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Original article

Effects of competing vegetation on juvenile white spruce (*Picea glauca* (Moench) Voss) growth in Alaska

Elizabeth COLE[a]*, Andrew YOUNGBLOOD[b], Michael NEWTON[a]

[a] Department of Forest Science, Oregon State University, Corvallis, OR, USA
[b] USDA Forest Service, Pacific Northwest Research Station, LaGrande, OR, USA

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Abstract – We examined the impacts of competing vegetation on survival and juvenile growth of white spruce (*Picea glauca* (Moench) Voss) on 3 units in south-central Alaska and on 3 units in interior Alaska. Treatments consisted of herbicide site preparation and release treatments, and also included a treatment in which competition was minimized for 5 years (weed-free treatment). At all units, the weed-free treatment resulted in significant increases in white spruce height and basal diameter by ages 10 or 11 compared to untreated plots. Average heights and diameters in the weed-free treatments were 1.5 to 3.8 times and 2.0 to 3.8 times those in the untreated plots, respectively. Results from the other treatments differed by unit based on the efficacy of a particular treatment on the vegetation at that unit. For all units, regression equations indicated a significant decrease in diameter at year 10 or 11 with increasing competitive cover and overtopping.

vegetation management / competition / *Picea glauca* / Alaska / survival

Résumé – Effects de la végétation concurrente sur la croissance juvénile de *Picea glauca* (Moench) Voss en Alaska. Nous avons étudié les effets de la végétation concurrente sur la survie et la croissance de *Picea glauca* (Moench) Voss dans 3 dispositifs situés au centre sud de l'Alaska ainsi que 3 dispositifs installés dans l'Alaska intérieur. Il s'agissait de traitement de préparation des sites et de dégagements par application d'herbicides. L'un des traitements consistait à contrôler la végétation pendant 5 ans (traitement éliminant la végétation concurrente). Dans tous les dispositifs, ce dernier traitement se traduit par un accroissement significatif de la hauteur et du diamètre au collet des plants âgés de 10 et 11 ans, par comparison avec les parcelles témoins. La hauteur moyenne et le diamètre sont alors respectivement mutlipliés par 1,5 à 3,8 et 2,0 à 3,8 par rapport aux témoins. Les résultats des autres traitements diffèrent selon les dispositifs en fonction de l'efficacité de chaque traitement pour le contrôle de la végétation. Sur tous les dispositifs, des équations de régression révèlent une réduction sur le diamètre à 10 et 11 ans, alors que la végétation concurrente se développe et domine les plants.

gestion de la végétation / concurrence / *Picea glauca* / Alaska / survie

1. INTRODUCTION

Recent logging of boreal white spruce (*Picea glauca* (Moench) Voss) forests in Alaska has led to increased interest in white spruce regeneration and juvenile growth. White spruce regeneration and juvenile growth are highly variable, and are impeded by factors such as competition, site quality, low soil temperature, climate, and seed predation. Natural regeneration of white spruce is often inadequate to meet reforestation standards due to its sporadic seed production cycle, the lack of persistence of seeds in soil, and inadequate seedbed or microsite conditions [38, 40, 42, 43]. Even when white spruce does regenerate successfully, overstocking and other competition can result in slow growth rates; after 27 years, naturally regenerated white spruce on an interior Alaska site measured less than 4 m in height [40]. Planting white spruce seedlings has been a successful method of establishing regeneration on some upland and floodplain white spruce sites in interior and south-central Alaska [11, 14, 41].

During the critical establishment phase, juvenile growth of white spruce is typically slow. In Canada, numerous studies from the white spruce zone indicate that applying herbicide release and site preparation treatments increases juvenile growth (e.g. [2, 4–7, 9, 10, 18, 23, 39]). For example, glyphosate release treatments applied 1 to 4 years after planting resulted in height and diameter increases of up to 41% and 83% respectively in white spruce forests of British Columbia [4–7]. In Ontario, herbicide site preparation resulted in height and diameter increases of about 40%, and annual release treatments resulted in height increases of 72% and diameter increases of 120% 5 years after planting [39]. In these studies, growth increases were dependent upon site quality, treatment efficacy, and timing of treatment.

* Corresponding author: cole@fsl.orst.edu

In Alaska, few studies have examined how to increase juvenile growth of white spruce. Scarification has been shown to increase growth of container seedlings on an Alaskan interior floodplain site [41], but not on interior burned, upslope sites [14] or south-central low-elevation sites [11]. On the south-central sites, site preparation with herbicides resulted in increased spruce growth compared to untreated areas. The different results from these few studies indicate that the best method for increasing juvenile growth in Alaska remains unknown, and may be highly dependent on site-specific factors.

Our objectives were (i) to determine if vegetation management treatments (both herbicide release and site preparation) increase survival of white spruce in interior and south-central Alaska and (ii) to determine if those treatments increase absolute growth of juvenile white spruce.

2. MATERIALS AND METHODS

2.1. Study sites

2.1.1. Bonanza Creek experiment

Bonanza Creek Experimental Forest is located in interior Alaska, approximately 20 km south of Fairbanks (64° 51' N latitude, 148° 44' W longitude). This area has some of the most productive white spruce stands in Alaska, with annual production averaging 366 g m^{-2} [36]. Soils are deep loess silt [32]. The climate is continental, with mean daily temperatures of < –20 °C in January and 17 °C in July [32]. Winter extremes reach –50 °C [32]. Annual precipitation averages 280 mm, with nearly 30% as snow [37], and the growing season in Fairbanks averages 97 frost-free days [20]. Permafrost does not occur in the study areas, but is common on level or north-facing slopes nearby.

We selected three units: (1) Old clearcut — clearcut harvested 4 years prior to planting; (2) New clearcut — clearcut harvested the year prior to planting; and (3) Burn — clearcut harvested 4 years prior to planting and burned the summer prior to planting. Units were south-facing with 0% to 15% slope. Prior to harvest, mixed stands of white spruce, scattered with aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh) populated the units.

On each unit, we established 18 plots, 12 m × 15 m (0.02 ha) in size. Each plot was randomly assigned one of 6 vegetation management treatments that included combinations of herbicide release and site preparation (Tab. I), and each vegetation management treatment was replicated three times. We selected vegetation management treatments that would result in an array of competing conditions from minimal vegetation (weed-free) to natural development of competing vegetation (untreated). Herbicides and rates were selected based on results from local efficacy trials. Twenty white spruce 1+0 plug seedlings from the Alaska State Nursery were planted in each plot in the spring of 1991. Seedlings had been overwintered on a site close to the study units and were lifted the day of planting.

2.1.2. Fort Richardson experiment

Fort Richardson is located in south-central Alaska, near Anchorage (61° 15' N latitude, 149° 45' W longitude). Soils are of glacial origin, mostly cobble, with a thin mantle of silty loess [24]. The climate is more moderate than Bonanza Creek, with mean daily temperatures of 2.2 °C and mean daily maximum and minimum temperatures of 5.9 °C and –1.6 °C [24]. Precipitation averages 400 mm annually, about half of that occurring as snow, and the growing season averages 125 days [24].

We chose three recently cleared units that varied in site quality due to differences in soil depth, elevation, and cold air drainage: (1) Firewood — the warmest unit, lowest in elevation, and with the lowest amount of rock in the soil, was cleared the year prior to planting; (2) Davis — intermediate in temperature, amount of rock in the soil, and site quality, was cleared three years prior to planting; and (3) Bulldog — the coldest unit with the poorest site quality and greatest component of rock in the soil, was cleared with a Hydro-ax™ three years prior to planting. The Davis and Bulldog units were at similar elevations. Prior to harvest, white spruce, paper birch, and aspen populated the sites. On the Firewood unit, balsam poplar (*Populus balsamifera* L.) grew as well. On each unit, we established 2 blocks of 4 plots; plots were 15 m × 24.4 m (0.04 ha) in size. Each plot was randomly assigned one of four vegetation management treatments (Tab. II). Forty white spruce 1+0 plug seedlings and 40 0.5+0 paper

Table I. Vegetation management treatments for Bonanza Creek.

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

[a] Acid equivalent of glyphosate.

Table II. Vegetation management treatments for Fort Richardson.

Treatment	Herbicide application	Date applied
Untreated	None	None
Weed-free	(a) Broadcast application of 2.2 kgae[a] ha^{-1} glyphosate (b) Directed applications of 2% glyphosate	(a) August 1991 (b) Annually June 1992–1996
Site preparation	Broadcast application of 1.7 kg ha^{-1} hexazinone + 1.7 kgae ha^{-1} glyphosate	August 1991
Year 1 release	Broadcast application of 1.4 kg ha^{-1} granular hexazinone	June 1992

[a] Acid equivalent of glyphosate.

birch plug seedlings from the Alaska State Nursery were planted on each plot in the spring of 1992. Birch seedlings were top-killed by frost in the first two years after planting and heavily browsed by moose. Results for birch are not included in this paper.

2.2. Measurements

At both study areas, we measured survival, height, basal diameter (Bonanza Creek and Fort Richardson later years) or root collar diameter (Fort Richardson), competing cover, and overtopping cover for each seedling. Basal diameter was measured 15 cm above ground. At both study areas, measurements were made immediately after planting and at the end of each of the first 5 growing seasons. Bonanza Creek seedlings were also measured at the end of the sixth, ninth, and eleventh growing seasons, and Fort Richardson seedlings were measured at the end of the eighth and tenth growing seasons. By the eighth year, basal swelling and uplifting were making it difficult to accurately measure root collar diameter. Therefore, at Fort Richardson, both basal and root collar diameters were measured in the eighth year, and only basal diameter was measured in the tenth year. Percent competing cover from grasses, forbs, alder (*Alnus* spp.), prickly rose (*Rosa acicularis* Lindl.), Labrador tea (*Ledum* spp.), willow (*Salix* spp.), birch, fireweed (*Epilobium angustifolium* L.), horsetail (*Equisetum* spp.), low shrubs (*Empetrum nigrum* L., *Linnaea borealis* L., *Vaccinium vitis-idaea* L., and *V. uliginosum* L.), other shrubs, and conifers was estimated within a 0.5-m radius of each seedling for the first 6 years at Bonanza Creek and the first 5 years at Fort Richardson. Because cover was estimated independently for each of the listed groups/species, total cover could exceed 100%. Overtopping cover (maximum 100%) for each seedling was estimated using a 60° cone projected above the first 2 whorls [22].

2.3. Statistical analyses

Analysis of variance (ANOVA, SAS® PROC MIXED) [31] was used to test for differences in total survival, height, and basal or root collar diameter among treatments at each study area. Although constructed as a randomized complete block design (unit=block), we were unable to analyze Bonanza Creek as such due to significant block X treatment interactions. Fort Richardson was analyzed as a randomized complete block design (2 blocks within each unit, no block X treatment interactions).

2.3.1. Survival analyses

Survival was analyzed for only the most recent time period — year 11 for Bonanza Creek and year 10 for Fort Richardson. An arcsine square root transformation, a common transformation for percentage data [26], was necessary to stabilize variance. Differences among treatment means were compared using protected least squared differences from the ANOVA least squared means comparisons after adjusting probabilities for all possible comparisons.

2.3.2. Height and diameter analyses

Height and diameter were repeatedly measured on the same saplings, leading to a repeated measures design with growing season (year) as the time interval. Saplings that had died prior to the last measurement were deleted from samples at all measurement intervals, and all analyses were weighted by the number of surviving saplings within each plot. At Fort Richardson, we did not have measurements of root collar diameter at the last measurement interval. Regressions of eighth-year root collar diameter and basal diameter indicated that basal diameter was 12% less than root collar diameter. This difference was not related to treatment or unit; therefore, the difference would not cause bias when treatments were compared. Root collar diameters were used in the analyses through year 5, and basal diameters used for years 8 and 10. For both Bonanza Creek and Fort Richardson, natural log transformations of both height and diameter were necessary to stabilize variances.

Because the number of replications was fewer than the number of measurement years, data could not be analyzed using ANOVA with years included as an “effect or class” variable. Year was considered a continuous regression variable within the standard ANOVA [25]. Including year as a continuous regression variable within the ANOVA allowed us to test for main effects (treatment for Bonanza Creek and treatment and unit for Fort Richardson) and to generate equations for height and diameter through time. Orthogonal and non-orthogonal contrasts were used to test for treatment and unit effects. These contrasts tested for slope differences among the equations, which indicated whether growth trajectories were different among treatments. For the time effect, both linear and quadratic terms were included, as well as interactions with the main effects; non-significant time effects were eliminated and data were reanalyzed.

Several of the covariance structures available for repeated measures in SAS®, such as, autoregressive, Toeplitz, and autoregressive moving average structures, could not be used because these structures assume equal spacing among time intervals. We experienced convergence problems with the compound symmetry covariance matrices. The spatial and unstructured covariance matrices allow unequal intervals, and time became the spatial coordinate within the spatial matrices. We selected among these matrices based upon Akaike’s Information Criterion (AIC), Schwarz’ Bayesian Criterion (BIC), and comparisons of predicted values, residual values, and replication means. Results were similar among all matrices for which convergence criteria were met. The spatial power matrix resulted in the best overall AIC and BIC values, and those results are presented here.

The estimation method used was residual maximum likelihood (REML), and the denominator degrees of freedom (DDF) calculation method was BETWITHIN. For the Fort Richardson analyses, DDF calculations were incorrect for two of the error terms. The correct DDF was specified for these terms, and the other error terms were calculated by BETWITHIN. Because we had year as a polynomial term within the ANOVA, fixed effects tests were based upon sum of squares type I [25].

2.3.3. Regression analyses

We also analyzed the data using regression techniques (SAS® PROC REG and PROC NLIN) in order to develop models relating diameter of individual saplings at year 10 or 11 to percent competing cover and overtopping cover estimates. To screen for potential independent variables, we used stepwise regression and correlation analyses that included the previously listed cover groups/species for each year (52 variables for Bonanza Creek, 55 for Fort Richardson), overtopping for each year (8 variables for Bonanza Creek, 7 for Fort Richardson), and combinations of these variables (46 variables for Bonanza Creek and 74 for Fort Richardson). From these analyses, we generated a list of 10 potential independent variables for further analyses in linear and nonlinear equations. Equations were developed for each unit, with saplings from all treatments and replications included, so that the impact of competing cover on sapling size could be evaluated independent of treatment. Then, equations were developed that included all units within each region with mean basal diameter at year 10 or 11 from the weed-free treatment used as a site productivity indicator. Mean basal diameter of saplings from the weed-free treatment was selected as a substitute for specific site index information, which was not available, because it should closely approximate the upper limit for average diameter growth at each unit. For the linear models, equations tested included linear combinations of the 10 potential independent variables. For nonlinear models, we started with 19 basic

Table III. Mean sapling survival after 11 years (Bonanza Creek) and 10 years (Fort Richardson) for vegetation management treatments. Means followed by the same letter within columns are not significantly different at $p = 0.05$.

Treatment	Bonanza Creek (%)			Fort Richardson (%)
	Burn	New Clearcut	Old Clearcut	
Site preparation	87 a	83 a	87 a	93 ab
Weed-free	77 ab	67 bcd	45 b	97 a
Year 1 release	63 bc	80 ab	88 a	85 b
Year 2 release	58 bc	62 cd	67 b	N/A
Years 1&2 release	48 c	50 d	48 b	N/A
Untreated	92 a	77 abc	90 a	87 b

equations that described the relationship between diameter and cover. From these, we selected 5 equations for further testing with the different cover variables. Models were selected based on R^2 values (linear models), error sums of squares, simplicity, and most importantly, comparisons of replication means and individual sapling basal diameters with predicted values.

3. RESULTS

3.1. Survival

The impact of the vegetation management treatments on year 10 or 11 survival differed between the regions (Tab. III). At the three Bonanza Creek units (Burn, New clearcut, and Old clearcut), site preparation and untreated treatments had significantly greater eleventh-year survival than years 1&2 release treatments. None of the herbicide treatments resulted in significantly greater survival compared to the untreated plots. At Fort Richardson, survival after 10 years averaged between 74% and 99% among the units and treatments, but differences among units were not significant. The release and untreated treatments had significantly lower survival than the weed-free treatment, but survival still averaged over 85% over all of the units for those treatments (Tab. III).

3.2. Height and diameter

3.2.1. Bonanza Creek

Treatment effects on height and diameter differed by unit (Figs. 1 and 2, ANOVA F and p values in Tabs. IV and V), and through time. Treatment effects were most apparent on the Burn unit. On the Burn unit, four treatments (weed-free, site preparation, year 1 release, and years 1&2 release) were not significantly different from each other, but did result in significantly taller and larger diameter saplings than those in untreated and year 2 release plots. Although there was no difference in height between saplings in untreated and year 2 release plots, saplings in year 2 release plots had significantly larger diameters (Fig. 2a). For reference purposes, eleventh-year height and diameters are listed in Table VI.

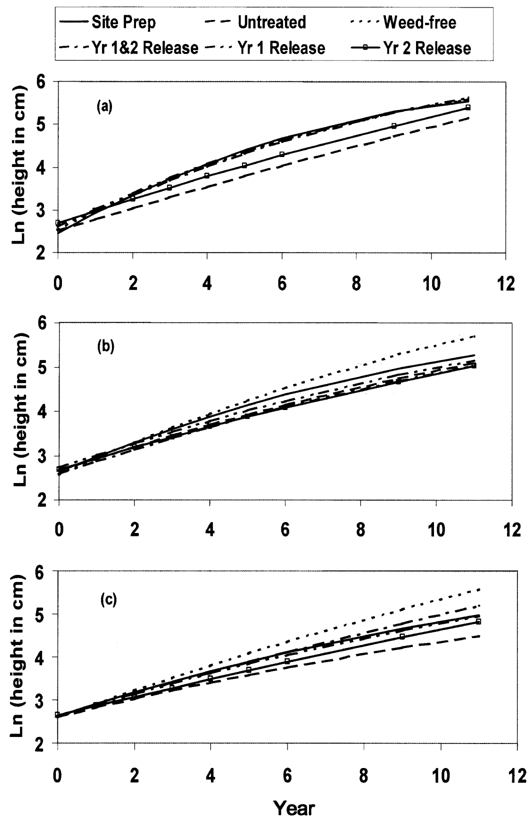

Figure 1. Sapling height curves for (a) Burn, (b) New clearcut, and (c) Old clearcut for Bonanza Creek units. Curves were derived from ANOVAs.

As on the Burn unit, the weed-free treatments on the New clearcut unit produced taller and larger diameter saplings than other treatments (Figs. 1b and 2b). For height, none of the other treatments was significantly different from the untreated plots. Although there was no difference between diameters of saplings in the site preparation and untreated plots, the site preparation treatment did produce larger diameter saplings than the year 2 release and years 1&2 release treatments.

At the Old clearcut unit, the weed-free treatment again produced taller and larger diameter saplings than other treatments (Figs. 1c and 2c). The years 1&2 release treatment had the next largest seedlings. By year 11, the saplings in untreated plots were significantly shorter and smaller in diameter than those in the treated plots (Tab. VI).

3.2.2. Fort Richardson

Height and diameter differed among units and treatments, and through time. The Unit X Treatment and Year X Unit X Treatment interactions were not significant for height, but for diameter, the Year X Unit X Treatment interaction was significant (Tab. VII). For reference purposes, tenth-year height and diameter are listed in Table VIII.

Saplings at the Firewood unit were significantly taller and larger in diameter than saplings at Davis and Bulldog (Figs. 3a and 4). Saplings on the Davis unit were larger in diameter than

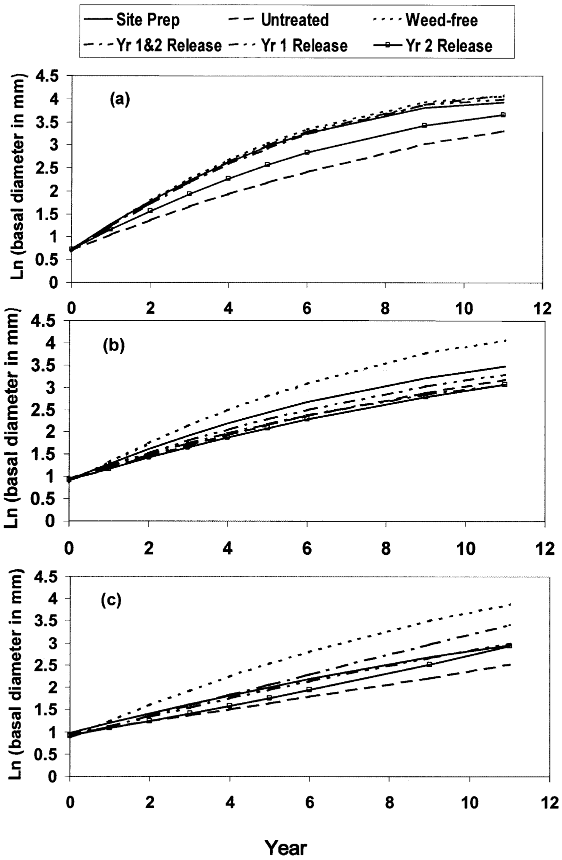

Figure 2. Sapling basal diameter curves for (a) Burn, (b) New clearcut, and (c) Old clearcut for Bonanza Creek units. Curves were derived from ANOVAs.

those on the Bulldog unit, but had similar heights. By year 10, the saplings in the weed-free treatment were significantly taller and larger in diameter than all other treatments (Figs. 3b and 4). Saplings in the site preparation treatment were taller and larger in diameter then those in the untreated plots. At Davis and Bulldog, the release treatment produced saplings that were larger in diameter than those in the untreated plots, but at Firewood, there was no difference between these treatments.

3.3. Regression

Regression analyses from Bonanza Creek indicated a strong negative correlation between basal diameter at year 11 and percent competing cover and overtopping (Fig. 5). Several linear models produced comparable R^2 values (ranging from 0.71 to 0.73). However, the linear models generally underestimated basal diameter at low levels of cover and overtopping more so than the non-linear models. The non-linear models also more accurately predicted basal diameters among all the treatments. Thus, we determined that equation 1 was the best predictive model for basal diameter.

$$\mathrm{BD11} = -13.016 + e^{0.0211\,(100 - \%\mathrm{overtopping\ year\ 6})} \times e^{0.00645\,(300 - \mathrm{TCOV123})} + 0.3852\mathrm{SP} \qquad (1)$$

where BD11 is basal diameter at year 11, TCOV123 is the sum of % total cover in years 1, 2, and 3, and SP is site productivity index (as defined in Methods); $n = 721$.

As at Bonanza Creek, regression analyses for Fort Richardson indicated strong trends for decreased basal diameter at year 10 with increased competing cover and overtopping (Fig. 6). Combining units into a single equation resulted in greatly underestimated diameters for the weed-free treatment at the Firewood unit, even though the site productivity variable

Table IV. Summary of ANOVAs for treatment effects on sapling height for Bonanza Creek units. UNTR: untreated, WEED: weed-free, SIPR: site preparation, Y1RE: year 1 release, Y2RE: year 2 release, and Y12R: years 1&2 release.

Factor	Burn			New clearcut			Old clearcut[a]	
	D.F.	F value	*P* value	D.F.	F value	*P* value	F value	*P* value
Treatment	5,12[b]	14.38	< 0.0001	5,12	3.25	0.0440	11.90	0.0003
Year	1,132	4218.49	< 0.0001	1,137	3219.37	< 0.0001	4152.96	< 0.0001
Year^2	1,132	99.33	< 0.0001	1,137	42.19	< 0.0001	24.06	< 0.0001
Year × treatment	5,132	3.54	0.0049	5,137	6.59	< 0.0001	15.48	< 0.0001
UNTR vs. WEED	1,132	18.79	< 0.0001	1,137	4.33	0.0394	68.19	< 0.0001
WEED vs. SIPR, Y12R, Y1RE	1,132	0.01	0.9331					
UNTR vs. Y2RE	1,132	0.47	0.4965	1,137	0.20	0.6553	6.44	0.0123
SIPR vs. Y2RE	1,132	18.27	< 0.0001					
WEED vs. Y12R	1,132			1,137	0.26	0.6121	7.19	0.0082
UNTR vs. SIPR	1,132			1,137	2.77	0.0985	17.98	< 0.0001
Year^2 × treatment	5,132	6.33	< 0.0001		NS[c]		NS[c]	

[a] Degrees of freedom (D.F.) for Old clearcut the same as for New clearcut.
[b] First number is factor degrees of freedom, second number is error (denominator) degrees of freedom.
[c] The year^2 × treatment term was not significant ($p < 0.05$); therefore, it was deleted and data were reanalyzed.

Table V. Summary of ANOVAs for treatment effects on sapling diameter for Bonanza Creek units. UNTR: untreated, WEED: weed-free, SIPR: site preparation, Y1RE: year 1 release, Y2RE: year 2 release, and Y12R: years 1&2 release.

Factor	Burn			New clearcut			Old clearcut[a]	
	D.F.	F value	*P* value	D.F.	F value	*P* value	F value	*P* value
Treatment	5,12[b]	16.05	< 0.0001	5,12	7.07	0.0027	32.20	< 0.0001
Year	1,132	6561.79	< 0.0001	1,137	2563.86	< 0.0001	3498.27	< 0.0001
Year^2	1,132	477.54	< 0.0001	1,137	64.96	< 0.0001	6.15	0.0144
Year × treatment	5,132	11.90	< 0.0001	5,137	9.89	< 0.0001	28.28	< 0.0001
UNTR vs. WEED	1,132	52.29	< 0.0001	1,137	29.50	< 0.0001	38.67	< 0.0001
WEED vs. SIPR, Y12R, Y1RE	1,132	0.95	0.3318					
UNTR vs. Y2RE	1,132	7.38	0.0075	1,137	0.39	0.5314	0.26	0.6109
SIPR vs. Y2RE	1,132	9.79	0.0022					
WEED vs. Y12R	1,132			1,137	30.89	< 0.0001	9.54	0.0024
UNTR vs. SIPR	1,132			1,137	3.17	0.0773	8.30	0.0046
Year^2 × treatment	5,132	9.97	< 0.0001		NS[c]		3.14	0.0103

[a] Degrees of freedom (D.F.) for Old clearcut the same as for Burn.
[b] First number is factor degrees of freedom, second number is error (denominator) degrees of freedom.
[c] The year^2 × treatment term was not significant ($p < 0.05$); therefore, it was deleted and data were reanalyzed.

Table VI. Year 11 total sapling height and basal diameter for Bonanza Creek units.

	Burn	New clearcut	Old clearcut	Burn	New clearcut	Old clearcut
	Height (cm)			Basal diameter (mm)		
Site preparation	256	194	148	53.3	33.4	19.8
Untreated	171	163	90	28.0	24.7	12.5
Weed-free	263	289	256	59.9	57.5	47.3
Years 1&2 release	273	156	179	60.9	22.8	29.7
Year 1 release	264	172	143	57.7	27.4	20.3
Year 2 release	213	150	126	40.2	22.3	18.8

was not significant. Therefore, two equations were developed; equation 2 was for the Firewood unit, and equation 3 for the Davis and Bulldog units combined.

$$\mathrm{BD10} = 13.6536 + e^{0.0305\,(100 - \%\text{overtopping year 5})} \times e^{0.0101\,(100 - \%\text{total cover year 5})} \quad (2)$$

where BD10 is basal diameter year 10; $n = 273$.

$$\mathrm{BD10} = -1.0883 + e^{0.0189\,(100 - \mathrm{LOSH5})} \times e^{0.0205\,(100 - \%\text{overtopping year 5})} \quad (3)$$

where BD10 = basal diameter year 10, LOSH5 = low shrub cover year 5 + Labrador tea cover year 5, $n = 584$.

3.4. Regional comparison

Although the experiments were not designed to allow for statistical comparisons between the regions, a graph of two of the common treatments (weed-free and untreated) for all of the units can provide some visual comparisons among the curves (Fig. 7). For both height and diameter and for the weed-free and untreated treatments, the Firewood unit currently has the largest saplings of all units in both regions. The Old clearcut unit has the smallest saplings. Saplings on the Bulldog unit at Fort Richardson were similar in size to those on the Old clearcut unit near Fairbanks. The New clearcut, Davis, and Burn units were similar in size, and differences among those units were not apparent.

4. DISCUSSION

Results from the two experiments indicate that absolute growth of juvenile white spruce in Alaska can be increased with vegetation management treatments. The degree to which the treatment controls competing vegetation determines, in part, the impact on growth. The largest saplings were found where competing vegetation was kept to a minimum for more than one growing season. However, these conditions may result in decreased survival, with certain climatic events.

Survival trends differed between the two regions, with the treatments that were the most effective at decreasing competing vegetation (weed-free at both study areas and years 1&2 release at Bonanza Creek) resulting in reduced survival at Bonanza Creek and increased survival at Fort Richardson. In areas where early freezes occur frequently, vegetation management treatments may leave seedlings particularly vulnerable to damage and mortality. Most of the mortality at Bonanza Creek was due to an uncommon, early freeze that occurred just after the third growing season. Before the freeze, mortality at Bonanza Creek was similar among all treatments. On September 8, 1993, the minimum temperature dropped to –1 °C, and on September 17, minimum temperatures dropped even lower

Table VII. Summary of ANOVAs for treatment effects on height and diameter for Fort Richardson units. UNTR: untreated, WEED: weed-free, RELE: release, and SIPR: site preparation treatments.

Factor	Height			Diameter		
	Degrees of freedom	F value	*P* value	Degrees of freedom	F value	*P* value
Unit	2,3[a]	7.48	0.0683	2,3[a]	15.92	0.0253
Treatment	3,9	10.53	0.0027	3,9	45.00	< 0.0001
Unit × treatment	6,9	0.86	0.5581	6,9	0.63	0.7060
Year	1,161	3770.08	< 0.0001	1,150	6538.64	< 0.0001
Year^2	1,161	54.65	< 0.0001	1,150	206.42	< 0.0001
Year × unit	2,161	18.37	< 0.0001	2,150	27.43	< 0.0001
Davis vs. Firewood	1,161	17.34	< 0.0001	1,150	12.32	0.0006
Bulldog vs. Davis	1,161	2.41	0.1223	1,150	0.02	0.8985
Year × treatment	3,161	18.96	< 0.0001	3,150	64.38	< 0.0001
WEED vs. SIPR	1,161	23.60	< 0.0001	1,150	31.54	< 0.0001
SIPR vs. UNTR	1,161	5.68	0.0183	1,150	7.92	0.0055
RELE vs. UNTR	1,161	2.73	0.1003	1,150	3.43	0.0658
Year^2 × unit		NS[b]	NS[b]	2,150	3.37	0.0370
Year^2 × treatment		NS[b]	NS[b]	3,150	8.08	< 0.0001
Year × unit × treatment		NS[b]	NS[b]	6,150	2.50	0.0247
RELE vs. UNTR Firewood				1,150	0.52	0.4702
RELE vs. UNTR Davis & Bulldog				1,150	5.45	0.0209

[a] First number is factor degrees of freedom, second number is error (denominator) degrees of freedom.
[b] This factor was not significant ($p < 0.05$); therefore, it was deleted and data were reanalyzed.

Table VIII. Year 10 sapling total height and basal diameter for Fort Richardson units.

	Bulldog	Davis	Firewood	Bulldog	Davis	Firewood
	Height (cm)			Basal diameter (mm)		
Release	128	177	198	21.4	27.6	32.6
Site preparation	133	181	234	22.4	29.3	40.2
Untreated	92	129	208	14.4	18.4	33.4
Weed-free	259	283	318	54.5	57.5	65.6

and remained below freezing until spring. Many of the seedlings in treatments with little competition from other vegetation had not hardened for the winter, and consequently suffered top dieback and mortality. Although most of the seedlings with top dieback recovered, these seedlings were of poor form (multiple tops) and had reduced growth compared to undamaged seedlings. No such freezes occurred at Fort Richardson.

At Fort Richardson, survival was 85% or greater for all treatments. The greatest mortality (40%) occurred in one of the untreated plots at the Firewood unit that had a dense cover of bluejoint grass (*Calamagrostis canadensis* (Michx.) Beauv.). Bluejoint grass is a serious competitor to conifers in boreal forests and has been associated with decreased survival of white spruce in Canada [8, 15, 19].

At Bonanza Creek, more treatments were effective on the Burn unit than on the two clearcut units. Burning slowed the growth of competing vegetation. It is also likely that the removal of vegetation and organic material during burning decreased the albedo of the soil [33], leading to higher summer soil temperatures on the Burn unit in treated areas than in untreated areas. In white spruce boreal forests, soil temperature can be one of the most limiting factors for seedling and tree growth [12, 13, 17, 18, 33, 35].

Even without burning, the reduction in vegetative cover in the weed-free treatments over untreated plots at both Bonanza Creek and Fort Richardson may have increased summer soil temperatures [21, 29, 34], as well as reduced competition. Previous studies from Canada [1, 16, 39] have reported increases in summer soil temperatures of 1 to 5 °C at depths of 15 cm or less after removal of vegetation. We did not measure soil temperature and therefore cannot separate the extent to which decreased competition or increased summer soil temperature is important for growth on these sites.

The New and Old clearcut units at Bonanza Creek are almost adjacent to each other and are similar in site quality, yet the rankings of treatments differed between the units. The greatest increases in height and diameter compared to the untreated plots occurred with the weed-free treatment on both units. On the Old clearcut, the year 1&2 release treatment resulted in moderate increases in both height and diameter; however, on the New clearcut, the second best treatment was the site preparation treatment. On the New clearcut, the site

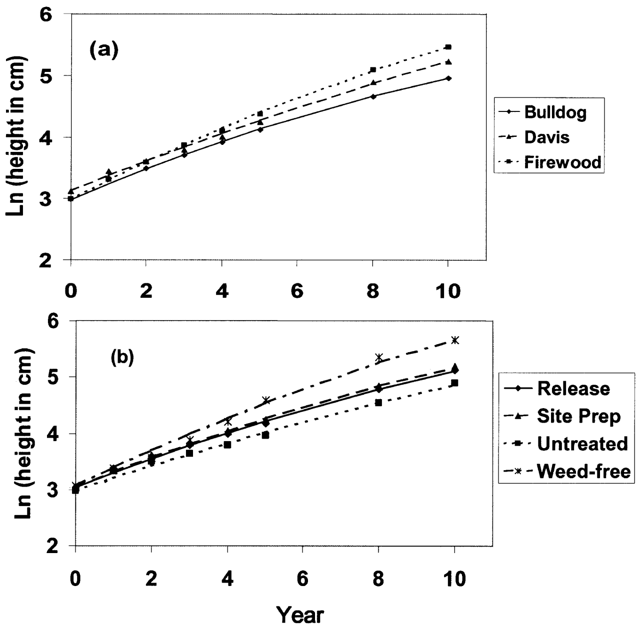

Figure 3. Sapling height curves illustrating (a) unit and (b) treatment effects at Fort Richardson. Symbols represent unit means averaged over blocks and treatments and treatment means averaged over units and blocks. Curves were derived from ANOVAs.

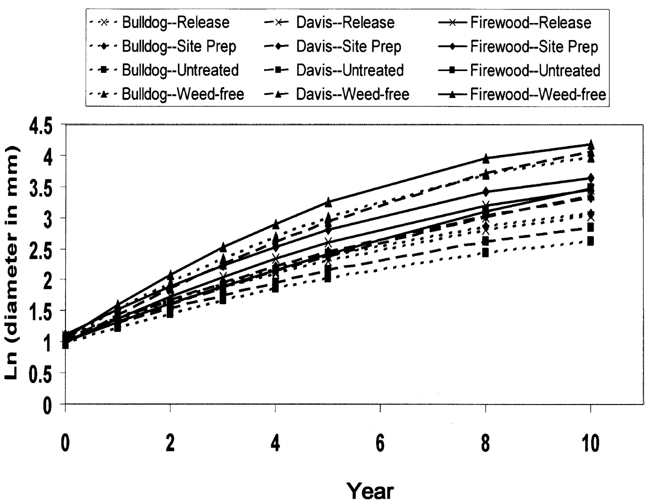

Figure 4. Sapling diameter curves illustrating unit and treatment effects at Fort Richardson. Diameter is root collar diameter through year 5, and basal diameter from years 8 to 10. Curves were derived from ANOVAs.

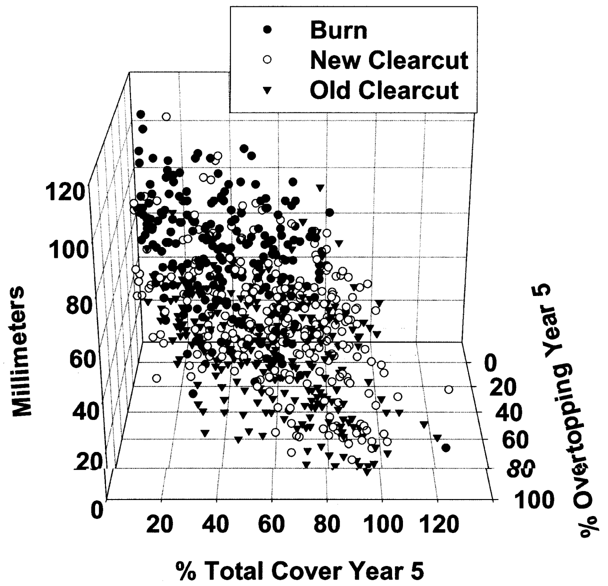

Figure 5. Relation among basal diameter year 11, percent overtopping year 5, and percent competing cover year 5 at Bonanza Creek. Symbols represent individual saplings.

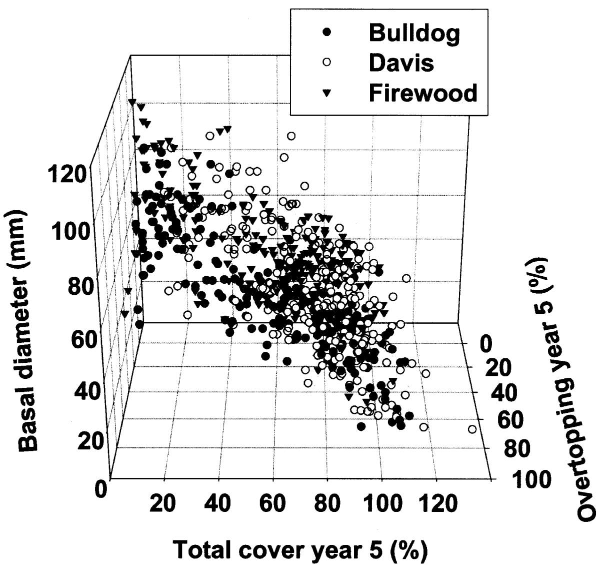

Figure 6. Relation among basal diameter year 10, percent overtopping year 5, and percent competing cover year 5 for units at Fort Richardson. Symbols represent individual saplings.

preparation treatment reduced aspen cover, because it included glyphosate, but the rates of hexazinone used for the release treatments were not effective at reducing aspen cover. The site preparation treatment was not as effective in removing established vegetation on the Old clearcut. It took another application of herbicide to decrease competing vegetation to the point that moderate size differences occurred. For both the weed-free and untreated treatments, the Old clearcut unit had less height and diameter than the New clearcut unit, suggesting the importance of planting seedlings before competing vegetation becomes established.

Absolute growth from the weed-free treatments on the New and Old clearcuts and the site preparation (New clearcut) and years 1&2 release (Old clearcut) treatments were similar to growth of scarified saplings on a nearby site that was salvage-logged, seeded, and planted with white spruce three years after a wildfire [14]. Growth from the weed-free, year 1 release,

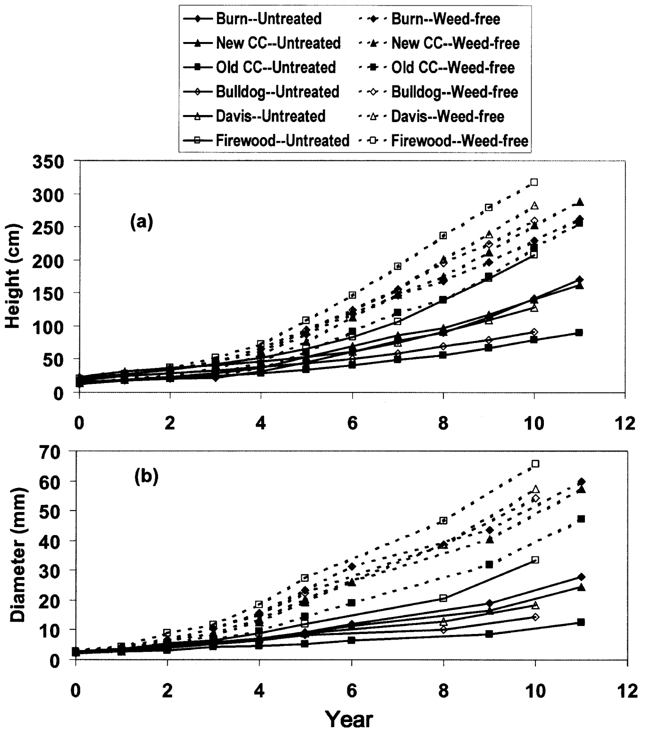

Figure 7. Sapling (a) height and (b) diameter curves for the weed-free and untreated treatments at Bonanza Creek and Fort Richardson. Diameter is root collar diameter for Fort Richardson through year 5 and basal diameter for Bonanza Creek (all years) and Fort Richardson years 8 to 10.

years 1&2 release, and site preparation treatments on the Burn unit were higher than that previously reported. When compared to directly seeded or naturally regenerated saplings on nearby sites, our saplings exhibited substantially greater growth [14, 40]. Seedlings regenerated from directed seeding averaged less than 25 cm in height after 5 years and were 34 to 63 cm tall after 10 years, depending upon site and treatment on the wildfire units [14]. On another nearby site, the tallest natural regeneration averaged 370 cm tall and 40 mm diameter after 27 years [40]. This unit was next to the Burn unit, but had not been burned. The differences in growth illustrate the increases attainable by planting and vegetation management in interior Alaska.

Wood and von Althen [39] reported results similar to our study on a site near Matheson, Ontario. White and black spruce (*Picea mariana* (Mill.) B.S.P.) in treatments with annual release (similar to our weed-free treatment) exhibited the best growth 5 years after planting. The next best treatment was a site preparation treatment, followed by a release treatment the year of planting. The release treatment the year after planting was not significantly different from the untreated treatment. Jobidon [23] also reported that moderate to medium levels of vegetation cover significantly reduced height and diameter growth of white spruce compared to growth on plots with no competing vegetation.

At Fort Richardson, saplings on the Firewood unit exhibited greater absolute growth than those on the Davis and Bulldog units. Although there were differences in soil depth (degree of rocks) and cold air drainage, there was also a difference in the time between clearing and planting. The Firewood unit had been cleared the fall before planting, while the other units had been cleared 3 years prior to planting, which allowed for competing vegetation to establish. In the weed-free treatments, vegetation control was similar among all of the units; so it is likely that the greater growth in the weed-free treatment at the Firewood unit compared to the weed-free treatments at Davis and Bulldog was attributable to differences in site quality.

The presence of Labrador tea and low shrub cover are inversely correlated with spruce growth at the Bulldog and Davis units. (These shrubs were virtually absent at the Firewood unit.) Several studies from Sweden have shown that dense cover of the ericaceous dwarf shrub *Empetrum hermaphroditum* Hagerup inhibited growth of Scots pine (*Pinus sylvestris* L.) by root competition, allelopathy, and reduced nutrient uptake, particularly nitrogen [27, 28, 44]. Similar processes may account for the reduced growth at the Bulldog and Davis units.

Analyzing data with year as a continuous regression variable within the ANOVA allows for creation of height and diameter curves through time. Analyses limited to only the most recent measurements do not show how treatment differences are expressed in time. For most treatments, our data show early divergence in the curves, with some treatments now parallel and other treatments still diverging. Of particular interest was the result from the Year X Unit X Treatment interaction at Fort Richardson. This interaction was significant because of changes in time between two of the treatments at the Firewood unit. Early in the analyses, the release treatment resulted in seedlings with larger diameters than the untreated plots. Previous single year analyses indicated that these differences in diameter were significant. By year 11, those differences were no longer significant, and it appears that the curves are on different trajectories. Future measurements will be needed to confirm this observation. Results from other spruce vegetation management studies [3, 30] have also indicated that longer-term observations may differ from early results, emphasizing the importance of longer-term studies when evaluating vegetation management treatments.

For our study, we speculate that the difference in early and longer-term results is related to different species composition between the treatments. The Firewood unit had a dense cover of bluejoint grass throughout the area when the study was established. The release treatment decreased this cover, allowing for other species, such as birch and alder to develop. These species are capable of obtaining greater heights than the grass and shrubs present in the untreated plots. In the untreated plots, surviving spruce are now taller than the grass, and mean overtopping of saplings alive at year 10 has decreased from a high of 39% in year 2 to 1% in year 10. In contrast, overtopping in the release treatment has remained relatively constant through time—10% in year 2 and 6.5% year 10.

Based on surrounding natural stands, the Bonanza Creek units appear to have higher site qualities than any of the units at Fort Richardson. For the weed-free and untreated treatments, the Firewood unit at Fort Richardson had greater absolute growth than any of the Bonanza Creek units. Under weed-free conditions, poor sites at Fort Richardson had growth similar to the Bonanza Creek units. These early results indicate that site quality based on older, unmanaged stands in the white spruce zone may not reflect the potential of the site for increased juvenile growth. However, it is not known if increased juvenile growth would continue as the stands mature. It is possible that some site-limiting factors would result in decreased growth later.

5. CONCLUSIONS

White spruce competition studies in Alaska indicate that survival of white spruce can be impacted by vegetation management treatments. Although decreasing competing vegetation may result in increased survival, it may also increase susceptibility of seedlings to fall freezing injury.

Height and diameter of white spruce were increased by decreasing competing vegetation. Increases depend upon the efficacy of the treatment in controlling competing vegetation and may also be related to increases in soil temperature caused by reduced vegetative cover, as well as site factors such as site quality, climatic conditions, and freezing injury. The greatest absolute growth was seen with repeated vegetation control. Where vegetation was kept at a minimum for 5 years, 10- and 11-year-old saplings were 1.5 to 3.8 times taller and 2.0 to 3.8 times larger on the average than saplings in untreated plots. Although a single site preparation treatment resulted in greater growth on most sites, it was not as effective on areas where competing vegetation was well established.

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