# Survival and growth response of white spruce stock types to site preparation in Alaska

**Andrew Youngblood, Elizabeth Cole, and Michael Newton**

**Abstract:** To identify suitable methods for reforestation, we evaluated the interacting effects of past disturbance, stock types, and site preparation treatments on white spruce (*Picea glauca* (Moench) Voss) seedling survival and growth across a range of sites in Alaska. Replicated experiments were established in five regions. At each site, two complete installations differed in time since disturbance: "new" units were harvested immediately before spring planting and "old" units were harvested at least 3 years before planting. We compared mechanical scarification before planting, broadcast herbicide application during the fall before planting, and no site preparation with 1-year-old container-grown seedlings from two sources, 2-year-old bare-root transplants from two sources, and 3-year-old bare-root transplants. Seedlings were followed for 11 years on most sites. Based on meta-analyses, seedling survival increased 10% with herbicide application and 15% with mechanical scarification compared with no site preparation. Scarification and herbicide application increased seedling height by about 28% and 35%, respectively, and increased seedling volume by about 86% and 195%, respectively, compared with no site preparation. Soil temperature did not differ among site preparation methods after the first 7 years. Results suggest that white spruce stands may be successfully restored through a combination of vegetation control and use of quality planting stock.

**Résumé :** Dans le but de trouver des méthodes de reboisement appropriées, nous avons évalué les effets interactifs des perturbations passées, du type de plants et des traitements de préparation de terrain sur la survie et la croissance de semis d'épinette blanche (*Picea glauca* (Moench) Voss) sur une gamme de stations en Alaska. Des expériences répétées ont été établies dans cinq régions. Sur chaque station, le dispositif comprenait deux unités qui se distinguaient par le temps écoulé depuis la perturbation. Les unités récentes ont été récoltées juste avant la plantation printanière alors que les unités plus âgées ont été récoltées au moins trois ans avant la plantation. À l'aide de semis en contenant âgés d'un an provenant de deux sources, de semis à racines nues âgés de deux ans provenant de deux sources et de semis à racines nues âgés de trois ans, nous avons comparé un scarifiage mécanique avant la plantation, une application à la volée d'herbicide l'automne précédant la plantation et un témoin non traité. Le suivi des semis a été effectué pendant une période de 11 ans sur la plupart des stations. En se basant sur des méta-analyses, la survie des semis a augmenté de 10 % à la suite du traitement à l'herbicide et de 15 % à la suite du scarifiage mécanique comparativement au témoin. Le scarifiage et l'application d'herbicide ont produit des hausses respectives de la hauteur des semis de 28 et de 35 % et des hausses respectives du volume des semis d'environ 86 et 195 % comparativement au témoin. La température du sol n'était pas différente entre les méthodes de préparation de terrain après les sept premières années. Les résultats indiquent que les peuplements d'épinette blanche peuvent être restaurés avec succès à l'aide d'une combinaison de maîtrise de la végétation et d'utilisation de plants de bonne qualité.

[Traduit par la Rédaction]



## Introduction

The circumboreal forest is the most extensive terrestrial biome in the world (Burton et al. 2003) and the largest forest region in North America. About one-third of Alaska (522 070 km$^2$) supports boreal forests dominated by *Picea glauca* (Moench) Voss (white spruce), *Picea mariana* (Mill.) Britton, Sterns, and Poggenb. (black spruce), *Betula neoalaskana* Sarg. (resin birch), *Populus balsamifera* L. (balsam poplar), *Populus tremuloides* Michx. (quaking aspen), *Larix laricina* (Du Roi) K. Koch (tamarack), and, on the Kenai Peninsula, *Picea* × *lutzii* Little (Lutz spruce), a natural hybrid of *P. glauca* and *Picea sitchensis* (Bong.) Carrière (Sitka spruce) (Burton et al. 2003).[1] Over the past several decades, three major forms of disturbance have occurred at unparalleled levels in the boreal forests in Alaska. First, fire regimes have shifted, with an increase in the total area burned, a doubling of decadal frequency of large fires (>1000 km$^2$), and a greater proportion of early and mid-growing season fires compared with the 1960s and 1970s (Kasischke and Turetsky 2006). At the same time, major insect infestations grew to unprecedented levels. Spruce bark beetle (*Dendroctonus rufipennis* Kirby) infested nearly 12 000 km$^2$ of white spruce and *Picea* × *lutzii* forests, killing more than 90% of the

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[1]Plant species nomenclature follows the PLANTS database (U.S. Department of Agriculture (USDA) and Natural Resources Conservation Service (NRCS) 2010).

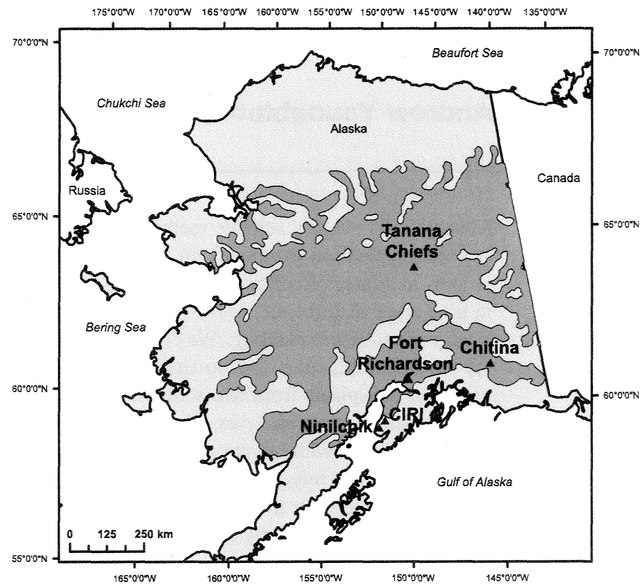
trees >11 cm in diameter (Werner et al. 2006), and recent spruce budworm (*Choristoneura fumiferana* Clemens) outbreaks resulted in spruce top kill and dieback, little cone production, and mortality of seedlings and saplings (USDA Forest Service 2008). Finally, as production of softwood timber from the Pacific Northwest diminished in the early 1990s over concerns for wildlife habitat, product demand of Pacific Rim markets shifted to accept more white spruce round logs and chips from interior Alaska and the Kenai Peninsula, leading to increased harvesting. Increasing levels of wildfire, insect-caused mortality, and timber activity have brought into question the adequacy of natural and artificial white spruce regeneration (Van Hees 2005; Boucher and Mead 2006; Boggs et al. 2008).

Natural regeneration of white spruce after site disturbance is often inadequate to meet reforestation standards due to sporadic seed production cycles, rapidly diminishing seed viability after dispersal, and inadequate site conditions for seedling establishment (Cole et al. 2003). When natural regeneration does occur, seedling growth is often impeded by competing vegetation, limited by reduced light availability, and hindered by cold soils that restrict root growth and by a short growing season, and the distribution of natural seedlings is unreliable (Youngblood and Zasada 1991).

Many of the principal competitor species on white spruce sites in Alaska are herbaceous or woody perennials that reproduce by both seed and asexual means and are highly adapted for rapid establishment and growth in areas with disturbed soils. Above- and below-ground biomass of *Calamagrostis canadensis* (Michx.) P. Beauv. (bluejoint grass), *Chamerion angustifolium* (L.) Holub = *Epilobium angustifolium* (L.) (fireweed), *Alnus viridis* (Chaix) DC. subsp. *crispa* (Aiton) Turrill (mountain alder), and *P. tremuloides* frequently increase after disturbance to levels that restrict the establishment and growth of other plant species, especially small white spruce seedlings. Artificial regeneration becomes more difficult once sites are fully occupied by these competitive species compared with sites immediately after disturbance. Chemical herbicides have been used increasingly to control these and other competitor species in Canada (Thompson and Pitt 2003), but similar experience in Alaska has been lacking.

Herbicides are an effective tool in vegetation management on some sites, yet the primary use in northern latitudes has been for release of already established plantations once competing vegetation affects seedling growth rather than as a site preparation treatment to improve conditions for seedling establishment (Grossnickle 2000). We asked whether the choice of chemical or mechanical site preparation offers important advantages over planting with no site preparation. Second, because white spruce seedlings with larger shoot and root sizes and greater root collar diameters may grow faster and tolerate competing vegetation better than small seedlings (Cole et al. 2003), we asked whether, across a range of sites, large planting stock have significant and persistent advantages over small stock in the ability to grow quickly and occupy sites before naturally occurring competitors become dominant, as suggested by Sutherland and Day (1988); Newton et al. (1993), and South et al. (1993). Finally, secondary successional processes after disturbances allow broadleaf trees, shrubs, and herbaceous species to rapidly reoccupy boreal forest sites (Boucher and Mead 2006; Chen et al. 2009), and these dynamics can influence stand development for decades (Youngblood 1995). We asked whether reforestation success immediately after disturbances differs from reforestation success after a delay of several years during which competing vegetation may become fully established, and whether this difference imparts advantages for seedling survival and growth that are influenced by choices of seedling stock sizes.

**Fig. 1.** Map of five Alaskan study sites, with distribution of white spruce (*Picea glauca*) shaded.




## Methods

### Study sites

Field installations for this study were established in five regions of Alaska (Fig. 1). Sites ranged in elevation from 109 to 274 m, with slopes less than 25%. The Tanana site is about 58 km west of Fairbanks, Alaska, in the Tanana River uplands. It has the coldest winter temperatures, the shortest growing season, but the warmest summer temperatures of our five sites; details on 30-year climatic records for the sites are found in Supplemental Appendix S1.[2] Mean annual temperature was –3.9 °C, and mean annual precipitation was 273 mm. Daily air temperature increases rapidly in the spring with increasing daylight, yet snow may persist through late May. Soils at the Tanana site are very deep, well-drained Typic Haplocryepts formed from micaceous loess. Surrounding stands belong to the *Picea glauca – Betula papyrifera / Hylocomium splendens* community type (Youngblood 1993) and include *B. neoalaskana*, *A. viridis*, *Viburnum edule* (Michx.) Raf. (squashberry), *Linnaea borealis* L. (twinflower), and *C. canadensis*.

The Fort Richardson site is about 20 km northeast of An-

[2]Supplemental data are available with the article through the journal Web site (www.nrcresearchpress.com/cjfr).

chorage, Alaska, in the Matanuska–Susitna Valley on the Fort Richardson Army Base. This site is in a transition zone between maritime and continental climate zones. Mean annual temperature was 1.8 °C, and mean annual precipitation was 410 mm. Soils at the Fort Richardson site are very deep, well-drained Typic Haplocryods formed in a thin mantle of ash-influenced loess overlying friable to firm gravelly glacial till. Surrounding stands are white spruce and mixed hardwoods, including *B. neoalaskana*, *P. tremuloides*, and *P. balsamifera*. Understory shrubs include *A. viridis*, *V. edule*, *Shepherdia canadensis* (L.) Nutt. (russet buffaloberry), and *Rosa acicularis* Lindl. (prickly rose).

The Chitina site is in the Copper River Basin about 90 km southeast of Glennallen. Mean annual temperature was –2.7 °C, and mean annual precipitation was 280 mm. The Chitina site belongs to the same cold, dry continental climate type as the Tanana site, but differs because of frequent winds and cold air drainage along the Copper River. Soils at the Chitina site are very deep, well-drained Cumulic Cryoborolls formed in silty loess. Surrounding stands are mostly white spruce with *A. viridis*, *L. borealis*, *R. acicularis*, and *Hylocomium splendens* (Hedw.) Schimp. (splendid feather moss).

The CIRI study site is about 40 km south of Soldotna, Alaska. Soils are very deep, well-drained Andic Haplocryods formed from ash-influenced loess overlying gravelly outwash. Surrounding stands are predominantly white spruce mixed with *Picea* × *lutzii*, *B. neoalaskana*, and *P. balsamifera*, with *A. viridis*, *R. acicularis*, *Ledum groenlandicum* Oeder (bog Labrador tea), *Menziesia ferruginea* Sm. (rusty menziesia), *Geocaulon lividum* (Richardson) Fernald (false toadflax), and *C. canadensis* in the understory.

The final study site is Ninilchik, about 28 km north of Homer, Alaska. Soils are similar to those at CIRI. Surrounding stands are predominantly *P. glauca* and *Picea* × *lutzii* and scattered *B. neoalaskana*, with *A. viridis*, *R. acicularis*, *L. groenlandicum*, *Sanguisorba canadensis* L. (Canadian burnet), *G. lividum*, *Gymnocarpium robertianum* (Hoffm.) Newman (scented oakfern), and *C. canadensis* in the understory. Both CIRI and Ninilchik sites lie in a narrow transitional climate zone between maritime and continental influences on the Kenai Peninsula; typically summers are cooler, and more snow accumulates in the winter compared with Fort Richardson. Mean annual temperature was 6.2 °C, and mean annual precipitation was 442 mm. Both sites experience a relatively high number of days with cloud cover during the growing season because of proximity to Cook Inlet. Soil moisture is rarely limiting.

At each site, we installed two complete experimental installations (units) that differ in time since disturbance. The "new" unit was an operational clearcut unit with overstory trees harvested immediately before site preparation. The "old" unit was operationally harvested at least 3 years before planting. A few residual live trees in or immediately adjacent to each unit were killed by chemical injection (imazapyr). Within sites, units were judged to be ecologically similar based on adjacent vegetation and physical site characteristics. The study was established at four sites in 1995 with planting in spring 1997; the Chitina site was established and planted 1 year later.

**Experimental design and treatments**

The experimental design for each unit was a completely randomized design with a split-plot arrangement of treatments with repeated measurements of survival and growth through time. We compared planting immediately after harvesting with planting after a delay of ≥3 years, three site preparation treatments, and five seedling stock types. Each experimental installation (unit) was divided into nine uniform square plots, each plot about 0.2 ha in size and surrounded by a 5 m buffer. The whole plots were treated at random with one of three choices of site preparation with three replications:

- mechanical scarification using a bulldozer with brush blade or straight blade to remove plant cover and expose about 85% bare mineral soil before planting (blade),
- control of vegetation by a single broadcast herbicide application of 1.65 $kg \cdot ha^{-1}$ of hexazinone (Velpar L®) plus 1.1 $kg \cdot ha^{-1}$ glyphosate (Roundup®) using a waving wand attached to a backpack sprayer, applied in the fall before planting (spray), and
- no site preparation (control).

Five seedling stock types with 30 seedlings of each were hand planted at 3 m × 3 m spacing in each plot in randomly assigned rows of 15 seedlings. Stock types included the following:

- 1-year-old container-grown seedlings from a commercial nursery in Washington State (S10),
- 1-year-old container-grown seedlings from a commercial nursery in southern British Columbia (P10),
- 2-year-old bare-root transplants grown at the Alaska State Nursery at Palmer as container stock for 1 year and then transplanted for 1 year in a nursery field (AP1),
- 2-year-old bare-root transplants grown as container stock for 1 year at a commercial nursery in Washington State and then transplanted to a nursery field for 1 year (SP1), and
- 3-year-old bare-root transplants grown at the Alaska State Nursery as container stock for 1 year and then transplanted for 2 years in a nursery field (AP2).

All stock types were grown from local seed sources furnished by the Alaska Division of Agriculture, Plant Materials Center, Palmer, Alaska. Seeds collected from the Tanana and Chitina areas likely were from the western variety of white spruce (*P. glauca* var. *albertiana* (S. Brown) Sarg.) characterized by relatively tall, narrow crowns, whereas seeds collected from the Kenai Peninsula likely were from *P. glauca* var. *porsildii* Raup, with relatively short, broad crowns and persistent branches. Kenai Peninsula seed lots also likely included *Picea* × *lutzii*, characterized by poor growth form at maturity. As a minor objective, we hypothesized that seedlings grown from *P. glauca* var. *albertiana* seed originating from the Tanana site would perform better than seedlings from seed collected from the Kenai Peninsula. Thus, a sixth stock type (T10) was 1-year-old container-grown seedlings from the same British Columbia nursery using seeds from our Tanana area; this stock type was planted only on blade-scarified and control plots on the Ninilchik and CIRI new units. AP1 and AP2 seedlings were lifted from the Alaska State Nursery under freezing conditions in October 1996. The larger AP2 seedlings may have sustained root damage

**Table 1.** Summary statistics (mean ± SE) for white spruce (*Picea glauca*) seedlings, by stock type, at the time of planting at five sites in Alaska.

| Stock type | Number | Height (cm) | Root collar diameter (mm) | Stem volume (cm$^3$) |
|---|---|---|---|---|
| **Tanana** | | | | |
| S10 | 540 | 22.8±0.25 | 2.7±0.02 | 0.47±0.010 |
| P10 | 534 | 13.2±0.21 | 3.1±0.02 | 0.34±0.008 |
| AP1 | 538 | 12.0±0.18 | 3.0±0.03 | 0.33±0.011 |
| SP1 | 537 | 20.4±0.17 | 4.8±0.03 | 1.30±0.025 |
| AP2 | 540 | 39.9±0.32 | 6.4±0.04 | 4.63±0.091 |
| **Fort Richardson** | | | | |
| S10 | 548 | 18.1±0.21 | 2.7±0.02 | 0.36±0.007 |
| P10 | 539 | 15.3±0.17 | 3.2±0.02 | 0.43±0.007 |
| AP1 | 437 | 8.3±0.10 | 2.6±0.02 | 0.16±0.005 |
| SP1 | 547 | 27.7±0.28 | 5.1±0.04 | 2.12±0.006 |
| AP2 | 541 | 28.4±0.27 | 6.1±0.04 | 3.02±0.066 |
| **Chitina** | | | | |
| S10 | 540 | 12.1±0.16 | 2.1±0.01 | 0.14±0.003 |
| P10 | 546 | 15.7±0.12 | 2.5±0.01 | 0.27±0.005 |
| SP1 | 540 | 29.6±0.23 | 5.8±0.04 | 2.79±0.058 |
| **CIRI and Ninilchik** | | | | |
| S10 | 1079 | 22.1±0.17 | 2.7±0.01 | 0.46±0.007 |
| P10 | 1078 | 17.2±0.12 | 3.1±0.01 | 0.44±0.005 |
| T10 | 289 | 14.4±0.30 | 3.2±0.02 | 0.39±0.011 |
| AP1 | 1079 | 9.3±0.06 | 2.5±0.01 | 0.16±0.002 |
| SP1 | 1087 | 28.5±0.21 | 5.0±0.03 | 2.10±0.040 |
| AP2 | 950 | 34.1±0.24 | 5.9±0.03 | 3.39±0.054 |

**Note:** See text for stock type descriptions. Stock types for CIRI and Ninilchik came from the same seed source and are summarized together.



that influenced subsequent growth and development. All stock types were stored in wax-impregnated seedling boxes at –2 °C for several weeks and then overwintered at –7 °C. Deficiencies in seedling numbers prevented a full component of all stock types at some sites, especially AP2 at CIRI and Ninilchik and AP1 at Fort Richardson. AP1 and AP2 stock types were not planted at Chitina. A total of 12 489 seedlings were planted and measured at the time of planting (Table 1). Frozen soil was encountered within 15 cm of the surface of some plots at the time of planting at Tanana, Ninilchik, and CIRI.

### Response variables and data analysis

Seedling measurements were made after the growing season in years 1 (1997), 2, 3, 5, 7, and 11, except at Chitina, where measurements were made in years 1 (1998), 2, and 4. During the summer of 2002, uncharacteristic flooding of the Kotsina River destroyed a bridge that provided the only access to the new unit at Chitina, and this site had to be abandoned. Diameter was measured at ground line (root collar diameter or RCD), at 15 cm above ground (basal diameter), and at 137 cm (breast height) above ground when possible. Total height was recorded and verified by checking previous growth nodes. Seedlings that had died at any time during the study were deleted from the sample at all measurement intervals, and all analyses were weighted based on the number of surviving seedlings for each stock type within each plot.

Survival was analyzed for year 11 at four sites and for year 4 at Chitina. Using the formula of a cone, seedling stem volume was calculated as

$$[1] \quad V = \pi(\mathrm{RCD}/2)^2 H/3$$

where $V$ is volume, RCD is seedling root collar diameter, and $H$ is seedling height. Overtopping cover (maximum 100%) for each seedling was estimated by visual measures of occlusion of a 60° conical volume projected above the second node from the top as a measure of competition (Howard and Newton 1984; Cole et al. 2003). We evaluated the change in overtopping cover (Δovertopping) as the difference between overtopping in year 1 and overtopping in year 11 (year 4 at Chitina). These data were first transformed by an angular transformation ($\sin^{-1}\sqrt{y}$) to stabilize the variance of percentage data before the ANOVA (Quinn and Keough 2002).

Soil temperature in much of the range of white spruce is close to the minimum for perennial plant development, with temperature above freezing for only a few months of the year. As an indirect measure of site preparation efficacy, we measured soil temperature with buried thermisters in a single blade-scarified, herbicide-sprayed, and control plot in each old and new unit at each of the five sites. Thermisters had an operating range between –20 and +70 °C, with accuracy of ± 0.7 °C at 20 °C. Each thermister was buried 15 cm below the mineral soil – forest floor interface without disturbing the soil and vegetation profile directly above. Soil temperature was recorded at intervals of 2 to 8 h depending on the year, beginning at the time of planting in late May 1997 at Fort Richardson, CIRI, and Ninilchik or early June 1997 at Tanana, continuously through late August 2003. Thermisters at Chitina recorded from early June 1998 until mid-August 2001.

Primary response variables describing seedling adaptability were survival, total height, volume, and Δovertopping and were compared with a split-plot analysis of variance (ANOVA) of treatment means for each unit, with site preparation treatments as the main plot and stock types as subplots. We fitted a generalized linear mixed model for survival by using PROC GLIMMIX in SAS (ver. 9.1; SAS Institute Inc., Cary, North Carolina) with the ilink option because this procedure maintains the non-normal distribution of the data and outputs proportions, thus avoiding issues of asymmetrical confidence intervals. Mixed models for total height, volume, and Δovertopping were fit with PROC MIXED in SAS and with Statistix (ver. 9; Analytical Software, Tallahassee, Florida); the generalized linear mixed model procedure was not used for Δovertopping because of the high number of negative values. Fine structure differences in means were examined by using a priori single degree-of-freedom tests within the context of the ANOVA. The two main plot contrasts were specified as (*i*) the difference between mechanical scarification and no site preparation (blade vs. control), and (*ii*) the difference between herbicide application and no site preparation (spray vs. control). The four subplot contrasts were specified as (*i*) the difference between 1-year-old container-grown seedlings and older bare-root transplants (S10 + P10 vs. AP1 + SP1 + AP2), (*ii*) the difference between relatively small seedlings and the larger seedlings (S10 + P10 + AP1 vs. SP1 + AP2), (*iii*) the difference between seedlings produced within Alaska and those produced elsewhere (AP1 + AP2 vs. S10 + SP1 + P10), and (*iv*) the apparent best container-grown seedling and the apparent best bare-root transplant (P10 vs. SP1). For these contrasts, we used Student's *t* test because it is appropriate for a priori tests, recognizing that it does not control the experiment-wise error rate. A paired *t* test was used to compare S10 seedlings with the offsite T10 seedlings at CIRI and Ninilchik under the hypothesis that the mean of the differences between pairs is not zero. Daily soil temperature recordings were summarized across all years of record to obtain mean monthly soil temperature by site preparation for each installation. We focused only on the 6-month potential growing season of May through October. Mean monthly temperature for each of the 6 months of interest was compared across all installations ($n = 10$) for difference among site preparation treatments by using ANOVA in Statistix. A statistical significance level of $p < 0.05$ was used for all univariate tests.

In addition to these within-site analyses, we also conducted an analysis of treatment effects across the five sites by using a meta-analysis approach. This higher-order analysis was conducted to identify commonalities not apparent at site levels with various conflicting interactions. Differences among responses at each site were summarized by a unitless index of effect size and these indices were summarized across the various studies in a meta-analysis (Gurevitch and Hedges 1999; Rosenberg et al. 2000). In this work, effect size was the magnitude of the standardized mean difference between two treatments. Hedges' *G* was used to calculate effect size because it accounts for unequal sampling variances among treatments (Hedges 1981). Using treatment means and standard deviations from the analyses of variance for survival, height, stem volume, and Δovertopping, Hedges' effect size *G* was calculated as:

$$[2]\qquad G = \frac{\overline{X}_{E} - \overline{X}_{C}}{S_{P}}$$

where $\overline{X}_E$ is the mean for an experimental site preparation method, $\overline{X}_C$ is the mean for the control, and $S_P$ is the pooled standard deviation for the two groups. Hedges' *G* calculated in this manner is biased when used with small sample sizes (Rosenberg et al. 2000); an adjustment was made to account for this bias. Hedges' *d* was calculated as

$$[3]\qquad d_i = G\left(1 - \frac{3}{4(N_C + N_E - 2) - 1}\right)$$

where $d_i$ is the adjusted effect size for each individual site, $N_C$ and $N_E$ are the number of replicates for the treatment in question at site *i*, and *G* is the unadjusted effect size.

To calculate the cumulative effect size across all sites, a fixed-effects model was used on the assumption that the population of study sites in Alaska shares a true effect size for the treatments under investigation (Gurevitch and Hedges 1993). Under this model, the test of $H_o$ that the true effect size was zero was tested by constructing confidence intervals for the true average effect size. Means and 95% confidence intervals of the effect size for each site by unit by site preparation treatment by stock type combination were calculated using MetaWin 2.0, and effect sizes were considered statistically significant if the 95% confidence interval did not overlap zero (Rosenberg et al. 2000). A summary analysis was conducted to calculate effect sizes by categories and a cumulative effect size, which represented the overall magnitude of the effect across all studies, and the degree of variation within effect sizes. Heterogeneity was the total variation in effect sizes and was similar to the total sum of squares in an analysis of variance. Heterogeneity was calculated as

$$[4]\qquad Q_T = \sum_{i=1}^{n} w_i\,(d_i - \overline{d})^2$$

where $Q_T$ is the total heterogeneity, *n* is the number of studies, *d* is the effect size, $\overline{d}$ is the cumulative effect size, and *w* is the weight for the *i*th study. The statistic $Q_T$ was tested against a $\chi^2$ distribution with $n - 1$ degrees of freedom (Gurevitch and Hedges 1993). The fixed-effect model used study weights defined as the reciprocal of the study variance. When the test of total heterogeneity suggested that the variance among effect sizes was greater than expected by sampling error, the underlying structure of the data was examined. Cumulative effect size for groupings based on site, unit age, or stock type was calculated as

$$[5]\qquad Q_T = Q_M + Q_E$$

where $Q_M$ is the variation in effect sizes that was explained by the model containing groupings and thus a description of the difference among group cumulative effect sizes, and $Q_E$ is the residual error heterogeneity. The off-site T10 seedlings were not included in this meta-analysis because they were planted in only two of the 10 units.

## Results

### Survival

In the final year of measurement (year 4 at Chitina and year 11 at other sites), a total of 9361 live seedlings remained. Survival across stock type and site preparation treatments was generally above 70% except for several stock type × site preparation × site combinations. Lower than expected survival occurred in S10 (21% ± 3%), P10 (30% ± 3%), and AP2 (35% ± 3%) stock types in control plots on the new unit at CIRI, AP1 (48% ± 5%) and AP2 (49% ± 5%) stock types in control plots on the new unit at Ninilchik, AP1 (38% ± 3%) and S10 (48% ± 3%) stock types in control plots on the old unit at Ninilchik, and the S10 (41% ± 3%) stock type in sprayed plots on the old unit at Ninilchik (Fig. 2). Survival tended to stabilize by the 5th year except in S10 and P10 stock types in control plots on the new unit at CIRI, in the AP1 stock type in blade-scarified plots on the old unit at Fort Richardson, in S10, AP1, and AP2 stock types in sprayed plots on the old unit at Ninilchik, and in the AP1 stock type in control plots on old units at Fort Richardson and Ninilchik.

Details on the results of the ANOVA for survival by unit are found in Supplemental Appendix S2.[2] Blade scarification increased survival compared with the control treatment on four units: the new unit at Tanana (87% ± 1% vs. 77% ± 2%), the new unit at CIRI (84% ± 1% vs. 30% ± 2%), the old unit at Tanana (97% ± 1% vs. 75% ± 1%), and the old unit at Ninilchik (90% ± 1% vs. 63% ± 2%). Herbicide application increased survival on three units: the new unit at Tanana (88% ± 1% vs. 77% ± 2%), the new unit at CIRI (75% ± 2% vs. 30% ± 2%), and the new unit at Ninilchik (90% ± 2% vs. 68% ± 4%). Younger stock types (P10 and S10) survived better compared with older stock types (AP1, SP1, and AP2) on new units at Chitina (SP1 only) and Ninilchik and old units at Fort Richardson, Chitina (SP1 only), and CIRI. Older stock types survived better on the old unit at Ninilchik. Larger stock types (SP1 and AP2) survived better than smaller stock types on both new and old units at Fort Richardson and the old unit at Ninilchik. In contrast, smaller stock types (S10, P10, and AP1) survived better than large stock types on the old unit at CIRI. Stock types grown outside Alaska survived better than the two locally grown stock types on seven of the 10 units: both new and old units at Tanana, CIRI, and Ninilchik and the old unit at Fort Richardson. On both units at Chitina, the best container stock type (P10) survived better than the best bare-root stock type, whereas on the old units at CIRI and Ninilchik, the best bare-root stock type (SP1) survived better. Finally, the offsite stock type (T10) survived as well as the S10 stock type regardless of site preparation: 95% vs. 92% in blade-scarified plots and 13% vs. 20% in control plots at CIRI, and 88% vs. 92% in blade-scarified plots and 63% vs. 78% in control plots at Ninilchik.

Based on meta-analysis, blade scarification increased survival across all treatment combinations compared with no site preparation (82% ± 3% vs. 67% ± 3% survival; overall effect size = 1.54 ± 0.36). Across all sites, there was no difference in survival between blade-scarified and control plots by age since disturbance (new units vs. old units) ($Q_M$ = 0.536, df = 1, and $p$ = 0.464). In contrast, blade scarification increased survival at all sites except Fort Richardson; the effect size for this site was positive, yet the confidence interval contained the value 0 (Table 2). The effect size for blade scarification at Chitina was positive but only marginally significant. Similarly, blade scarification increased survival across all stock types except for AP2 seedlings (Table 3).

Based on meta-analysis, herbicide application also increased seedling survival across all treatment combinations compared with no site preparation, although the difference was not as great as with blade scarification (77% ± 3% compared with 67% ± 3% survival; overall effect size = 1.03 ± 0.33). Herbicide application was more effective on new units: herbicide application increased survival by about 16% in new units and about 4% in old units over that of the untreated plots ($d$ = 1.68 ± 0.53 for new units, $d$ = 0.61 ± 0.43 for old units, $Q_M$ = 10.425, df = 1, and $p$ = 0.001). There was no difference in seedling survival between herbicide application and no site preparation by site ($Q_M$ = 3.547, df = 4, and $p$ = 0.471). In contrast, herbicide application increased survival of small stock types but not the larger AP2 and SP1 seedlings (Table 3).

Blade scarification was slightly more effective than herbicide application in increasing seedling survival across all treatment combinations (82% ± 3% compared with 77% ± 3% survival; overall effect size = 0.32 ± 0.30). Scarification and herbicide application resulted in similar survival in new units, whereas scarification increased survival by about 9% over that of the sprayed plots on old units ($d$ = 0.03 ± 0.41 for new units, $d$ = 0.70 ± 0.48 for old units, $Q_M$ = 4.861, df = 1, and $p$ = 0.027). Survival after blade scarification was about 9% greater than survival after herbicide application at Tanana ($d$ = 1.09 ± 0.83), whereas blade scarification and herbicide application resulted in similar seedling survival at other sites ($Q_M$ = 14.559, df = 4, and $p$ = 0.006). There was no difference in seedling survival between blade scarification and herbicide application by stock type ($Q_M$ = 3.081, df = 4, and $p$ = 0.544).

The SP1 stock type performed poorly at Chitina, with survival averaging 10% on the new unit and 1% on the old unit. This may have been the result of inadequate storage conditions in addition to treatment response; because of this low survival, the SP1 stock type at Chitina was removed from all further analyses.

### Seedling height

All summaries of seedling height and volume were based on a total of 9194 live seedlings, which excluded seedlings that were severely impacted by animal browsing or clipping. Seedling stock types displayed wide variation in height growth in response to age since disturbance, site preparation, and location (Fig. 3). All stock types exceeded 100 cm in height by year 11, and most of the stock types on new units exceeded 200 cm in height. The SP1 stock type in the sprayed plot on the old unit at Fort Richardson exceeded 330 cm in height in year 11. The S10, P10, and AP1 stock types were exceptionally consistent on old units across all sites. All stock types on both new and old units at Tanana displayed growth reductions attributed to spruce budworm defoliation.

Details on the results of the ANOVA for seedling height by unit are found in Supplemental Appendix S2.[2] Blade scarification resulted in taller seedlings compared with no site preparation on the old unit at Tanana (212 ± 5 cm vs. 126 ± 5 cm in height), both new (234 ± 10 cm vs. 138 ± 10 cm) and old (177 ± 5 cm vs. 144 ± 5 cm) units at CIRI,

**Fig. 2.** Mean survival (%) of planted white spruce (*Picea glauca*) stock types over time by three site preparation treatments (blade, blade scarification; spray, herbicide application; control, no site preparation) at five sites in Alaska, for (*a*) new units, with overstory removal immediately before site preparation, and (*b*) old units, with overstory removal at least 3 years before planting. See text for stock type descriptions.

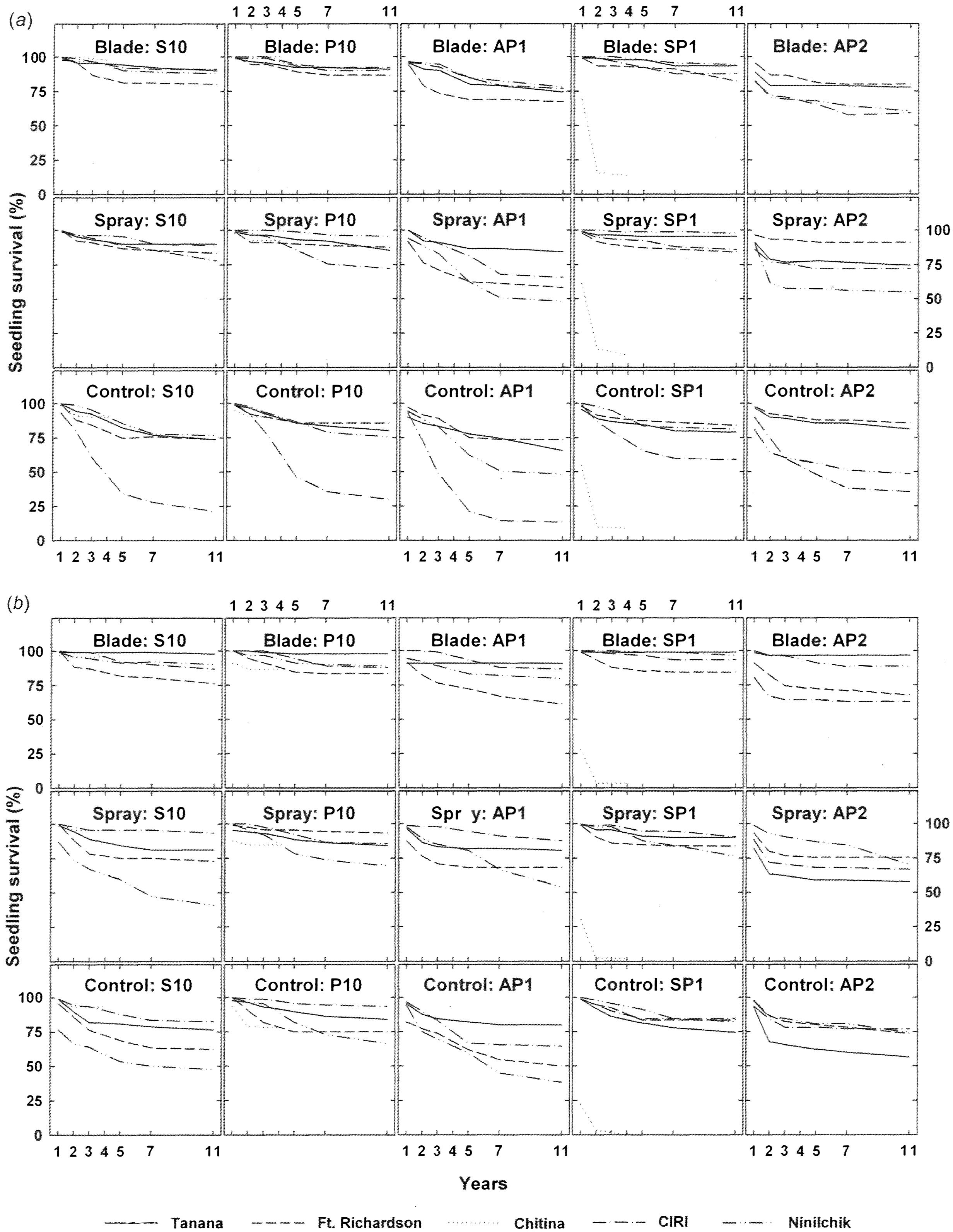


**Table 2.** (*a*) Survival (%) (mean ± SE) of planted white spruce (*Picea glauca*) seedlings after two site preparation treatments, by site, and effect size (*d*). (*b*) Results of a meta-analysis on the effect of blade scarification compared with no site preparation on seedling survival (within-group heterogeneity ($Q_M$)), with site as a category, at five sites in Alaska.

(*a*) Survival and effect size.

| Site | Blade | Control | *d* |
|---|---|---|---|
| Tanana | 90.9±2.7 | 75.2±2.6 | 2.92±1.02 |
| Fort Richardson | 85.8±3.3 | 64.2±5.3 | 0.20±0.67 |
| Chitina | 66.1±18.4 | 60.1±17.8 | 1.16±1.00 |
| CIRI | 82.5±3.9 | 56.0±9.2 | 1.64±0.71 |
| Ninilchik | 85.8±3.3 | 64.2±5.3 | 3.99±1.09 |

(*b*) Meta-analysis results.

| | Blade vs. control | | |
|---|---|---|---|
| Model | Heterogeneity | *p* | df |
| Between ($Q_M$) | 56.718 | <0.001 | 4 |
| Within ($Q_E$) | 169.350 | <0.001 | 41 |
| Total ($Q_T$) | 226.068 | <0.001 | 45 |

**Note:** Survival percentages were derived from a generalized linear mixed model ANOVA. Probability values (*p*) represent the probability that the variance would be exceeded based on a $\chi^2$ distribution. Blade, blade scarification; control, no site preparation; df, degrees of freedom.

**Table 3.** (*a*) Survival (%) (mean ± SE) of planted white spruce (*Picea glauca*) seedlings after three site preparation treatments, by stock type, and effect size (*d*). (*b*) Results of a meta-analysis on the effect of blade scarification compared with no site preparation and the effect of herbicide application compared with no site preparation on seedling survival (within-group heterogeneity ($Q_M$)), with stock type as a category, at five sites in Alaska.

(*a*) Survival and effect size.

| Stock type | Blade | *d* | Spray | *d* | Control |
|---|---|---|---|---|---|
| S10 | 89.5±2.2 | 2.73±0.92 | 82.2±5.2 | 1.99±0.84 | 69.8±6.8 |
| P10 | 90.7±1.6 | 1.53±0.84 | 85.2±2.7 | 1.08±0.75 | 76.0±5.7 |
| AP1 | 77.2±3.4 | 2.07±1.11 | 72.3±4.5 | 1.99±1.14 | 54.6±7.6 |
| SP1 | 74.9±11.3 | 1.55±0.83 | 71.6±11.2 | 0.67±0.76 | 64.0±10.3 |
| AP2 | 74.4±4.9 | −0.02±0.96 | 70.5±3.9 | 0.04±0.81 | 66.6±6.3 |

(*b*) Meta-analysis results.

| | Blade vs. control | | Spray vs. control | | |
|---|---|---|---|---|---|
| Model | Heterogeneity | *p* | Heterogeneity | *p* | df |
| Between ($Q_M$) | 24.872 | <0.001 | 20.082 | <0.001 | 4 |
| Within ($Q_E$) | 201.196 | <0.001 | 185.873 | <0.001 | 41 |
| Total ($Q_T$) | 226.068 | <0.001 | 205.955 | <0.001 | 45 |

**Note:** Survival percentages derived from a generalized linear mixed model ANOVA. Probability values (*p*) represent the probability that the variance would be exceeded based on a $\chi^2$ distribution. Blade, blade scarification; spray, herbicide application; control, no site preparation; df, degrees of freedom.

and the old unit at Ninilchik (210 ± 6 cm vs. 150 ± 6 cm). In contrast, blade scarification resulted in shorter seedlings on the new unit at Chitina (26 ± 1 cm vs. 31 ± 1 cm). Herbicide application resulted in taller seedlings compared with no site preparation on all units except the new unit at Tanana. Older stock types (AP1, SP1, and AP2) were taller compared with younger stock types on the new unit at Tanana and new and old units at Fort Richardson. Planting larger stock types (SP1 and AP2) resulted in taller seedlings compared with smaller stock types on both new and old units at Tanana, Fort Richardson, CIRI, and Ninilchik. Alaska stock types did not result in seedlings as tall as those from outside Alaska on both new and old units at Fort Richardson, CIRI, and Ninilchik. The best bare-root stock type resulted in taller seedlings compared with the best container stock type on both new and old units at Tanana, Fort Richardson, and the old unit at CIRI. The P10 stock type was taller than the S10 stock type on both units at Chitina. Finally, the off-site stock type (T10) was equal in height to the S10 stock type in blade-scarified plots at CIRI (213 cm vs. 210 cm), in control plots at CIRI (95 cm vs. 129 cm), and in blade-scarified plots at Ninilchik (159 cm vs. 194 cm), but was shorter in height compared with the S10 stock type in control plots at Ninilchik (139 cm vs. 180 cm).

Based on meta-analyses, several patterns emerged. Seedlings were taller after blade scarification compared with no

**Fig. 3.** Mean total height (log scale, cm) of planted white spruce (*Picea glauca*) stock types over time by three site preparation treatments (blade, blade scarification; spray, herbicide application; control, no site preparation) at five sites in Alaska, for (*a*) new units, with overstory removal immediately before site preparation, and (*b*) old units, with overstory removal at least 3 years before planting. See text for stock type descriptions.

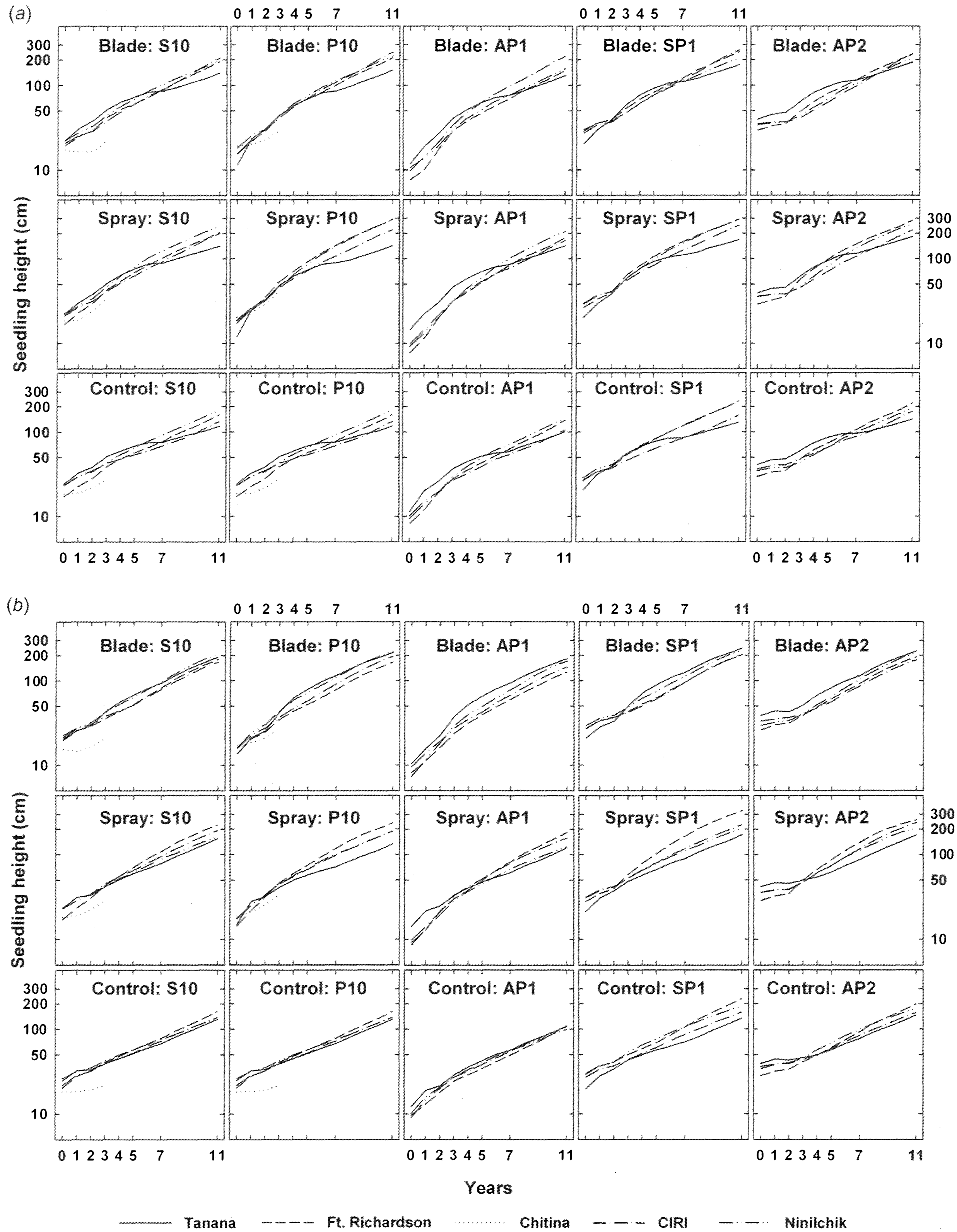


**Table 4.** (*a*) Total height (cm) (mean ± SE) of planted white spruce (*Picea glauca*) seedlings after three site preparation treatments, by site, and effect size (*d*). (*b*) Results of a meta-analysis on the effect of blade scarification compared with no site preparation and the effect of herbicide application compared with no site preparation on seedling height (within-group heterogeneity ($Q_M$)), with site as a category, at five sites in Alaska.

(*a*) Total height and effect size.

| Site | Blade | *d* | Spray | *d* | Control |
|---|---|---|---|---|---|
| Tanana | 184.4±7.1 | 2.50±0.81 | 152.7±24.0 | −0.98±0.68 | 124.1±4.2 |
| Fort Richardson | 189.6±7.8 | 0.51±0.61 | 248.9±9.7 | 1.99±0.74 | 175.9±8.6 |
| Chitina | 28.2±1.6 | −0.61±1.44 | 34.6±1.3 | 3.90±2.23 | 30.0±1.9 |
| CIRI | 205.9±6.4 | 2.38±0.78 | 205.4±6.3 | 0.09±0.64 | 136.4±5.7 |
| Ninilchik | 200.5±5.4 | 1.08±0.66 | 215.1±10.5 | 0.18±0.68 | 167.0±6.8 |

(*b*) Meta-analysis results.

| | Blade vs. control | | Spray vs. control | | |
|---|---|---|---|---|---|
| Model | Heterogeneity | *p* | Heterogeneity | *p* | df |
| Between ($Q_M$) | 47.326 | <0.001 | 71.515 | <0.001 | 4 |
| Within ($Q_E$) | 43.524 | 0.285 | 80.406 | <0.001 | 39 |
| Total ($Q_T$) | 90.851 | <0.001 | 151.921 | <0.001 | 43 |

**Note:** Probability values (*p*) represent the probability that the variance would be exceeded based on a $\chi^2$ distribution. Blade, blade scarification; spray, herbicide application; control, no site preparation; df, degrees of freedom.

site preparation (180 ± 5 cm vs. 141 ± 5 cm tall; overall effect size = 1.20 ± 0.30). Across all sites, there was no difference in seedling height between blade scarification and no site preparation by age since disturbance (new units vs. old units) ($Q_M$ = 2.515, df = 1, and $p$ = 0.113) or seedling stock type ($Q_M$ = 1.774, df = 4, and $p$ = 0.777). In contrast, the effect of blade scarification compared with no site preparation differed among sites (Table 4): seedlings were taller after blade scarification at Tanana, CIRI, and Ninilchik, but not at Fort Richardson and Chitina.

Seedlings were taller after herbicide application compared with no site preparation (190 ± 6 cm vs. 141 ± 5 cm tall; overall effect size = 2.03 ± 0.32). Across all sites, there was no indication of underlying structure in the data that would further explain variation ($Q_T$ = 36.557, df = 43, and $p$ = 0.745).

Finally, seedlings were taller after herbicide application compared with blade scarification (190 ± 6 cm vs. 180 ± 5 cm tall; overall effect size = 0.40 ± 0.30). There was no difference in seedling height between herbicide-treated plots and blade-scarified plots by age since disturbance (new units vs. old units) ($Q_M$ = 3.299, df = 1, and $p$ = 0.096) or among stock types ($Q_M$ = 0.958, df = 4, and $p$ = 0.069). In contrast, the effect of herbicide application compared with blade scarification differed among sites (Table 4): seedlings were taller after herbicide application at Fort Richardson and Chitina, were taller after blade scarification at Tanana, and did not differ between spray application and blade scarification at CIRI and Ninilchik.

### Seedling volume

Seedling volume likely provided the best metric of seedling performance and overall vigor (Fig. 4). After 11 years, seedling volume across all treatment combinations averaged 1489 ± 135 $cm^3$ at Fort Richardson, 1001 ± 78 $cm^3$ at Ninilchik, 862 ± 59 $cm^3$ at CIRI, and 501 ± 36 $cm^3$ at Tanana. After 4 years, seedling volume averaged 4 ± 1 $cm^3$ at Chitina. After 11 years, seedling volume after blade scarification averaged 923 ± 46 $cm^3$, volume after herbicide application averaged 1469 ± 110 $cm^3$, and volume without site preparation averaged 497 ± 36 $cm^3$. The largest stock types were SP1 seedlings (1456 ± 230 $cm^3$) in blade-scarified plots on the new unit at Tanana, SP1 seedlings (5318 ± 265 $cm^3$) in sprayed plots on the old unit at Fort Richardson, AP2 seedlings (1987 ± 106 $cm^3$) in sprayed plots on the old unit at CIRI, and P10 seedlings (2671 ± 735 $cm^3$) in sprayed plots on the new unit at Ninilchik.

Details on the results of the ANOVA for seedling volume by unit are found in Supplemental Appendix S2.[2] Blade scarification resulted in greater volume compared with no site preparation on the new unit (531 ± 64 $cm^3$ vs. 261 ± 64 $cm^3$) and the old unit (926 ± 18 $cm^3$ vs. 226 ± 18 $cm^3$) at Tanana, the new unit (1305 ± 184 $cm^3$ vs. 403 ± 184 $cm^3$) and the old unit (740 ± 48 $cm^3$ vs. 355 ± 48 $cm^3$) at CIRI, and the old unit (1011 ± 46 $cm^3$ vs. 367 ± 46 $cm^3$) at Ninilchik. Herbicide application increased seedling volume on all units except the old unit at Chitina and the new unit at Ninilchik. Planting with older seedlings compared with 1-year-old seedlings resulted in greater volume on both new and old units at Tanana and Fort Richardson. Initially larger seedlings developed with greater volume compared with smaller seedlings at all locations except Chitina. Stock types from outside Alaska had larger volume compared with those raised in Alaska on the old unit at Fort Richardson, the new unit at CIRI, and both units at Ninilchik. Bare-root stock types had larger volume than container stock types on both new and old units at Tanana, Fort Richardson, and CIRI. The P10 stock type was larger than the S10 stock type on both new and old units at Chitina. Finally, the off-site stock type (T10) had similar volume compared with S10 seedlings at CIRI in blade-scarified plots (1098 $cm^3$ vs. 912 $cm^3$) and control plots (113 $cm^3$ vs. 339 $cm^3$), and similar volume to S10 seedlings at Ninilchik in blade-scarified plots (593 $cm^3$ vs. 858 $cm^3$), but the volume was less than S10 seedlings in control units at Ninilchik (343 $cm^3$ vs. 666 $cm^3$).

Based on meta-analysis, blade scarification increased seedling volume compared with the no site preparation (839 ± 47 $cm^3$ vs. 452 ± 35 $cm^3$; overall effect size = 1.12 ± 0.28).

**Fig. 4.** Volume (mean ± standard error) of planted white spruce (*Picea glauca*) stock types after 11 years (4 years at Chitina) by three site preparation treatments (blade, blade scarification; spray, herbicide application; control, no site preparation) at five sites in Alaska, for new units, with overstory removal immediately before site preparation (solid circles), and old units, with overstory removal at least 3 years before planting (open circles). See text for stock type description. Standard errors are pooled across the unit.

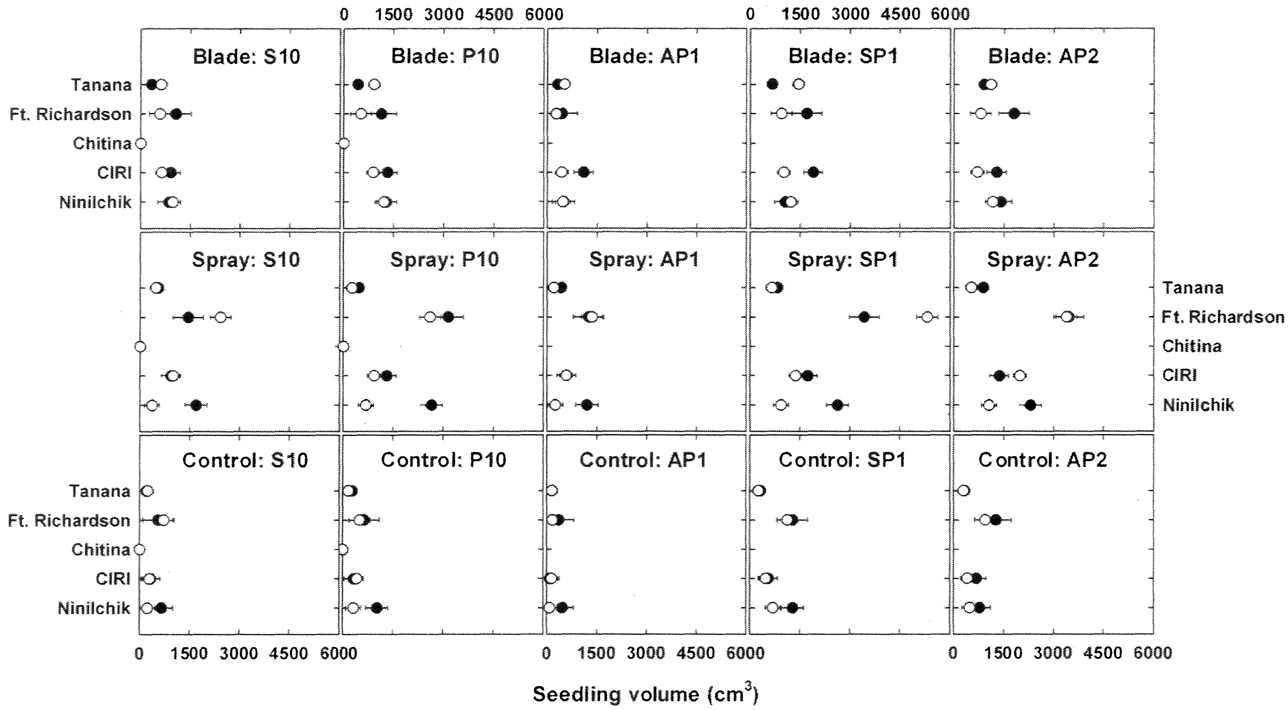



**Table 5.** (*a*) Seedling volume (cm$^3$) (mean ± SE) of planted white spruce (*Picea glauca*) seedlings after three site preparation treatments, by site, and effect size (*d*). (*b*) Results of a meta-analysis on the effect of blade scarification compared with no site preparation and the effect of herbicide application compared with no site preparation on seedling volume (within-group heterogeneity ($Q_M$)), with site as a category, at five sites in Alaska.

(*a*) Seedling volume and effect size.

| Site | Blade | *d* | Spray | *d* | Control |
|---|---|---|---|---|---|
| Tanana | 728.3±71.4 | 1.89±0.74 | 531.3±42.3 | 1.39±0.68 | 243.7±26.5 |
| Fort Richardson | 926.7±120.4 | −0.35±0.60 | 2780.8±243.4 | 3.19±0.95 | 758.8±87.5 |
| Chitina | 3.9±0.5 | 0.81±1.38 | 6.3±1.0 | 1.74±1.57 | 3.0±0.5 |
| CIRI | 1022.6±81.6 | 1.89±0.72 | 1183.3±98.9 | 2.34±0.79 | 378.8±42.6 |
| Ninilchik | 1014.0±71.6 | 1.06±0.66 | 1381.1±186.7 | 1.61±0.71 | 608.0±71.9 |

(*b*) Meta-analysis results.

| | Blade vs. control | | Spray vs. control | | |
|---|---|---|---|---|---|
| Model | Heterogeneity | *p* | Heterogeneity | *p* | df |
| Between ($Q_M$) | 22.797 | <0.001 | 14.786 | 0.005 | 4 |
| Within ($Q_E$) | 37.451 | 0.541 | 49.819 | 0.115 | 39 |
| Total ($Q_T$) | 60.248 | 0.042 | 64.606 | 0.018 | 43 |

**Note:** Probability values (*p*) represent the probability that the variance would be exceeded based on a $\chi^2$ distribution. Blade, blade scarification; spray, herbicide application; control, no site preparation; df, degrees of freedom.

There was no difference in seedling volume between blade-scarified plots and plots lacking site preparation by age since disturbance (new units vs. old units) ($Q_M$ = 0.970, df = 1, and $p$ = 0.325) or seedling stock type ($Q_M$ = 2.345, df = 4, and $p$ = 0.672). In contrast, seedling volume differed with site (Table 5): seedlings had greater volume when planted after blade scarification compared with no site preparation at Tanana, CIRI, and Ninilchik, whereas seedling volumes did not differ at Fort Richardson and Chitina. Seedling volume was greater after herbicide application compared with no site preparation (1336 ± 106 cm$^3$ vs. 452 ± 35 cm$^3$, overall effect size = 1.94 ± 0.32). Seedling volume was greater after herbicide application on new units (1472 ± 141 cm$^3$ vs. 508 ± 52 cm$^3$, effect size = 2.32 ± 0.48) and greater after herbicide application in old units, but the effect was not as great (1201 ± 159 cm$^3$ vs. 373 ± 43 cm$^3$, effect size = 1.15 ±

**Table 6.** (*a*) Seedling volume ($cm^3$) (mean ± SE) of planted white spruce (*Picea glauca*) seedlings after two site preparation treatments, by stock type, and effect size (*d*). (*b*) Results of a meta-analysis on the effect of herbicide application compared with no site preparation on seedling volume (within-group heterogeneity ($Q_M$)), with stock type as a category, at five sites in Alaska.

(*a*) Seedling volume and effect size.

| Stock type | Spray | Control | *d* |
|---|---|---|---|
| S10 | 888.5±149.7 | 327.2±58.8 | 1.60±0.70 |
| P10 | 1213.6±219.8 | 370.7±61.1 | 2.10±0.78 |
| AP1 | 731.8±109.0 | 207.0±36.2 | 1.35±0.78 |
| SP1 | 2115.5±326.9 | 754.2±89.6 | 2.61±1.00 |
| AP2 | 1873.8±241.4 | 654.3±86.1 | 2.66±1.01 |

(*b*) Meta-analysis results.

| | Spray vs. control | | |
|---|---|---|---|
| Model | Heterogeneity | *p* | df |
| Between ($Q_M$) | 10.014 | 0.040 | 4 |
| Within ($Q_E$) | 54.592 | 0.050 | 39 |
| Total ($Q_T$) | 64.606 | 0.018 | 43 |

**Note:** Probability values (*p*) represent the probability that the variance would be exceeded based on a $\chi^2$ distribution. Spray, herbicide application; control, no site preparation; df, degrees of freedom.

0.45) ($Q_M$ = 5.127, df = 1, and $p$ = 0.023). In addition, the effect of herbicide application varied with site (Table 5). Herbicide application was most effective at increasing seedling volume at Fort Richardson and CIRI. Herbicide application was more effective than no site preparation at increasing seedling volume for the P10, SP1, and AP2 stock types compared with S10 and AP1 stock types (Table 6). Herbicide application increased seedling volume compared with blade scarification, and the effect was relatively strong (1336 ± 106 $cm^3$ vs. 839 ± 47 $cm^3$; overall effect size = 2.19 ± 0.38). Seedling volume was greater after herbicide application on new units (1472 ± 141 $cm^3$ vs. 928 ± 79 $cm^3$, effect size = 1.01 ± 0.42) but did not differ on old units (1201 ± 159 $cm^3$ vs. 751 ± 51 $cm^3$, effect size = –0.03 ± 0.90) ($Q_M$ = 12.414, df = 1, and $p$ < 0.001). There was no difference in seedling volume between herbicide application and blade scarification by seedling stock type ($Q_M$ = 0.657, df = 4, and $p$ = 0.957). Herbicide application increased seedling volume at Fort Richardson but was equal to blade scarification at the other sites (Table 7).

## Overtopping

Stock types were variously affected by competing vegetation as reflected by overtopping; details of overtopping by unit are found in Supplemental Appendix S3.[2] Blade scarification was incomplete and left patches of competing vegetation, especially *C. angustifolium*, *C. canadensis*, *A. viridis*, and *P. tremuloides* on new units at Tanana and Fort Richardson and *C. angustifolium* and *C. canadensis* on old units at Fort Richardson, CIRI, and Ninilchik. Herbicide application helped moderate the amount of initial overtopping at all sites, yet *C. angustifolium* was consistently noted as contributing to overtopping. Units lacking site preparation provided the best indicator of baseline conditions; the highest percentage of initial overtopping occurred on the new unit at Tanana with *C. canadensis*, *C. angustifolium*, and *A. viridis*; in the old unit at Fort Richardson with *C. canadensis*, *C. angustifolium*, *Rubus idaeus* L. (American red raspberry), and *R. acicularis*; and on the new unit at CIRI with *C. canadensis*. Shifts in the amount of overtopping over time are reported in Supplemental Appendix S2.[2] Overtopping increased 10% ± 2% in blade-scarified plots as hardwoods such as *B. neoalaskana*, *P. tremuloides*, and *A. viridis* invaded and declined 4% ± 2% in control plots on the old unit at Tanana as seedlings dominated herbaceous layers. Overtopping increased 39% ± 3% in blade-scarified plots with rapid growth of *A. viridis* but was essentially unchanged in control plots on the old unit at Fort Richardson. In contrast, overtopping by herbaceous species such as *C. canadensis* and *C. angustifolium* remained relatively constant in blade-scarified plots and decreased 22% ± 4% in control plots on the new unit at CIRI. Overtopping decreased 10% ± 3% in sprayed plots, even with a shift from herbaceous to woody cover, and was essentially unchanged in control plots on the old unit at Fort Richardson. Overtopping by herbaceous species, especially *C. canadensis* and *C. angustifolium*, increased 6% ± 1% in sprayed plots and decreased 22% ± 4% in control plots on the new unit at CIRI.

Based on meta-analysis, the change in overtopping was greater with blade scarification compared with the control treatment (6% ± 1% vs. –3% ± 1%; overall effect size = 0.50 ± 0.29). Overtopping increased more at Fort Richardson with blade scarification compared with no site preparation (Table 8). There was no difference in the change in overtopping between plots with blade scarification and no site preparation in new units compared with old units ($Q_M$ = 0.093, df = 1, and $p$ = 0.761) or among stock types ($Q_M$ = 2.288, df = 4, and $p$ = 0.683). The change in overtopping with herbicide application was equal to the change in overtopping with no site preparation (0% ± 1% vs. –3% ± 1%; overall effect size = 0.20 ± 0.28, $Q_T$ = 123.170, df = 43, $p$ = <0.001). Finally, there was no difference in the change

**Table 7.** (*a*) Seedling volume ($cm^3$) (mean ± SE) of planted white spruce (*Picea glauca*) seedlings after two site preparation treatments, by site, and effect size (*d*). (*b*) Results of a meta-analysis on the effect of herbicide application compared with blade scarification on seedling volume (within-group heterogeneity ($Q_M$)), with site as a category, at five sites in Alaska.

(*a*) Seedling volume and effect size.

| Site | Spray | Blade | *d* |
|---|---|---|---|
| Tanana | 531.3±42.3 | 728.3±71.4 | –0.40±0.66 |
| Fort Richardson | 2780.8±243.4 | 926.7±120.4 | 2.67±0.88 |
| Chitina | 6.3±1.0 | 3.9±0.5 | 0.84±1.42 |
| CIRI | 1183.3±98.9 | 1022.6±81.6 | 0.34±0.63 |
| Ninilchik | 1381.1±186.7 | 1014.0±71.6 | 0.30±0.70 |

(*b*) Meta-analysis results.

| | Spray vs. blade | | |
|---|---|---|---|
| Model | Heterogeneity | *p* | df |
| Between ($Q_M$) | 41.083 | <0.001 | 4 |
| Within ($Q_E$) | 104.368 | <0.001 | 39 |
| Total ($Q_T$) | 145.451 | <0.001 | 43 |

**Note:** Probability values (*p*) represent the probability that the variance would be exceeded based on a $\chi^2$ distribution. Blade, blade scarification; spray, herbicide application; df, degrees of freedom.

**Table 8.** (*a*) Change in overtopping (%) (mean ± SE) between the first and last year of measurement of planted white spruce (*Picea glauca*) seedlings after two site preparation treatments, by site, and effect size (*d*). (*b*) Results of a meta-analysis on the effect of blade scarification compared with no site preparation on percentage seedling overtopping (transformed) (within-group heterogeneity ($Q_M$)), with site as a category, at five sites in Alaska.

(*a*) Change in overtopping and effect size.

| Site | Blade | Control | *d* |
|---|---|---|---|
| Tanana | 0.13±0.31 | 1.63±0.06 | 0.06±0.91 |
| Fort Richardson | 10.32±0.15 | 0.03±0.11 | 1.62±0.70 |
| Chitina | 9.67±0.18 | 9.38±0.06 | 0.08±1.20 |
| CIRI | 1.06±0.03 | 5.22±0.10 | 0.74±0.64 |
| Ninilchik | 0.00±0.04 | 0.03±0.06 | –0.08±0.60 |

(*b*) Meta-analysis results.

| | Blade vs. control | | |
|---|---|---|---|
| Model | Heterogeneity | *p* | df |
| Between ($Q_M$) | 22.449 | <0.001 | 4 |
| Within ($Q_E$) | 104.224 | <0.001 | 39 |
| Total ($Q_T$) | 126.673 | <0.001 | 43 |

**Note:** Probability values (*p*) represent the probability that the variance would be exceeded based on a $\chi^2$ distribution. Blade, blade scarification; control, no site preparation; df, degrees of freedom.

in overtopping between blade scarification and herbicide application (6% ± 1% vs. 0% ± 1%; overall effect size < –0.01 ± 0.29, $Q_T$ = 150.988, df = 43, $p$ = <0.001).

### Soil temperature

Mean monthly soil temperature among site preparation treatments and installations followed several patterns; these patterns are graphically presented by site in Supplemental Appendix S4.[2] Our initial assessment of soil temperatures based on data collected during the first year after treatment suggested dramatic warming of soils with blade scarification; blade-scarified plots were 2 to 3 °C warmer in July than control plots, and sprayed plots were somewhat intermediate in temperature. Continued monitoring indicated that these differences were transitory.

## Discussion

The type of site preparation, age since disturbance, and seedling stock type resulted in dramatic differences in white spruce seedling survival, height, volume, and the composition and structure of competing vegetation across five Alaskan sites. Survival of seedlings after 11 years was greater with blade scarification than with herbicide application or no site preparation, seedling volume was greater with herbicide application, and the amount of competition represented by overtopping increased with blade scarification compared with no site preparation. Exposure of mineral soil by scarification provided opportunities for wind-disseminated seeds to colonize, leading to a greater abundance of *C. angustifolium*, *A. viridis*, *B. neoalaskana*, and *P. tremuloides* at some sites. The trend of increased seedling overtopping with blade scarification may have an impact on future white spruce growth; height growth of mature white spruce was limited by hardwoods (Youngblood 1995).

Mechanical site preparation treatments typically manipulate forest floor and upper mineral soil layers to modify soil temperature and moisture, increase nutrient availability, and remove competing vegetation, thereby enhancing seedling microclimate (Örlander et al. 1990; Youngblood and Zasada 1991; Cole et al. 1999; Densmore et al. 1999). Various methods can be categorized into one of four broad types: (*i*) scalping, or the removal of litter and roots and rhizomes of competitors and exposure of mineral soil surface; (*ii*) mixing, or the chopping and mixing of litter, roots and rhizomes of competitors, and mineral soil to form a new growing medium; (*iii*) inverting, or the turning of a uniform amount of surface layers of litter, roots and rhizomes of competitors, and mineral soil to bury the competing vegetation, and (*iv*) some combination of the above. Our scarification treatment was a broad-scale scalping designed to remove about 85% of all surface vegetation and litter, yet this treatment proved difficult to control because of differences among sites in the use of scarifying equipment. Because scarification treatments were applied using operational techniques, we relied on locally available equipment and operators rather than any single operator and standard piece of equipment. The new unit at Tanana was scarified with a D6 dozer with a straight blade leaving about 60% bare and moist mineral soil, whereas the old unit was more completely scarified with the same equipment when soils were frozen. Our Fort Richardson units were scarified with a larger D7 dozer, and CIRI and Ninilchik sites were scarified to about 90% bare mineral soil with a relatively small Caterpillar 953 crawler loader. We made no effort to monitor or control the number of equipment passes within a plot. Thus there were differences in the amount of organic and A horizons retained in each scarified plot. Some piling of surface soils occurred outside the scarified plots at the old units of Tanana, Fort Richardson, and Ninilchik and both new and old units at CIRI.

Blade scarification is one of the most common forms of mechanical site preparation in forests of northern latitudes and may increase soil temperature by exposing mineral soil and increase light availability by removing vegetation and slash that either competes with or prevents establishment of seedlings (Boateng et al. 2006). Blade scarification also can increase seedling exposure, hence the occurrence of frost-heaving among planted seedlings on sites with fine soil texture, high soil moisture content, poor soil drainage, and limited vegetation cover (Bergsten et al. 2001). In our study, frost-heaving during the first or second year after outplanting was especially prevalent with S10 seedlings in blade-scarified plots on the old units at Tanana and CIRI. Initially, scarification appeared to increase growing season soil temperatures, but differences lasted only 3–4 years as vegetation developed on the sites. There was some indication that effects may last longer at some sites such as CIRI; however, lack of pretreatment data and replication within sites limited our ability to detect clear treatment differences.

Mechanical site preparation was the dominant form of site preparation across Canada through the late 1990s (Bock and Van Rees 2002; Thompson and Pitt 2003), and the most commonly used method consisted of inverting or mounding to mix deep organic layers and diminish the effect of high soil water content (Sutton 1993; Archibold et al. 2000). Mounding and early chemical herbicide release treatments resulted in taller seedlings after 20 years compared with blade scarification or the use of large seedlings without site preparation on sites with a high water table (Boateng et al. 2006). Similarly, mixing or inverting proved as successful as burned windrows or continual hand control of brush for survival and growth of white spruce (Macadam and Kabzems 2006). In contrast, the majority of upland sites in Alaska that support white spruce have soils derived from either loess or volcanic ash, and issues of high soil water are less prevalent.

Site preparation with a single broadcast application of hexazinone plus glyphosate in the fall before spring planting resulted in greater seedling survival, greater seedling height, and greater seedling volume across all sites compared with no site preparation. Spraying also resulted in greater seedling height and volume compared with blade scarification across all sites. The mixture of two herbicides with different species specificity led to general short-term suppression of most woody and herbaceous species. Our herbicide treatment did not disturb the forest floor layer but left a decaying litter layer, which later was augmented by recovering vegetation. In some cases, species composition was changed. Spraying reduced deciduous species abundance without providing the same kinds of microsites for seed germination as blade scarification. Overtopping by *A. viridis*, *C. angustifolium*, or *C. canadensis* occurred in sprayed units because of resprouting from root collars or buried rhizomes. Prior screening trials are advised whenever moving from area to area to account for variations in plant composition and seasonal sensitivity.

Hexazinone is a soil-active inhibitor of photosynthesis, whereas glyphosate acts in plants by inhibiting formation of two essential amino acids after being taken up through foliage. Hexazinone residues remain biologically active in soil for several months, thus it is effective in control of vegetation that proliferates by rhizomes such as *C. canadensis*, whereas glyphosate is neither readily mobile in soil nor taken up by roots. Uptake of glyphosate in plants requires photosynthetically active biomass; applications late in the growing season may be problematic if target species have already entered dormancy or if little leaf area is available for uptake. Our new unit at Fort Richardson was harvested in the summer, and residual fuels were masticated, leaving little undisturbed ground and little live aboveground biomass at the time of spraying. This unintended action before our treatments probably accounts for the lack of differences among site preparation responses on this unit.

Chemical herbicide applications for site preparation have not commonly been used for managing white spruce regeneration in Alaska. Although chemical applications comprise a small proportion of site preparation treatments in Canada (5% of about 335 000 ha treated per year averaged from 1990 to 2008), chemical herbicides are frequently used in Canada for seedling release programs after seedlings and competing vegetation are well established (Thompson and Pitt 2003). Studies from Canada have indicated that release treatments can improve white spruce height growth (Fu et al. 2008; Man et al. 2009; Pitt et al. 2010), diameter growth (Comeau et al. 2000), and volume (Pitt et al. 2010). Delaying treatment until seedlings and competing vegetation are well established may negatively impact white spruce growth (Thevathasan et al. 2000; Cortini and Comeau 2008; Pitt et al. 2010). Thus there may be advantages for ensuring that seedlings are free to grow when planted. White spruce root collar diameter increased by 140% after glyphosate was applied for site preparation compared with no site preparation in Ontario (Wood and von Althen 1993). Previously, we showed the value of herbicides for site preparation prior to planting white spruce and *B. neoalaskana* seedlings near our Fort Richardson site (Cole et al. 1999). Collectively, these studies indicate that white spruce growth can be enhanced by vegetation control over a wide range of site conditions and regions. Site quality, environmental conditions, treatment efficacy, and timing of treatment influence expected growth increases.

Over 400 million spruce seedlings are planted annually in Canada, and the majority of these are container-grown seedlings (Grossnickle 2000). A large forestry sector has developed to produce, convey, and outplant these seedlings, and much is known about the adaptability of specific stock types for various planting sites in Canada (Burdett 1990; Grossnickle 2000; Boateng et al. 2006). Much of this work comes from more southern latitudes in eastern Canada, whereas artificial regeneration of sites at comparable northern latitudes in western Canada emphasizes interior spruce, a natural hybrid between *P. glauca* and *Picea engelmannii* Parry ex Engelm.) (Engelmann spruce). Where white spruce is the preferred conifer in areas such as Alberta, it often is regenerated and managed in combination with *P. tremuloides* (Pitt et al. 2010). Widespread applicability of this work to Alaska sites supporting white spruce and *Picea* × *lutzii* is problematic.

We observed several clear patterns in stock type performance. First, 1-year-old container-grown seedlings sometimes survived as well as or better than older seedlings grown in the same nurseries, older seedlings were taller than younger seedlings after 11 years only at the new unit at Tanana and both old and new units at Fort Richardson, and older seedlings had greater volume than younger seedlings only at Tanana and Fort Richardson. Thus, direct seedling age was not a strong predictor of seedling performance. Second, large seedlings had greater survival after 11 years compared with small seedlings at Tanana, the new unit at Fort Richardson, and the old unit at Ninilchik, and larger seedlings were taller and had greater volume than small seedlings at all of the units except those at Chitina. Thus, nursery practices that resulted in large stock types provided the greatest future gains in growth and productivity, consistent with South et al. (1993). Third, seedlings produced in nurseries outside Alaska, requiring direct manipulation of day length, had greater survival, height, and volume after 11 years than did seedlings produced by a nursery in Alaska without light environment modification or machine lifting. Thus, rearing, lifting and handling, storage, and distribution processes used elsewhere can accommodate seedlings intended for Alaska. Although there was no clear advantage in survival between the best container-grown seedling and the apparent best bare-root transplant, there was clear evidence at Tanana, Fort Richardson, and CIRI that the best bare-root transplant (SP1) outperformed the best container-grown seedling (P10) in both height and volume. Thus, planting large stock with root systems that develop in transplant beds after a year in containers provides advantages that translate into long-term gains in growth. Finally, offsite T10 seedlings survived equally as well as S10 seedlings and were as tall and had equal volumes as S10 seedling with or without scarification at CIRI and with scarification at Ninilchik but did not perform as well without scarification at Ninilchik. Thus, transfer of genetic material from north of the Alaska Range likely provides little gain in future growth.

Despite efforts to characterize planting stock by age class and method of culture, there remain large differences in morphology and physiology that lead to unpredictable plantation performance (Burdett 1990). For example, 3-year-old bare-root and 2-year-old containerized *Picea abies* (L.) Karst. (Norway spruce) seedlings performed equally well after 5 years on sites that were mounded or treated with glyphosate (Nilsson and Örlander 1999). In contrast, seedling height, diameter, and volume increment were greater for small 3-year-old bare-root and 2-year-old container stock types compared with large 3-year-old bare-root stock types of *P. abies* after several growing seasons (Renou-Wilson et al. 2008). After 10 years, Thomson and McMinn (1989) found inconsistencies in the performance of 2-year-old bare-root and 2-year-old container-grown white spruce seedlings across a number of plantations in British Columbia and suggested that there were likely genetic variation in the planting stock and differences in site variability combined with subtle differences in cultural practices leading to disparate results. Jobidon et al. (2003) reported that early release treatment was essential and the use of large stock types diminished the amount of release treatment that was required. Thus, more trials are needed before a clear picture of gains resulting from the use of large bare-root stock will likely emerge.

Our work identified a difference in seedling volume between new and old units when herbicide was applied as site preparation, but no difference for other response variables. Although seedling volume remains one of the most important metrics of seedling physiology and morphology, we anticipated greater separation between new and old sites with respect to treatment efficacy. We found no difference in seedling survival or height growth that can be attributed to efficacy of site preparation treatments on sites where secondary successional processes have resulted in establishment of a full component of competing species. This suggests that areas that are not immediately reforested, because of logistical and (or) financial reasons, or areas for which sufficient nursery stock is not readily available may successfully be restored to productive white spruce forests through a combination of vegetation control and use of quality planting stock.

Previous research on white spruce artificial regeneration in Alaska focused on trials of small container-grown seedlings (1 + 0 plugs in 65 cm$^3$ containers) (Youngblood and Zasada

1991; Cole et al. 1999; Densmore et al. 1999). Planting density standards in Canada specify larger numbers of seedlings than are used in Alaska, hence cost and bulk are major considerations. Although these considerations apply everywhere, seedlings grown to larger sizes before outplanting have higher survival and initial growth rates, are less likely to succumb to the effects of competing vegetation, and may be more likely to withstand herbivory by small mammals compared with smaller seedlings (McMinn 1986; Sutherland and Day 1988; Thomson and McMinn 1989; Simpson 1991; Newton et al. 1993; South et al. 1993). In addition to seedling size and condition, other important aspects of seedling survival and growth include conditions for storage, handling, and transportation (Thiffault et al. 2003; Grossnickle 2005). In Alaska, these factors will continue to be influenced by remoteness of plantations and availability of skilled labor.

Long-term studies such as this require a commitment to maintain study designs even in the face of changing environmental constraints. Our Tanana study location was established before an outbreak of spruce budworm began in 2002 and peaked in 2007. Marked declines in seedling height growth were evident in 2002 and subsequent years. Although growth rates initially were the highest at Tanana, continued defoliation caused significant declines in growth and led us to question the advisability of maintaining these plots. Our rationale was that this location may continue to inform our understanding of the resilience of white spruce plantations under projected future climate changes that may lead to new disturbances regimes. A major forest management concern in Alaska is whether knowledge of current disturbance regimes, chiefly wildfire, insect outbreaks, and timber harvesting, provides an understanding for sustainable forest management under increasing public scrutiny. Also, whether shifting demands for safeguarding healthy environments, conserving biological diversity, and providing some level of economic prosperity can be met operationally. Taken in whole, our work represents major investments by research and land management organizations to enhance the science and understanding for sustainable management and helps clarify the measures needed to ensure restoration of productive white spruce sites after disturbance throughout Alaska.

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