a randomized complete block design and FRMF as a split-plot design with whole plots arranged in a randomized complete block design.

Because treatment effects on overtopping varied among the experiments, we tested an equation that incorporated all sites and years using overtopping as an index of competition. For simplification, we only utilized plug seedlings in the model. We selected a modification of the equation

$$(1)\qquad y_1 - y_0 = a[1 - (1 - e^{m_1 \mathrm{CI}})^d]\, y_0{}^b$$

where y_0 and y_1 are volume at the beginning and end of the time period (year), respectively; CI is a competition index; and a, b, and m_1 are model parameters to be estimated, as presented in Richardson et al. (1999). Volume was derived using the formula for a cone (one-third height × basal area at 15 cm). Our competition index was overtopping. As suggested by Richardson et al. (1999), we modified the equation to account for climatic differences in

Table 2. Vegetation management treatments for two studies at Fort Richardson, south-central Alaska.

Treatment	Herbicide application	Date applied
Fort Richardson Competition Study		
Untreated (UNTR)	None	None
Weed-free (WEED)	Broadcast application of 2.2 kgae·ha⁻¹ glyphosate[a]	August 1991
	Directed applications of 2% glyphosate	Annually June 1992–1996
Site preparation (SIPR)	Broadcast application of 1.7 kg·ha⁻¹ hexazinone + 1.7 kgae·ha⁻¹ glyphosate[a]	August 1991
Year 1 release (RELE)	Broadcast application of 1.4 kg·ha⁻¹ granular hexazinone	June 1992
Fort Richardson Mature Forest Study		
Untreated (UNTR)	None	None
Blade (BLAD)	Mechanical scarification with a large bulldozer with straight blade	August 1992
Site preparation (SIPR)	Broadcast application of 1.7 kg·ha⁻¹ hexazinone + 1.7 kgae·ha⁻¹ glyphosate[a]	August 1992 before logging
Spot (SPOT)	1.7 kgae·ha⁻¹ glyphosate[a] + 1.7 kg·ha⁻¹ hexazinone, applied in a 1.5 m strip within each planting row	May 1993 before planting

[a]ae, acid equivalent of glyphosate.

growth for each year and to allow for a differential effect of overtopping based on the age of the seedling. In addition, we included a term for site index

$$(2)\qquad y_1 - y_0 = (a_1\text{age}_1 + a_2\text{age}_2 + \ldots a_{17}\text{age}_{17}) \times \text{SI} \times m \times y_0{}^{b}$$

where

$$(3)\qquad m = 1 - \{1 - e^{[\text{over}(m_1\text{age}_1 + m_2\text{age}_2 + \ldots\ m_{17}\text{age}_{17})]}\}^{d}$$

and *over* is overtopping for each measurement period, SI is site index (m), and age is a dummy variable with a value of 1 for the corresponding year and a value of 0 otherwise. We used the year-15 height of the top 5% of the seedlings at each site as a measure of site index. Measurements of seedlings at the different sites varied in their intervals. This necessitated interpolating volume and overtopping between measurements. We used relative volume growth rate within a growing period to estimate volume for nonmeasurement years within that period and did a linear estimation for overtopping. Although the power function is not applicable once growth increments approach asymptotes, our seedlings had not reached that stage, and we found the previously mentioned equation provided a better fit to the data than modifications of other growth functions. All models used data from individual seedlings rather than treatment and site means. Parameter estimates were made and models tested using PROC NLIN in SAS software. Even though many spruce reached sapling size before our last set of measurements, we refer to them as seedlings throughout.

Results

Overtopping changed through time as competing vegetation developed after logging disturbance and treatments and as seedlings simultaneously grew in height. The general pattern was for overtopping by herbaceous vegetation to peak in the first 2–5 years (Fig. 1), and shrub overtopping to peak later (Fig. 2). The timing of maximum shrub overtopping was highly dependent upon the shrub species present at each site and the density of its crown cover. Shrub overtopping on sites with predominantly low shrubs (Labrador tea and prickly rose (*Rosa acicularis* Lindl.)) tended to reach the highest levels prior to year 8. Sites with a mixture of low shrubs and hardwoods attained the highest peaks after year 8. A few of the sites exhibited two peaks of overtopping as seedlings outgrew low shrubs yet faster growing hardwoods developed higher canopies, leading to subsequent overtopping.

Treatment effects on overtopping

Treatments influenced overtopping both initially and through time. At BCCS, all of the herbicide treatments on the Burn unit resulted in less overtopping than the untreated controls (Table 3). At OC and NC, results were more varied, with some of the herbicide treatments resulting in lower overtopping and some having overtopping similar to the untreated. At NC by year 17, two of the treatments had greater overtopping than the untreated, reflecting incomplete control of sprouting hardwoods. The Weed-free (WEED) treatments resulted in the lowest overtopping through time at NC and OC, but had overtopping similar to other treatments at BU, where overtopping was generally low in the first few years after the prescribed burn.

Results from FRCS indicated that although there were treatment effects on overtopping, the results varied by site (Table 4). At all sites, the WEED treatments resulted in the least overtopping, and this trend continued over time, reflecting elimination of perennial sprouts by repeated treatment. At FW, the site preparation treatment led to relatively low-level overtopping largely from seedling-origin Sitka alder, but this treatment was less effective in reducing overtopping at BD and DA. By year 16, none of the treatments averaged more than 10% overtopping at all FRCS sites (Table 4).

Disturbance during logging reduced early overtopping, which was less than 18% for all treatments in year 1 at FRMF (Table 5). By year 2, overtopping had increased, especially on site 1 in the spot treatment. While some comparisons were insignificant, the overall trend was for less overtopping of plug+1 seedlings than for plug seedlings within most treatments.

Model results

The competition model developed from individual seedlings from all sites and all years indicated that volume growth was related to overtopping, accounting for 85% of the variation in stem volume by overtopping when previous year's volume was included in the model (Fig. 3 and Table 6). Comparisons of means calculated for each site and treatment from the data and from the predicted values for the model, indicated that the model was representing site and treatment means well (Table 6, data and predicted model). We tested the model by doing a simulation run using the overtopping data from the individual seedlings, but

Fig. 1. Percentage of herbaceous overtopping of white spruce seedlings over time by vegetation management treatment at three study areas in interior and south-central Alaska. Overtopping by herbaceous species is not available for the first 2 years for some study areas. Note: refer to Methods for site abbreviations and Tables 1 and 2 for treatment abbreviations.

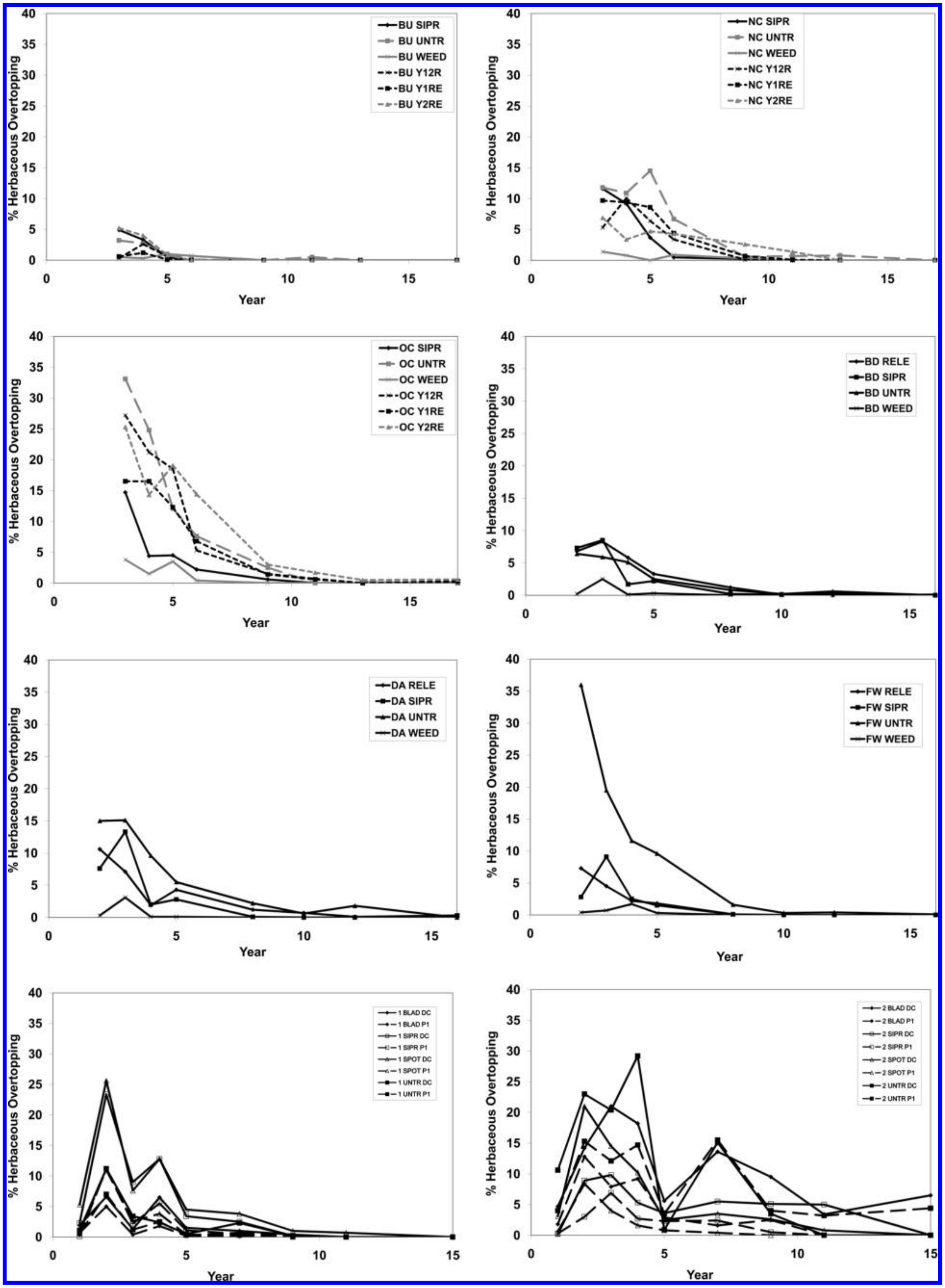


Fig. 2. Percentage of shrub overtopping of white spruce seedlings over time by vegetation management treatment at three study areas in interior and south-central Alaska. Note: refer to Methods for site abbreviations and Tables 1 and 2 for treatment abbreviations.

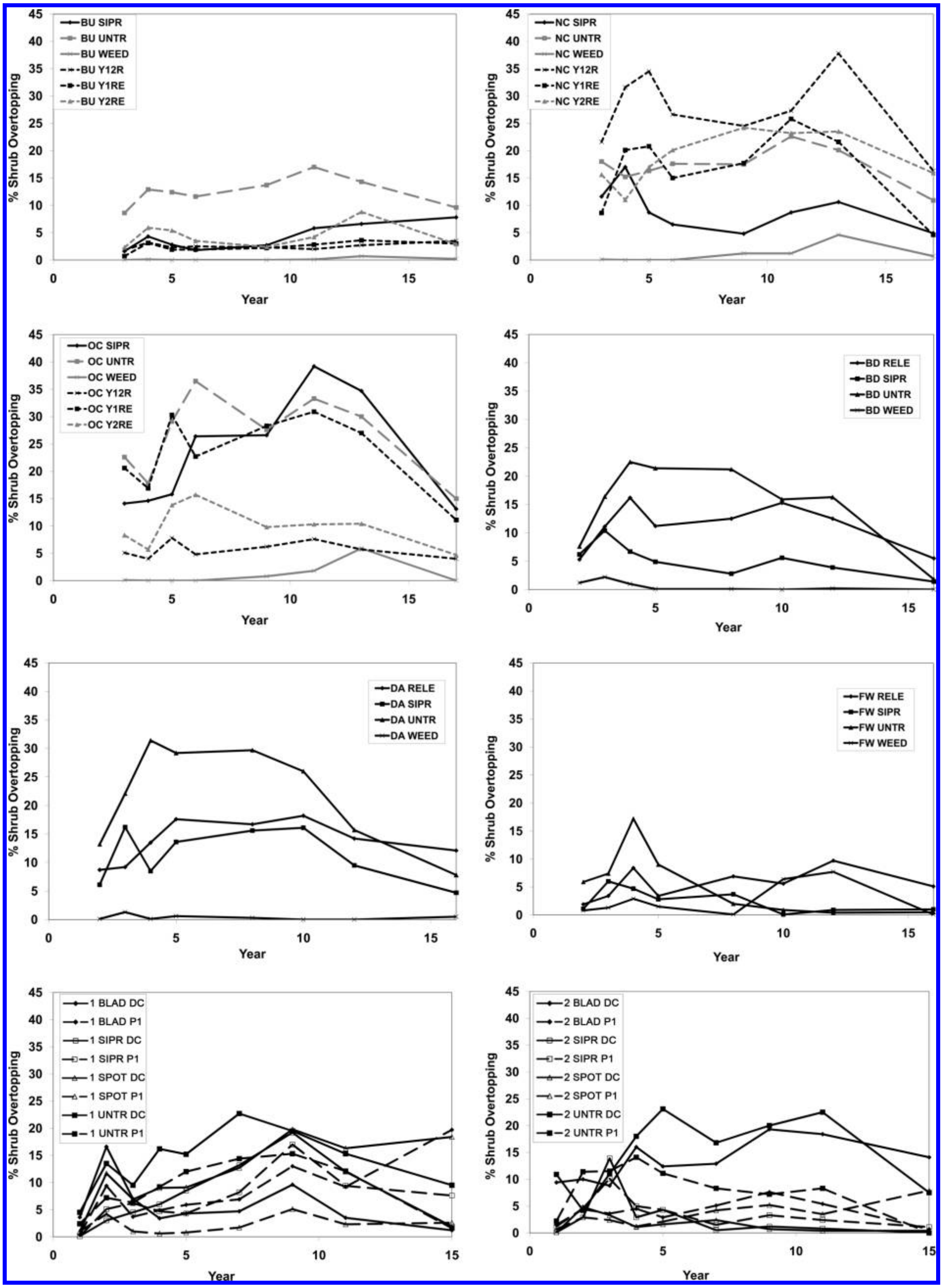


Table 3. ANOVA results for % overtopping in years 1, 2, and 17 for the Bonanza Creek Competition Study.

	Burn			New clearcut			Old clearcut		
	Year 1	Year 2	Year 17	Year 1	Year 2	Year 17	Year 1	Year 2	Year 17
Treatment	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
LSMEANS for % overtopping									
SIPR	0.5d	8.6b	8.0a	2.4d	21.8bc	5.4c	14.0d	31.0b	15.7a
UNTR	8.7a	21.7a	9.6a	7.0b	28.9a	12.0b	36.4b	55.2a	16.2a
WEED	0.5d	0.9d	0.2c	0.1e	3.6e	0.7d	6.1e	2.3d	0c
Y12R	3.0c	0.8d	3.5b	15.9a	17.8d	17.2a	33.8b	17.2c	4.9b
Y1RE	1.0cd	0.4d	3.0b	4.6c	23.7b	4.6c	25.2c	30.7b	14.7a
Y2RE	5.9b	3.4c	3.2b	5.6bc	20.0c	16.0a	41.4a	30.8b	5.4b

Note: Refer to Table 1 for treatment abbreviations. Same letters within columns are not significant at α = 0.05.

Table 4. ANOVA results for % overtopping in years 1, 2, and 16 for the Fort Richardson Competition Study.

	% Overtopping year 1	% Overtopping year 2	% Overtopping year 16
Site	0.0377	0.7769	0.6767
Treatment	<0.0001	<0.0001	<0.0001
Site × Treatment	0.0319	0.0100	0.0002
LSMEANS for % overtopping			
BD RELE	15.9abc	12.2ab	8.9a
BD SIPR	12.6abc	12.9ab	2.6b
BD UNTR	16.9ab	13.9ab	3.9ab
BD WEED	2.0bcd	1.4cd	0.9c
DA RELE	14.9abc	19.2ab	8.2ab
DA SIPR	7.4abc	13.9ab	3.6ab
DA UNTR	23.8a	28.6a	4.6ab
DA WEED	1.3cde	0.4d	0.6c
FW RELE	9.3abc	9.6ab	2.9ab
FW SIPR	0.6de	3.8bc	0.9c
FW UNTR	28.6a	38.2a	0.5c
FW WEED	0.2e	1.2cd	0.5c

Note: Refer to the Methods section for site abbreviations and Table 2 for treatment abbreviations. Same letters within columns are not significant at α = 0.05.

Table 5. ANOVA results for % overtopping in years 1, 2, and 15 for the Fort Richardson Mature Forest Study.

	% Overtopping year 1	% Overtopping year 2	% Overtopping year 15
Site	0.7140	0.8177	0.3003
Treatment	0.0911	0.7827	0.1189
Site × Treatment	0.7571	0.6095	0.2016
Type	<0.0001	<0.0001	<0.0001
Site × Type	0.0002	0.0005	0.0003
Treatment × Type	<0.0001	<0.0001	<0.0001
Site × Treatment × Type	<0.0001	0.0004	<0.0001
LSMEANS for % overtopping			
1 BLAD DC	4.1b	15.6bc	2.6ab
1 BLAD P1	1.3b	9.0bc	11.1a
1 BLAD SN	4.8b	12.4bc	12.3a
1 SIPR DC	1.7b	26.3abc	1.2c
1 SIPR P1	0.2b	16.6abc	7.2ab
1 SIPR SN	1.4b	30.4ab	10.0a
1 SPOT DC	5.8b	37.5a	17.9a
1 SPOT P1	1.9b	15.8bc	2.5ab
1 SPOT SN	4.8b	34.7a	3.6abc
1 UNTR DC	5.6b	23.8abc	6.9bc
1 UNTR P1	3.1b	13.4bc	2.7abc
1 UNTR SN	4.7b	22.1abc	10.5a
2 BLAD DC	14.0ab	21.3abc	24.1a
2 BLAD P1	3.3b	15.2bc	0.7c
2 BLAD SN	5.2b	22.5abc	22.6a
2 SIPR DC	0.1b	12.8bc	0c
2 SIPR P1	0.7b	6.8c	0.5c
2 SIPR SN	2.0b	12.9bc	3.7ab
2 SPOT DC	2.5b	25.0abc	0.4c
2 SPOT P1	1.0b	10.9bc	0.9bc
2 SPOT SN	4.5b	27.9abc	0.2c
2 UNTR DC	17.1a	22.9abc	3.7ab
2 UNTR P1	5.6b	22.9abc	3.9ab
2 UNTR SN	11.3b	31.8ab	4.1ab

Note: Refer to the Methods section for site and stock type abbreviations and Table 2 for treatment abbreviations. Same letters within columns are not significant at α = 0.05.

only using volume at the time of planting (year 0 volume) for each seedling with subsequent previous year's volume (y_0 in the model) based on model output rather than the actual data. The resulting predicted values for year 17 volume were highly correlated (r = 0.70) with actual year-17 volume, but the correlation was lower than if actual previous year's volume had been used to generate volume growth (r = 0.94). Although the correlation was lower, overall treatment means were similar to data means (Fig. 3), but treatment means by site varied (Table 6, data means and simulation means).

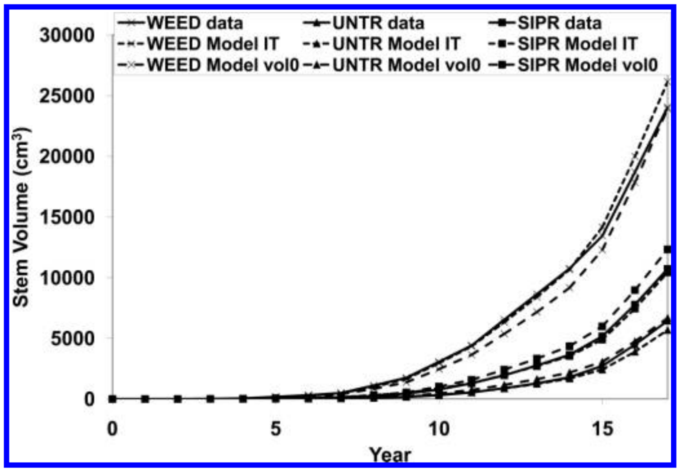
Standard errors for the parameter estimates indicated high variability within the model and difficulty in derivation of the estimates (Table 7). Concerns about the number of model parameters led us to examine the relationship between overtopping and growth by developing equations for each year. Resulting r^2 values ranged from 0.49 to 0.92, with the lower values usually occurring during the early years. When predicted values from the models were combined to examine year-17 volume, results were similar to those from the model using eq. (2) (Table 6, predicted model and yearly models).

Because the model appeared to be adequate in describing the relative differences among treatment means, based on the combined model, we developed overtopping "scenarios" to assess the impacts of various levels of overtopping on seedling volume. We used the average site index and year-0 volume for all sites and developed overtopping scenarios designed to mimic situations that might occur after outplanting. Scenarios ranged from no overtopping for 17 years to 75% overtopping in each year for 17 years (Table 8). Volume with overtopping ranged from 3% to 96% of seedlings with no overtopping, varying with the degree and duration of the overtopping. These scenarios indicated that sustained overtopping can result in drastic decreases in volume after 17 years.

Discussion

Overtopping influenced the volume growth of white spruce seedlings independent of treatment, apart from the role of treatment leading to various levels of overtopping. Seedlings tended to outgrow overtopping that was of short stature or short duration, which resulted in only minor growth losses; sustained overtopping resulted in losses of volume that increased with persistence of overtopping effect. Overtopping varied greatly among sites, depending upon whether herbaceous plants, low shrubs, or hard-

Fig. 3. Stem volume of white spruce seedlings over time for weed-free (WEED), site preparation (SIPR), and untreated (UNTR) vegetation management treatments averaged over three study areas, based on three calculations: (1) means from data (data) and data extrapolations, (2) means generated from the overtopping model using all data for individual seedlings (model IT), and (3) means from the same model using overtopping data over time for individual seedlings and only year-0 volume (model vol0) and using model-derived volumes for all subsequent y_0 in eq. (2). Data and model output have been averaged over all sites for UNTR and SIPR and over the BCCS and FRCS sites for WEED. Note: refer to Methods for study abbreviations.



woods dominated the site. The growth rate of competitors was critical in determining the duration of overtopping.

Vegetation management treatments ameliorated overtopping in both the short and longer term, but effects varied based on site and competitor species, as in other studies (Lautenschlager 1995; Cortini and Comeau 2008; Man et al. 2008). Overtopping was a dynamic expression of competitor growth relative to white spruce growth, so sites with low-growing or short-lived associated species might not register an impact from overtopping; sites supporting taller or longer lived species, such as hardwoods, presented greater challenges because the competing species might develop more rapidly and continue to overtop white spruce, especially if released by harvest. Lautenschlager (1995) and Jobidon (2000) reported greater losses in growth with hardwood than with shrub competition. Our treatments that controlled regrowth of these species maintained low levels of overtopping over time. Conversely, our treatments that failed to control these species, or allowed these species to establish, had higher levels of overtopping in later years. In British Columbia, Kabzems et al. (2011) reported that spruce growing within treatments that retained aspen failed free-to-grow standards after 11 years. Our model indicated that sustained overtopping severely limited white spruce growth. For 15-year-old black spruce in Ontario, Hoepting et al. (2011) reported that duration of competition was more important than timing of competition control.

Given the importance of competition for light in the boreal forests (Newton et al. 1992; Comeau et al. 2003; Jobidon et al. 2003; Macadam and Kabzems 2006; Man et al. 2008), the impact of overtopping on white spruce volume growth was not surprising. Some studies have indicated that spruce height growth will decline with less than 40% light transmission (Lieffers and Stadt 1994; Man and Lieffers 1997; Landhäusser and Lieffers 2001). Studies that assessed diameter or volume growth, however, have generally found systematically decreased growth associated with increased competition despite the relative shade tolerance of white spruce (Thiffault et al. 2003; Hangs et al. 2003; Man et al. 2008; Boateng et al. 2009). Our work indicated that, even at high latitudes, white spruce

Table 6. White spruce seedling volume (cm³) by site, vegetation treatment, and seedling stock type for the last year of measurement based on data means, predicted values from eq. (2), simulations based on eq. (2), and models developed for each year for three study areas in interior and south-central Alaska.

			Data means	Predicted means	Simulation means	Yearly model means
Bonanza Creek Competition Study year 17						
BU	SIPR		11071	13243	8039	13388
	UNTR		3632	3639	3784	3814
	WEED		14789	18483	10830	18567
	Y12R		12897	15170	9379	15312
	Y1RE		13632	15781	9307	15903
	Y2RE		6874	8028	7408	8212
NC	SIPR		5818	6266	5650	6471
	UNTR		2925	2935	3154	3068
	WEED		21679	21835	12395	21855
	Y12 R		3231	2906	2765	3031
	Y1RE		3388	4022	3822	4147
	Y2RE		3100	3004	3423	3159
OC	SIPR		1384	1414	1624	1511
	UNTR		560	527	806	576
	WEED		15932	13043	6632	12598
	Y12 R		4954	4817	2612	4388
	Y1RE		1927	1820	1388	1938
	Y2RE		2176	1664	1649	1783
Fort Richardson Competition Study year 16						
BD	RELE		2784	2310	5738	2561
	SIPR		3229	2859	7837	3123
	UNTR		1007	1024	3332	1182
	WEED		14754	16243	16317	16377
DA	RELE		7846	6655	9062	7017
	SIPR		6977	6197	8073	6517
	UNTR		2862	2484	3619	2721
	WEED		21326	21599	22180	21566
FW	RELE		9364	8576	18210	8940
	SIPR		14020	12584	20735	12986
	UNTR		13398	10194	11900	10605
	WEED		28015	30123	28603	29673
Fort Richardson Mature Forest year 15						
S1	BLAD	DC	15034	10575	8782	10855
	SIPR		6885	7006	7594	7374
	SPOT		4060	3409	5235	3807
	UNTR		6506	5664	5390	6140
	BLAD	SN	3765	3037	6026	3398
	SIPR		9367	7080	4611	7354
	SPOT		6153	4434	7436	4856
	UNTR		3732	3373	3600	3791
S2	BLAD	DC	2481	2391	4663	2754
	SIPR		16116	10205	11779	10579
	SPOT		8424	6456	8857	6881
	UNTR		12191	8982	9997	9247
	BLAD	SN	3416	2240	3064	2557
	SIPR		3878	3296	5119	3685
	SPOT		12689	7749	7004	7985
	UNTR		4614	2836	3154	3240

Note: Refer to the Methods section for site and stock abbreviations and Tables 1 and 2 for treatment abbreviations.

grown without overtopping will maintain moderately good growth for an extended period.

Our model adequately assessed relative impacts of overtopping and accounted for 85% of the variation in white spruce growth when predicted values were compared to data values used to develop the model parameter estimates. When we used data values for overtopping and data values only for year-0 volume and allowed the model to generate all subsequent previous year's volumes, the model accounted for about 50% of the variation in white

Table 7. Parameter estimates and their standard errors for each year for the overtopping model (eq. (2)).

	a		*m*	
Year	Estimate	SE	Estimate	SE
1	0.2560	12.0226	−0.0386	31.0273
2	0.6620	6.4046	−1.11380	62.5371
3	0.5201	1.9274	−0.7115	19.5581
4	0.7218	0.8096	−0.9084	10.0030
5	0.9654	0.5111	−5.7049	25.4245
6	0.4137	0.2161	−2.5139	15.5240
7	0.2593	0.0949	−0.00542	0.1317
8	0.5977	0.0694	−0.7553	1.3657
9	0.3364	0.0325	−0.00601	0.0332
10	0.4992	0.0267	−0.2250	0.01982
11	0.2910	0.0110	−0.00004	0.000035
12	0.3346	0.0148	−0.0436	0.0416
13	0.2475	0.0111	−0.0148	0.0185
14	0.2149	0.00947	−0.0151	0.0175
15	0.2864	0.0119	−0.0733	0.0397
16	0.3689	0.0142	−0.00259	0.00225
17	0.2878	0.0111	−0.00023	0.000018
	b		*d*	
	Estimate	SE	Estimate	SE
	0.8336	0.00367	0.2571	0.0249

Table 8. Volume (%) of white spruce seedlings relative to seedlings with no overtopping for 17 years by vegetation management scenarios resulting in different amounts of overtopping over time.

Overtopping scenarios	% Volume of 0% overtopping for 17 years
20% year 1, 0% years 2–17	96
50% year 1, 0% years 2–17	94
20% years 1–3, 0% years 4–17	66
20% years 1–5, 0% years 6–17	33
50% years 1–5, 0% years 6–17	22
20% years 1–17	12
20% years 1–3, 30% years 4–5, 50% years 6–10, 70% years 11–17	6
50% year 1, 30% year 2, 20% year 3, 10% year 4, 0% years 5–17	53
0% years 1–3, 30% years 4–5, 50% years 6–17	12
10% year 1, 20% year 2, 30% year 3, 50% year 4, 80% years 5–17	4
50% years 1–4, 20% years 5–10, 50% years 11–17	7
75% years 1–17	3

spruce growth. Previously reported models have accounted for 55% to 93% variation in spruce growth (Filipescu and Comeau 2007; Sharma et al. 2010; Cortini et al. 2012). These studies found that initial seedling size was an important component of the model. Sharma et al. (2010) reported that initial seedling size accounted for 55% to 70% of the variation in black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) growth, with competition variables accounting for an additional 4%–11% variation, depending upon species and site differences. Cortini et al. (2012) explained 88% of the variation in white spruce growth using a model that incorporated initial size, competition, and climate, with climate and competition accounting for 11% of the variation. Importance of climate varied among their locations. When our model was applied to individual sites without any SI term, correlation coefficients ranged from 0.86 to 0.96.

Overtopping is an index for primarily assessing light competition. Boreal competitors, such as bluejoint grass and ericaceous shrubs, may compete for site resources with white spruce without any detectable overtopping (Man et al. 2008; Hébert and Thiffault 2011; Milakovsky et al. 2011). One of our sites was dominated by Labrador tea, an ericaceous low shrub that has been studied for allelopathic effects on black spruce (Hébert et al. 2010). Several of our sites supported relatively high cover of bluejoint grass or fireweed that may not have overtopped seedlings in later years, but competed for resources. White spruce that were no longer overtopped may have been negatively influenced by the presence of these species, and this would not be reflected in the model. Other shrub and hardwood species may have specific effects on white spruce growth that have yet to be fully identified. We rated overtopping as a composite of all species, so the effect of individual species is not known. Likewise, consideration only of overtopping would not account for microsite variability, such as differences in soils, drainage, allelopathy, or soil temperature. A model that includes only overtopping may not adequately predict volume on sites where these factors predominate.

Overtopping was a fast and easy CI to assess, and despite lower correlations with treatment means for simulation runs, appears to be a useful tool for describing effects of competition on growth of white spruce. Studies that have compared visual estimates of competition with measured variables have found that visual estimates provided similar or better correlations with growth (Wagner and Radosevich 1991; Bell et al. 2000; Wang et al. 2000; Cortini and Comeau 2008). Problems may arise with visual estimates when evaluators have not been adequately calibrated (van Hees and Mead 2000; Klimeš 2003; Helm and Mead 2004). Calibration is essential to ensure that evaluations are consistent among observers and over time.

Overtopping was related to the initial size of seedlings, hence, relative differences in height. Tall plug+1 seedlings initially had less overtopping from a competitor of a given height and canopy density and had greater initial volume than smaller containerized stock. In Quebec, Jobidon et al. (2003) studied light around different stock types of spruce and found that the greatest gains in growth were from the 100 to 340 cm^3 stock that corresponded to the greatest increases in light, presumably accounting for decreases in overtopping with increasing seedling size. Vegetative cover affected the smaller stock types more than the larger stock types. In our study, larger white spruce had greater absolute growth when overtopping was low. The larger size, hence greater leaf area, thus gave the seedlings a consistent competitive edge over the smaller seedlings.

Large-caliper seedlings appear to stand up under lodging of cover, especially under snow. In our FRMF experiment, the P+1 stock type did not become flattened beneath bluejoint grass and fireweed as much as the smaller seedlings. Similarly, sturdier and larger seedlings were recommended for planting in British Columbia where potential snowpack and physical damage effects were anticipated (British Columbia Ministry of Forests 1998). This suggests that large planting stock alone will provide a relatively economical way of handling certain types of competition if planted soon after overstory removal, provided the large seedlings have the capacity to develop roots quickly (Grossnickle 2000, 2005; Youngblood et al. 2011).

What are the implications for future management of white spruce in interior and south-central Alaska, given the variation in short and longer term effects of overtopping? Our work provided strong evidence for the loss of growth directly attributable to competing vegetation that overtops seedlings. Our management scenarios were designed to simulate potential management activities over the first 17 years of stand development. They incorporated a range of typical conditions at the time of planting, complete vegetation control achieved at different times, and both increasing and decreasing levels of overtopping. Two scenarios depicted complete vegetation control after the first year but differed in the amount of overtopping at the time of plantings, while a third scenario simulated a release that eliminated overtopping in the fourth year. Three other scenarios projected seedling growth associated with increasing amounts of overtopping, all with relatively low but differing amounts of initial overtopping. One of these three was designed to simulate overtopping that might occur with establishment of fast-growing hardwood species that seed onto scarified sites. Two scenarios simulated relatively high overtopping initially, after which all overtopping declined gradually over time or completely after 5 years. This last set of conditions might best represent a release treatment or untreated low shrubs. An additional scenario called for overtopping to start high, then to remain relatively low for the second 5 years, and then increase to 50%. These conditions might represent a partial release with subsequent reestablishment of overtopping. Finally, two scenarios retained overtopping constant at either 20% or 75%, such as under either a partial or full hardwood canopy. These different scenarios resulted in widely varying outcomes and cause us to offer the following recommendations: (*i*) The elimination of all overtopping in the first year, so that no overtopping occurs in the second year, is essential for maximum growth. We based this on two scenarios that closely matched the maximum volume resulting from complete weed-free conditions; both scenarios included some overtopping in the first year, but no overtopping after that. (*ii*) Site preparation treatments are more important for future growth than are treatments that release seedlings from established competition, even a few years after planting. We based this on scenarios that suggested nearly 80% of the potential volume was lost when overtopping was not eliminated until year 6, and 33% of the potential volume was lost when overtopping was not eliminated until year 4. Likewise, a gradual decline of overtopping, such as when seedlings may grow out from under all competition, can reduce volume growth by nearly 50%. (*iii*) Long-term or increasing levels of overtopping, regardless of initial conditions, severely suppress white spruce volume growth. We based this on scenarios that may represent conditions such as fast-growing hardwood trees or shrubs that may remain or establish over seedlings. These scenarios resulted in about 10% or less of the volume growth compared with our scenario with no overtopping. Taken together, our work indicates the prominence of overtopping as a driving force that influences growth of white spruce in interior Alaska. If managers desire to maximize future seedling growth, the potential for overtopping may need to be considered in silvicultural prescriptions and reforestation management plans, and individual species that have the potential to either remain or grow above planted seedlings targeted in treatments that ameliorate the risk of overtopping.

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