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White Spruce Responses to Mechanical Site Preparation, Chemical Site Preparation, and Post-planting Vegetation Control over Three Decades in the Boreal White and Black Spruce Zone of British Columbia

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R. Allan Powelson, Jean L. Heineman, Lorne Bedford, John McClarnon, Amanda F. Linnell Nemec, and Jacob O. Boateng

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Site preparation is used to facilitate plantation establishment throughout the Boreal White and Black Spruce (BWBS) zone in northern British Columbia, where mechanical, burning, chemical, or manual techniques have been used on 88% of sites that were harvested and planted to white spruce between 1980 and 2014. Between 1984 and 1988, experiments to examine the effectiveness of mechanical site preparation, chemical site preparation, and post-planting vegetation control for relieving constraints to the establishment and juvenile growth of white spruce (*Picea glauca*) were established on three Moist Warm Boreal White and Black Spruce (BWBSmw) sites that had well-developed backlog vegetation. In the Wonowon experiment, bareroot spruce was planted into site preparation treatments that had been applied through a well-developed layer of bluejoint-dominated (*Calamagrostis canadensis*) vegetation. The other two sites (Inga Lake and Iron Creek) also supported well-established plant communities, but vegetation was sheared prior to installation of the experimental treatments, and container rather than bareroot stock was planted. Following site preparation, dense vegetation again developed at these two sites; at Inga Lake, it was dominated by willow and green alder, with scattered patches of aspen, while at Iron Creek, it was dominated by aspen and balsam poplar. Mechanical site preparation treatments examined in the three experiments included mounding, plowing, mixing, trenching, and scarification. At each of the three sites, a glyphosate treatment to reduce vegetation abundance was also included; at Iron Creek, glyphosate was applied as chemical site preparation, while at Inga Lake and Wonowon, it was applied as a post-planting vegetation control treatment. Glyphosate efficacy was low at Inga Lake, and follow-up manual cutting treatments were conducted to approximate a high-efficacy glyphosate treatment. In this report, we present results to age 25 from the Inga Lake and Wonowon studies and to age 26 from the Iron Creek study. Stand-level results for the mounding and untreated control treatments at Wonowon extend to age 29.

At Wonowon, bareroot white spruce stock sustained extensive mortality within 4 months of planting, regardless of treatment. Losses were particularly high in the patch and blade scarification treatments, where only 62% and 57% of seedlings survived the first growing season, respectively. By year 25, survival at this site ranged from 28% in the blade scarification treatment to 67% in the mounding treatment. The vegetation control treatment, which was not conducted until after the first growing season, resulted in 60% survival after 25 years. Early survival of container white spruce planted at the Inga Lake and Iron Creek sites was high regardless of site preparation, although there was gradual attrition of trees in the untreated controls at both sites and in the disc trenching treatment at Inga Lake, which were in poor condition due to early hare damage and competition for light. After 25–26 years, survival at Iron Creek and Inga Lake ranged from 75–77% in the untreated controls to 95–98% in the plow inverting treatments, respectively.

During the first decade after planting, white spruce growth responses tended to be largest in the mechanical treatments that created the most severe soil disruption without broadcast removal of forest floor material (as

occurred in the blade scarification treatment); this is presumably because these treatments both controlled vegetation and enhanced the rooting environment. Plow inverting, mixing, and mounding all produced significant responses relative to the controls, whereas disc trenching was ineffective, and the scarification treatments tended to produce either no response or a slight (non-significant) negative response relative to the controls. Spruce generally took longer to respond to the chemical site preparation and vegetation control treatments than to the mechanical treatments, especially at Inga Lake, where brushing was not done until after the third growing season. After year 10, however, growth responses in the chemical site preparation and vegetation control treatments were at least as good as those in the most effective mechanical treatments, and it was evident that the treatments that provided ongoing reductions in the abundance of overtopping vegetation produced the largest spruce growth responses. This phenomenon was most obvious at the Inga Lake site, where control spruce were overtopped by dense willow throughout the 25-year assessment period.

By age 25, planted spruce in the vegetation control treatment at Inga Lake had, on average, approximately 9 times the individual tree volume as overtopped control trees. The plow inverting and mixing treatments at that site also produced lasting vegetation control, which resulted in age 25 stem volume that was, on average, 7–8 times greater than that of the control. At Iron Creek and Wonowon, where lower proportions of untreated control spruce were overtopped at age 25–26 years, chemical site preparation or vegetation control resulted in 3-fold gains in stem volume relative to the untreated controls, as did plow inverting at Iron Creek. Mounding at Wonowon was associated with a 2-fold increase in stem volume relative to the control.

The results from these long-term experiments are most applicable to situations where there is a need to establish white spruce on sites with well-developed vegetation communities; however, these are now relatively rare in northern British Columbia because most of the backlog area has been rehabilitated. Nonetheless, the results from these long-term experiments are of interest because they examine a broader range of techniques than are currently in use. We anticipate that the data will be useful for calibrating growth and yield modelling tools as their sophistication increases to include the ability to model spruce growth in overtopped and mixedwood stands.

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White spruce (*Picea glauca*) is a dominant and productive tree species in the Moist Warm Boreal White and Black Spruce biogeoclimatic subzone (BWBSmw) (DeLong et al. 2011), which occupies nearly 3 million hectares of northeastern British Columbia. Although the BWBSmw is not particularly cold relative to other boreal ecosystems (DeLong et al. 2011), regenerating planted white spruce following harvest can be difficult, largely because of limitations imposed by the characteristic fine-textured soils, which tend to be cold, wet, and poorly aerated. Rapid development of highly competitive vegetation dominated by species such as green alder (*Alnus viridis* ssp. *crispa*), willow (*Salix* spp.), and bluejoint (*Calamagrostis canadensis*) following removal of the forest canopy also creates regeneration challenges (e.g., Haeussler et al. 1990; Örlander et al. 1990; Boateng and Comeau 1997a, b).

Site preparation is used to facilitate plantation establishment throughout the BWBS zone. Between 1980 and 2014, mechanical, burning, chemical, or manual site preparation techniques were applied on 88% of harvested sites that were planted to white spruce in the BWBS zone[1]; however, mechanical techniques were, by far, the most commonly used (Figure 1). The use of me-

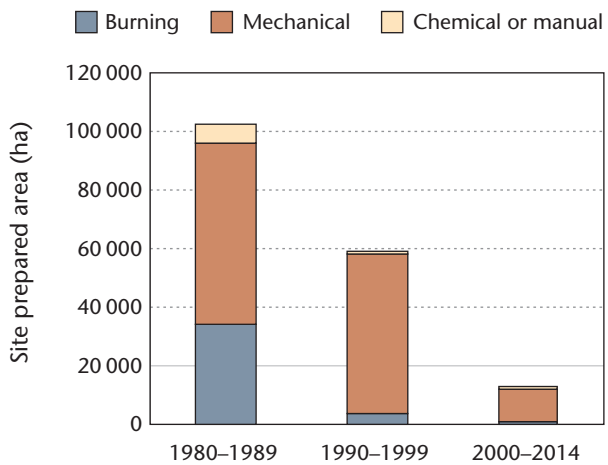

FIGURE 1 *Harvested area (not including landings and roads) that was site prepared in the BWBS zone by burning, mechanical, and chemical or manual techniques between 1980 and 2014 (based on information in the B.C. Ministry of Forests, Lands and Natural Resource Operations RESULTS database [May 2014]).*

chanical site preparation increased dramatically during the 1980s with the introduction of government initiatives to reduce the large backlog of not satisfactorily restocked (NSR) sites in northeastern British Columbia (B.C. Ministry of Forests 2002). The range of equipment options also expanded during this era as Scandinavian technology became available in British Columbia (Örlander et al. 1990). Techniques that were of interest in the 1980s were grouped into five general categories according to the type of microsite they created: scalping, mounding, mixing, plowing, and disc trenching (von

1 B.C. Ministry of Forests, Lands and Natural Resource Operations RESULTS database (May 2014).

der Gönna 1992). The efficacy of these techniques varied on a site-specific basis according to the degree to which they relieved the limitations to conifer establishment and growth (Spittlehouse and Childs 1990). Common objectives of mechanical site preparation include increasing rooting-zone soil temperature and aeration, improving soil drainage, increasing nutrient availability, and reducing vegetation abundance to increase light availability and decrease the risk of physical damage.

Chemical site preparation or broadcast burning can also be used to prepare harvested sites prior to planting; however, at present, these techniques are used relatively rarely in the BWBS zone (Figure 1). Chemical site preparation has played a limited role in northern British Columbia, despite studies suggesting that it is a more effective means of improving early conifer performance than is post-planting chemical brushing (Wood and von Althen 1993). In contrast, broadcast burning was a widely used method of site preparation in the region prior to 1990, but its use declined in response to concerns about air quality (e.g., Yole and Kranabetter 1996). The primary objectives of chemical and burning site preparation techniques tend to be reducing vegetation abundance as a means of increasing light availability to seedlings and lessening physical damage, but some degree of soil warming may also be achieved by these treatments (e.g., Örlander et al. 1990; Spittlehouse and Stathers 1990). In the case of broadcast burning, reducing slash loads is also a common goal. Although broadcast burning is no longer regularly prescribed, pile and burn treatments to dispose of slash continue to be common, and affect as much as 2% of the harvested area in the BWBS zone. The intense burns created by these treatments have long-lasting effects on soil chemistry (Macadam and Kabzems 2006; Boateng et al. 2010) and vegetation development (Haeussler et al. 1999) that are quite different from those that result from broadcast burning.

Improving conifer survival was an important objective of site preparation in the early 1980s, when bareroot stocktypes were the operational norm in British Columbia. The transition to more drought- and planting shock-resistant container stock (Nilsson and Örlander 1995) substantially reduced the risk of plantation failure, and in combination with prompt regeneration of harvested sites, has reduced the need for site preparation to meet stocking objectives. However, site preparation is also associated with improvements in early conifer growth (Bedford et al. 2000; Sutton et al. 2001), and in some cases, significant improvements in growth have persisted for more than two decades (e.g., Boateng et al. 2009; McClarnon et al. 2016). Many site preparation experiments were established in the 1980s; those where data collection has continued over the long term are now providing valuable information regarding the effects of site preparation on timber supply, and are increasing our understanding of causal factors related to ongoing growth responses. Twenty-year responses of planted white spruce to site preparation and vegetation control treatments have previously been reported for the Inga Lake, Iron Creek, and Wonowon experiments (Boateng et al. 2006; Boateng et al. 2009). In this report, we summarize 25- to 26-year white spruce responses to a subset of the treatments that were originally applied at each site. The treatments included in this analysis are those that best characterize site preparation techniques that have been tested in the BWBS zone since the mid-1980s. Results from these three studies are most relevant to backlog conditions where

vegetation is well developed, or to sites where vigorous vegetation has the potential to rapidly develop following harvest. Although these conditions are relatively rare under current management practices, where most openings are regenerated promptly following harvest and vegetation is proactively managed, the work provides a basis for comparing the effectiveness of broad categories of site preparation. We synthesize the findings in a discussion of treatment effects on white spruce during the establishment period (survival and early growth to age 5), at post-establishment age (9–10 years), and during the period of early mid-term growth (25–26 years).

2 METHODS

2.1 Site Characteristics

The Inga Lake, Iron Creek, and Wonowon research sites are 85–150 km north to northwest of Fort St. John, B.C., and are in the BWBSmw biogeoclimatic subzone (Delong et al. 2011). Site and climate characteristics are presented in Table 1. The Inga Lake site had no harvest history but was periodically burned by ranchers until the 1950s to improve forage for grazing, a practice that presumably contributed to the development of abundant willow and green alder. The Inga Lake site was mechanically sheared during

TABLE 1 *Site and climate characteristics at the Inga Lake, Iron Creek, and Wonowon research sites*

Sites	Inga Lake	Iron Creek	Wonowon
Site characteristics			
Latitude/longitude	56°37' N, 121°38' W	56°38' N, 122°19' W	56°37' N, 121°49' W
BEC unit/site series[a]	BWBSmw/101	BWBSmw/101	BWBSmw/101
Elevation	890 m	820 m	900 m
Soil moisture regime	Mesic (hygric)	Subhygric (mesic)	Mesic (subhygric)
Soil nutrient regime	Medium to rich	Medium to rich	Medium to rich
Slope	0–15%	5–10%	0–5%
Aspect	Variable (rolling terrain)	Easterly	North–northeasterly
Forest floor depth[b]	5 cm	≥ 10 cm	4–6 cm
Soil texture	Silt loam to clay loam	Silt loam to clay loam	Silt loam
Coarse fragment content	15%	< 5%	5%
Effective rooting depth	20–25 cm	10–25 cm	15–30 cm
Previous stand	n/a	White spruce, lodgepole pine, trembling aspen, and balsam poplar	Lodgepole pine, white spruce, and trembling aspen
Treatment history	Fire origin, no harvest history	Selectively logged 1966; clearcut 1977	Clearcut 1977
Climatic characteristics[c]			
Mean annual temperature	1.5°C	1.8°C	1.4°C
Mean annual precipitation	483 mm	523 mm	477 mm
Mean summer precipitation	309 mm	336 mm	302 mm
Precipitation as snowfall	143 mm	146 mm	143 mm
Average frost-free period	99 days	95 days	99 days

a Based on Delong et al. (2011) classification; BWBSmw/101 was previously referred to as BWBSmw1/01 (DeLong et al. 1990).

b Forest floor depth was estimated prior to treatment installation.

c From Climate BC using normals 1981–2010 (updated July 5, 2015) (Wang et al. 2012).

the winter of 1986/87, which resulted in little disturbance of the forest floor. Slash was piled into windrows, which left the site free of slash and relatively free of vegetation when the experimental treatments were installed in 1987. The Iron Creek site was selectively logged in 1966 and clearcut harvested in 1977. It regenerated to dense trembling aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera* L.), low shrubs, bluejoint, and fireweed (*Epilobium angustifolium* L.). The site was sheared and slash was piled into windrows during the winter of 1985/86 prior to installation of the experimental treatments in 1986; again, there was little disturbance of the forest floor. The Wonowon site was clearcut harvested in 1977. Vigorous vegetation that was dominated by bluejoint and fireweed interspersed with dense patches of aspen, alder, willow, and paper birch (*Betula papyrifera* Marsh.) subsequently developed. In contrast to the Inga Lake and Iron Creek experiments, vegetation at the Wonowon site was not sheared and piled prior to installation of the experimental treatments in 1983.

2.2 Experimental Design, Treatments, and Measurements

2.2.1 Inga Lake The Inga Lake experiment used a randomized complete block design (RCBD) that consisted of five blocks and seven of the eight treatments described in Table 2: plow inverting, fine mixing, coarse mixing, disc trench hinge, disc trench furrow, vegetation control (chemical brushing plus follow-up manual brushing), and untreated control. As described in Table 2, glyphosate efficacy was low in the vegetation control treatment at Inga Lake; therefore, six manual brushing treatments were subsequently applied at intervals to simulate the lasting effects of a successful glyphosate application. The eighth treatment, burned windrow, was applied to rows of piled slash that were between the mechanically prepared plots. Survival and growth results for white spruce planted in these long, linear, burned strips are presented for interpretive purposes; however, the burned windrow treatment is not included in the RCBD analysis because its effects were confounded by the open-grown conditions that resulted from the absence of buffer trees. In each block, each treatment (except burned windrow) was randomly allocated to a single treatment plot. An additional three treatments that were included in the original experiment, but which are not included in this analysis, are described in Appendix 1. Plot shape and size were somewhat variable due to the need to accommodate the different site preparation configurations; plots ranged in size from 0.014 to 0.052 ha (Appendix 2). The layout of the Inga Lake experiment is illustrated in Figure 2.

Mechanical treatments were applied between July and September 1987. Windrow piles were burned in the fall of 1987, and in each of the five blocks, a single burned windrow was selected for planting. Treatments were left to settle over one winter. In the first week of June 1988, each treatment plot was planted with 80 white spruce container seedlings (seedlot 4119). In all treatments but the disc trench furrow, the inner 48 seedlings that were intended for measurement were 2-year-old PSB 313 2+0 stock, while the outer 32 buffer trees were 1-year-old PSB 313 1+0 stock. In the disc trench furrow treatment, all 80 seedlings were PSB 313 2+0 stock. In each plot, the inner 48 trees were tagged, and were, on average, 23 cm tall and 0.4 cm in diameter at the time of planting. Forty-eight planted spruce (PSB 313 2+0) were also tagged for measurement in the burned windrow that had been selected for planting in each block. In total, 240 white spruce were assessed in each of the eight treat-

TABLE 2 *Treatments applied at Inga Lake*

Treatment	Treatment type	Machinery	Description
Plow inverting	Plowing	3-bottom breaking plow pulled by a D7 tractor	Continuous side-by-side mineral soil beds composed of approximately 15-cm deep mineral soil overlying inverted forest floor material. Mineral soil exposure was nearly 100%. White spruce seedlings were deeply planted to 5 cm above the root collar.
Fine mixing	Mixing	Madge rotoclear with a toothed cylindrical drum rotating at a speed of 300 rpm	Forest floor and mineral soil were thoroughly mixed to a depth of 12–15 cm and a width of 1.75 m, which created planting spots that were level with the surrounding ground surface. Soil exposure was 100%. White spruce seedlings were planted to the root collar.
Coarse mixing	Mixing	Eden relief bedding plow with six hydraulically controlled discs	Raised beds composed of a coarse mixture of mineral soil and forest floor material that were approximately 50 cm wide and 40 cm high, separated by approximately 40-cm wide trenches. Mineral soil exposure was nearly 100%. White spruce seedlings were deeply planted to 5 cm above the root collar.
Disc trench hinge	Trenching	TTS Delta disc trencher	Continuous, shallow, linear furrows with loosely mixed berms spaced 3 m apart. Mineral soil exposure averaged 48%. White spruce seedlings were planted to the root collar at the hinge of the furrow and berm.
Disc trench furrow	Trenching	TTS Delta disc trencher	Same treatment as for disc trench hinge but with white spruce seedlings planted to the root collar in the furrow bottom.
Vegetation control	Herbicide	None	No site preparation and no mineral soil exposure. White spruce seedlings were planted to the root collar without screefing. After three growing seasons, glyphosate (Vision®) was broadcast applied at a rate of 2.14 kg ae/ha. The treatment failed to control willow, which had been defoliated by insects in the year of herbicide application. Manual cutting treatments were subsequently applied 4, 6, 8, 9, 11, and 14 years after planting to achieve lasting vegetation control and simulate a high-efficacy herbicide treatment.
Burned windrow	Burn	None	Slash that had been piled in windrows during the shear and pile treatment prior to installation of the experiment was burned. All fine and medium slash was fully consumed, leaving a 2- to 3-m wide continuous strip of mineral soil overlain by an ash layer. Mineral soil exposure was minimal, but surface soil materials were subjected to intense heat to a considerable depth. White spruce seedlings were planted to the root collar without screefing.
Untreated control	No treatment	None	No site preparation and no mineral soil exposure. Seedlings were planted to the root collar without screefing.

ments. There was considerable variation in planting density due to the difficulty of adapting tree spacing to the different site preparation configurations: densities ranged from 1097 to 1483 stems/ha in the various treatments.

For all treatments at Inga Lake (including the three treatments that are not included in this analysis [Appendix 1]), spruce survival and growth were assessed annually in late summer from years 1 to 15 (1988–2002), and again in years 24–25 (2011–2012). From year 16 (2003) to year 23 (2010), assessments were conducted at intervals that varied by treatment (Appendix 3). During each assessment, spruce height (± 5 cm) and diameter (± 0.1 cm) were measured, with diameter assessed at ground-level (GLD) until year 17 (2005) and at a height of 1.3 m (diameter at breast height [dbh]) from years 19 to 25 (2006–2012). We present survival results for all years for which data are available, individual tree growth results for years 5, 10, and 25, and stand-level volume results for years 19, 24, and 25. In spring 1992, hare damage to

FIGURE 2 *Experimental layout at the Inga Lake site. Treatment names in the legend are those used in earlier reports and can be cross-referenced to this report using Appendix 2.*

planted spruce was quantified at Inga Lake in response to subjective observations that it was having a substantial effect on crop-tree performance. In year 25, comments were recorded regarding damage to individual white spruce, and these comments were later assigned standardized codes to facilitate the calculation of summary statistics.

In order to provide information about the ongoing presence of competing vegetation, in year 25 (2012), average canopy height (based on measurement of a visually identified "average" stem) was determined for each broadleaf tree (trembling aspen, balsam poplar, or paper birch) and tall shrub species (willow or green alder) that was present in each plot. Target spruce were also visually assessed as to whether or not the leader was overtopped by non-coniferous vegetation within a 1-m cylinder, and where this occurred, the number of occupied quadrants and the overtopping species were recorded. Vegetation at the Inga Lake site was described in detail as part of a related project (Haeussler et al. 1999), and the results are summarized in Appendix 4.

2.2.2 Iron Creek The Iron Creek experiment used an RCBD experimental design that consisted of five blocks and five of the six treatments described in Table 3: plow inverting; mounding, patch scarification, chemical site preparation, and untreated control. The performance of lodgepole pine (*Pinus contorta* var. *latifolia*) planted into untreated ground was also examined, but this species–treatment combination was excluded from the RCBD analysis presented in this report because growth expectations for pine differ from those of spruce. An additional four treatments, described in Appendix 1, were part of the original experiment but were also excluded from this analysis. Each treatment was randomly allocated to a single plot in each of the five blocks. Plot shape and size were again variable due to the need to accommo-

TABLE 3 *Treatments applied at Iron Creek*

Treatment	Treatment type	Machinery	Description
Plow inverting	Plowing	3-bottom breaking plow pulled by a D8 tractor	Continuous side-by-side beds of mineral soil on top of inverted forest floor material. Beds averaged 66 cm wide. Mineral soil exposure was nearly 100%. White spruce seedlings were deeply planted to 5 cm above the root collar.
Mounding	Mounding	B.C. Ministry of Forests mounder using a D7 tractor as prime mover	Mounds averaging 36 cm high, including approximately 10-cm deep mineral soil capping. White spruce seedlings were deeply planted to 5 cm above the root collar on the sloped side of the mounds.
Patch scarification	Scalping	Bräcke scarifier with a 3-tined mattock wheel	Patches of mineral soil averaging 60–80 cm long were exposed. White spruce seedlings were planted to the root collar in mineral soil, at the hinge of overturned material.
Chemical site preparation	Herbicide	None	Glyphosate (Vision®) was broadcast applied at a rate of 2.5 kg ae/ha in August 1986 prior to planting the following spring. There was no mineral soil exposure. White spruce seedlings were planted to the root collar into boot-screefed patches. At intervals (every few years), scattered broadleaf stems that regenerated in these treatment plots were manually removed.
Untreated control	None	None	No site preparation and no mineral soil exposure. White spruce seedlings were planted to the root collar into boot-screefed patches.
Untreated control with pine	No treatment	None	No site preparation and no mineral soil exposure. Lodgepole pine seedlings were planted to the root collar into boot-screefed patches.

date the different site preparation configurations, and plots ranged in size from 0.036 to 0.061 ha (Appendix 2). The layout of the Iron Creek experiment is illustrated in Figure 3.

Mechanical treatments were conducted in July 1986. Due to the presence of seepage areas, the plow inverting treatment could not be installed in blocks B, C, and E, so two additional plots for that treatment were installed in each of blocks A and D (resulting in a total of four plots for the plow inverting treatment and deviation from the intended RCBD). Broadcast application of glyphosate for the chemical site preparation treatment was conducted in August 1986. At intervals of several years, scattered broadleaves that regenerated in the chemical site preparation treatment plots were manually removed. Treatments were left to settle over one winter and were planted with 1-year-

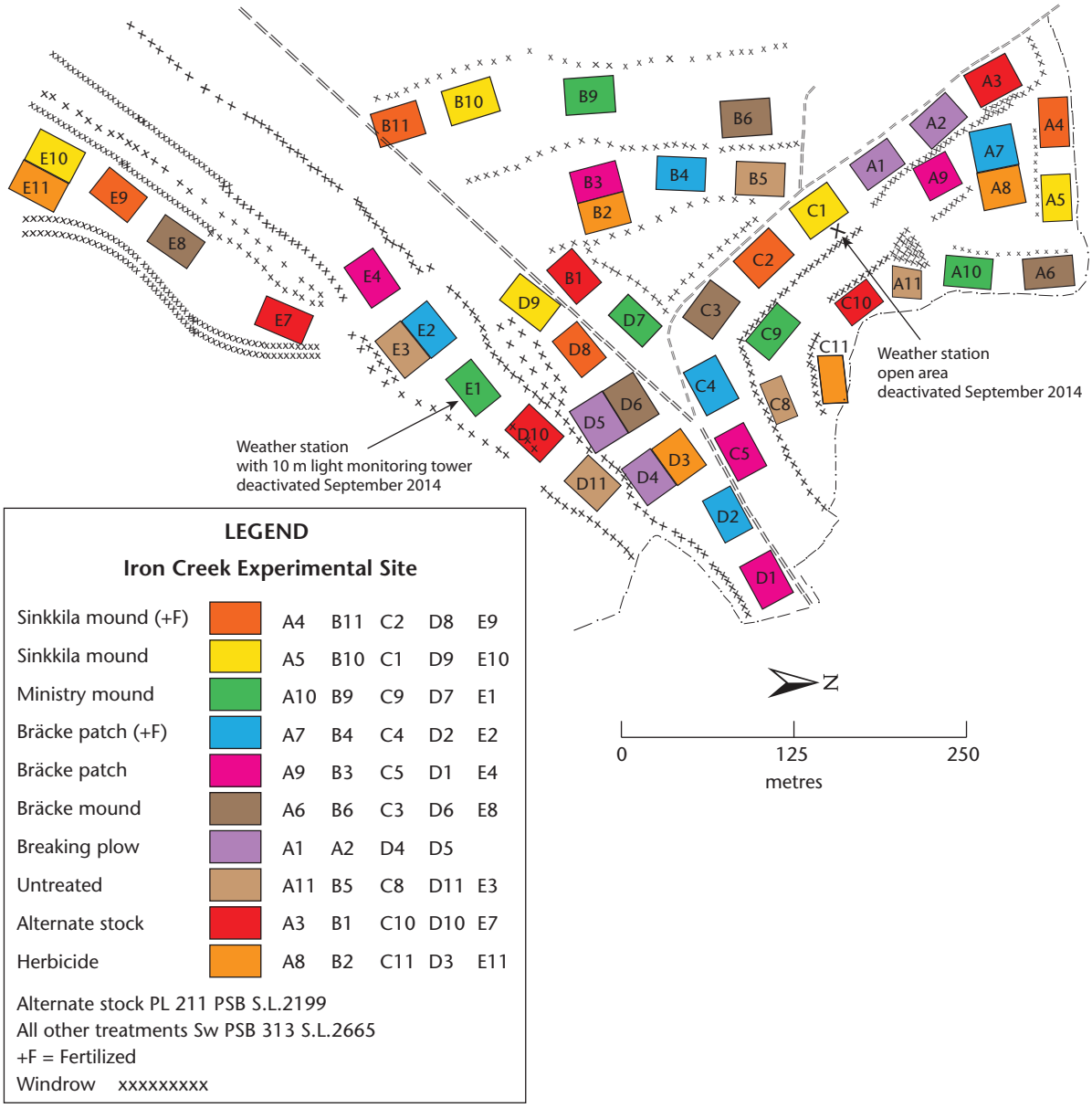

FIGURE 3 *Experimental layout at the Iron Creek site. Treatment names in the legend are those used in earlier reports and can be cross-referenced to this report using Appendix 2.*

old white spruce container stock (PSB 313 1+0, seed lot 2665) or 1-year-old lodgepole pine container stock (PSB 211 1+0, seedlot 2199). White spruce stock was, on average, 18 cm tall and had 0.3 cm diameter at the root collar at the time of planting; lodgepole pine size was not recorded at the time of planting, but the target height for 1-year-old stock of this species is typically 12–14 cm (B.C. Ministry of Forests 1998). Eighty seedlings were planted in each treatment plot: the inner 48 were tagged for measurement, and the outer 32 acted as buffer trees. In total, 240 seedlings were assessed in each treatment except plow inverting, where 192 seedlings, in total, were assessed. As at Inga Lake, because of the difficulty of adapting tree spacing to the different site preparation configurations, planting density was variable; at Iron Creek, it ranged from 947 to 1133 stems/ha in the various treatments.

Seedling survival and growth in all treatments (including the four treatments that are not included in this analysis [Appendix 1]) were assessed annually in late summer in years 1–3 (1987–1989), years 5–7 (1991–1993), and years 9–10 (1995–1996). The plow inverting, mounding, chemical site preparation, and untreated control treatments included in this report were also assessed annually in years 11–16 (1997–2002), but the patch scarification and the untreated control with pine treatments were not. From years 17 (2003) to 26 (2012), assessments were conducted at intervals that varied by treatment (Appendix 3). During each assessment, tree height (± 5 cm) and diameter (± 0.1 cm) were measured, with diameter measured as GLD from years 1 to 20 (1987–2006), and as dbh from years 20 to 26 (2006–2012). Both GLD and dbh were assessed in year 20 (2006). We present survival results for all years for which data are available; individual tree results are summarized for years 5, 10, and 26, and stand-level volume results are presented for years 20, 25, and 26. Comments regarding damage to individual white spruce were recorded in year 26, and these comments were later assigned standardized codes to facilitate the calculation of summary statistics.

In year 26 (2012), average canopy height (based on measurement of a visually identified "average" stem) was determined for each broadleaf tree (trembling aspen or balsam poplar) and tall shrub species (willow or green alder) that was present in each plot. Target spruce were also visually assessed as to whether or not the leader was overtopped by non-coniferous vegetation within a 1-m cylinder, and where this occurred, the number of occupied quadrants and the overtopping species were recorded.

2.2.3 Wonowon The Wonowon experiment used an RCBD experimental design that consisted of five blocks and the five treatments described in Table 4: mounding, blade scarification, patch scarification, vegetation control (chemical brushing), and untreated control. An additional four treatments, described in Appendix 1, were part of the original experiment but are not included in this analysis. Each treatment was randomly allocated to a single plot in each of the five blocks, but block B was dropped from the study when the untreated plot was determined to have a substantially different vegetation community than the rest of the study area; an atypical vegetation community also occupied the vegetation control treatment plot in block D, and that plot was also dropped from the experiment. Consequently, the vegetation control treatment at the Wonowon site is replicated three times, and all other treatments are replicated four times. Plot shape and size were variable due to the need to

TABLE 4 *Treatments applied at Wonowon*

Treatment	Treatment type	Machinery	Description
Mounding	Mounding	Bräcke mounder with a 4-tined mattock wheel towed by a D7 crawler	Bräcke mounds with 1–2 cm of mineral soil capping were supplemented with mineral soil (taken from the bottom of the adjacent scooped depression) until the mineral cap depth averaged 14 cm. White spruce seedlings were planted in the mound centre to a depth that allowed root systems to have contact with organic material beneath the mineral cap.
Blade scarification	Scalping	Front-mounted Beals V-Blade installed on a D7 crawler	Approximately 2-m wide strips of exposed mineral soil with accumulations of forest floor and Ah material forming berms along both edges of each strip. White spruce seedlings were planted to the root collar in mineral soil at the hinges of the accumulated forest floor material on either side of the exposed soil strip.
Patch scarification	Scalping	Bräcke scarifier with a 4-tined mattock wheel	Patches of mineral soil averaging 60–80 cm long were exposed. White spruce seedlings were planted to the root collar at the scalp edges, at the hinge of forest floor accumulations.
Vegetation control	Herbicide	None	There was no mechanical disturbance of soil and no mineral soil exposure. White spruce seedlings were planted to the root collar without screefing. After the first growing season (September 1984), glyphosate (Roundup® or Vision®) was applied at the high experimental rate of 5 kg ae/ha by backpack sprayer in a 1-m radius around each seedling.
Untreated control	No treatment	None	There was no mechanical disturbance of soil and no mineral soil exposure. White spruce seedlings were planted to the root collar without screefing.

accommodate the different site preparation configurations, and plots ranged in size from 0.038 to 0.063 ha (Appendix 2). The layout of the Wonowon experiment is illustrated in Figure 4.

Mechanical treatments were conducted in August 1983 and left to settle over one winter. All treatments were planted with white spruce bareroot stock that had been grown in the nursery for 2 years and then was transplanted into nursery beds for an additional year (BR 2+1, seedlot 4345). Although stock was not measured at the time of planting, that stocktype was typically 30–50 cm tall with 0.5–0.8 cm root collar diameter.[2] Eighty seedlings were planted in each treatment plot in June 1984, and all were tagged for measurement except in the vegetation control treatment, where only the inner 48 seedlings were tagged for measurement. These were spot treated with glyphosate in September 1984 after the first growing season; the outer 32 seedlings were left untreated to act as a buffer (Appendix 2). In total, 320 seedlings were assessed in each treatment except vegetation control, where 192 seedlings were assessed. Due to the difficulty of adapting tree spacing to the different site preparation configurations, planting density ranged from 1442 to 1756 stems/ha in the various treatments.

Seedling survival and growth in all treatments (including four treatments that are not included in this analysis [Appendix 1]) were assessed annually in late summer in years 1–6 (1984–1989), years 9–15 (1992–1998), and year 25 (2008). In addition, the vegetation control treatment was assessed from years 16 to 22 (1999–2005) and in years 28–29 (2011–2012), while the untreated control treatment was assessed from years 17 to 22 (2000–2005) and in years 28–29 (2011–2012). A full list of treatments and treatment dates for the

2 C. Kooistra, B.C. Ministry of Forests and Range, pers. comm., 2005.

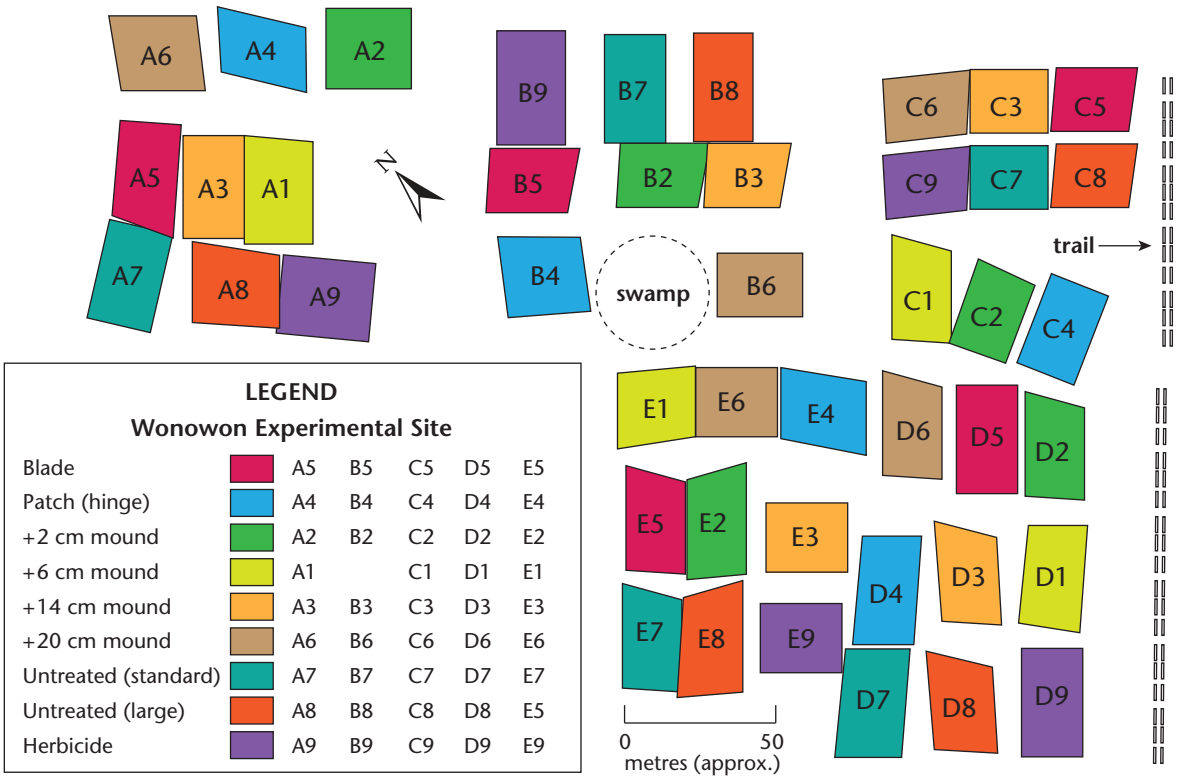

FIGURE 4 *Experimental layout at the Wonowon site. Treatment names in the legend are those used in earlier reports and can be cross-referenced to this report using Appendix 2; the Patch treatment referred to in the legend is the Bräcke patch and the mound treatments are supplemented Bräcke mounds.*

Wonowon experiment is presented in Appendix 3. During each assessment, spruce height (± 5 cm) and diameter (± 0.1 cm) were measured, with diameter measured as GLD from years 1 to 22 (1984–2005), and as dbh from years 25 to 29 (2008–2012). We present survival results for all years to age 25 for which data are available, individual tree results for years 5, 9, and 25, and stand-level volume results for year 25. For the vegetation control treatment and the untreated control only, year 29 stand-level volume is also presented. Comments regarding damage to individual white spruce were recorded in year 25, and these comments were later assigned standardized codes to facilitate the calculation of summary statistics. The height of overtopping vegetation was not assessed at the Wonowon site.

The year 25 assessment at Wonowon occurred in 2008, 4 years prior to the year 25–26 assessments at Inga Lake and Iron Creek, and it was conducted according to a slightly different assessment protocol that did not involve consistent recording of overtopping species. Spruce were visually assessed as to whether or not the leader was overtopped by vegetation, and for those that were, the number of occupied quadrants within a 1-m cylinder was recorded.

2.3 Data Collection

Height-to-diameter ratio (HDR) was calculated using GLD or dbh, according to the measurement schedule described in the previous section. Individual tree volume was calculated differently depending on whether diameter was measured as GLD or dbh. For years when diameter was measured as GLD

(years 5 and 10 at Inga Lake and Iron Creek, and years 5 and 9 at Wonowon), a "volume index" was calculated by applying the formula for a cone:

$$V = \pi(D/2)^2 H/3$$

where V is spruce volume index (cm^3), hereafter referred to as "volume," D is the GLD stem diameter (cm), and H is height (cm).

In subsequent years, when dbh was measured, taper equations developed by Kozak (1988) were used to calculate individual tree volumes. Stand-level volume (m^3/ha) was calculated by summing individual tree volumes and dividing by the measured plot area (Appendix 2). For Inga Lake, stand volume was calculated for years 19, 24, and 25, and volume increments (m^3/ha per time interval) were calculated for the intervals of years 19–24 and years 24–25. At Iron Creek, stand volume was calculated for years 20, 25, and 26, and volume increments were calculated for the intervals of years 20–26 and years 25–26. At Wonowon, stand volume was calculated for year 25, and in year 29 for the vegetation control treatment. Volume increment at Wonowon could be calculated only for the interval of years 25–29 in the vegetation control treatment.

Site index (SI) is an expression of site potential that is based on the growth of undamaged trees under unimpeded conditions (Stearns-Smith 2001). In this study, spruce were considered to be unimpeded in the vegetation control treatments at Inga Lake and Wonowon and the chemical site-preparation treatment at Iron Creek, and site index for each site was calculated based on spruce growth in these treatments. Site index was estimated by dividing the inner (measurement) plot area (Appendix 2) in each treatment plot into approximately 0.01-ha subplots, and for years when diameter was assessed as dbh, selecting the largest dbh planted white spruce in each of these 0.01-ha subplots as a site tree regardless of overtopping, and applying Nigh's (1999) growth intercept models for white spruce.

The Table Interpolation Program for Stand Yields (TIPSY), version 4.3 (B.C. Ministry of Forests, Lands and Natural Resource Operations 2013a), was used to project growth and yield to age 100 years for the vegetation control treatments at Inga Lake and Wonowon, and the chemical site preparation treatment at Iron Creek. The growth projections were generated at the treatment level by using (1) breast-height age 50 site index estimated from SI at age 25 (Inga Lake and Wonowon) or age 26 (Iron Creek) according to the growth intercept method (Nigh 1999), and (2) adjusted planting density based on average density per hectare at age 25 (Inga Lake and Wonowon) or age 26 (Iron Creek) calculated as the product of average planting density and average survival to age 25 or 26 (Table 5). Default operational adjustment factors (OAF1 = 0.85; OAF2 = 0.95) were used.

2.4 Data Analysis

Differences between treatments in years 5, 10, and 25 at Inga Lake (1992, 1997, and 2012), in years 5, 10, and 26 at Iron Creek (1991, 1996, and 2012), and in years 5, 9, and 25 at Wonowon (1988, 1992, and 2008) were assessed by univariate analysis of variance (ANOVA) based on a randomized-block design, where sources of variation in plot response (volume per hectare and proportion of live trees) and tree response (height, GLD, and HDR) were (excluding residual error) random block (B), fixed treatment (T), and, for the tree response, random B × T (plot). Tree responses and plot responses were

TABLE 5 *Input information for TIPSY[a] runs for vegetation control treatments at the Inga Lake and Wonowon sites and chemical site preparation at the Iron Creek site*

Site	SI at age 25 or 26 (m)[b]	Actual planting density (stems/ha)[c]	Actual density in year 25 or 26 (stems/ha)[d]	Adjusted planting density used for TIPSY runs (stems/ha)[e]
Inga Lake	23.6	1331	1180	1500
Iron Creek	24.0	971	894	1123
Wonowon	23.0	1679	1008	1271

a TIPSY = Table Interpolation Program for Stand Yield information.

b Site index (SI) was estimated using age 25 data for Inga Lake and Wonowon, and age 26 data for Iron Creek, as described in the Methods section.

c Actual planting density per hectare was calculated from individual measured plot areas (Appendix 2), and was averaged across blocks.

d Actual year 25 or 26 density was calculated by multiplying average survival in year 25 or 26 by average planting density.

e Adjusted planting density is the planting density required, according to TIPSY, to achieve the actual year 25 or 26 density that is based on measured survival.

analyzed separately for individual years. The statistical significance of differences between all pairs of (least-squares) treatment means was assessed by the Bonferroni method of multiple comparisons ($\alpha = 0.05$). At Inga Lake, differences between burned windrows (not directly comparable to mechanical treatments) and the untreated control were assessed using *t* tests. All data analyses were generated using SAS statistical software.[3]

3 RESULTS

3.1 Inga Lake

3.1.1 Spruce survival and year 25 damage at Inga Lake Twenty-five-year white spruce survival at Inga Lake was highest in the plow inverting treatment (98%) and ≥ 90% in the fine mixing, coarse mixing, vegetation control, and burned windrow treatments (Figure 5). Survival in the disc trench hinge, disc trench furrow, and untreated control treatments declined below 90% after age 14–15 years, and by year 25, it was 83%, 81%, and 77% in these treatments, respectively.

In spring 1992 (year 5), hare damage to live spruce was recorded on 23% of trees in the disc trench hinge and vegetation control treatments, 10% of trees in the untreated control, 2% of trees in the coarse mixing treatment, and < 1% of trees in the other treatments. In year 25, damage was recorded on 25% of surviving spruce in the untreated control and 34–49% of those in the other treatments (Table 6). Forking (above 1.3 m height) was the most common type of damage recorded on white spruce at Inga Lake: it affected 6% of surviving trees in the untreated control and 11–28% of trees in the other treatments. The second most common type of damage was multiple tops, which occurred on 10–22% of surviving trees. In addition to these damage types, 0–3% of surviving spruce had multiple stems (where the fork occurred

3 All data analyses for this report were generated using SAS/STAT software, Version 9.3 of the SAS System for Windows Copyright © 2002–2010 SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, N.C., USA.

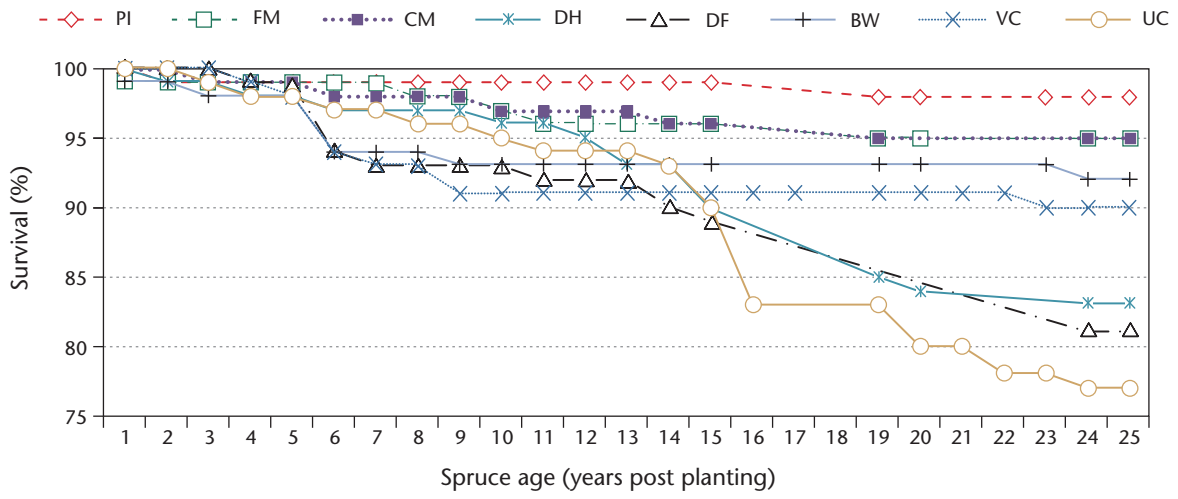

FIGURE 5 *White spruce survival at Inga Lake from 1988 (year 1) to 2012 (year 25). PI = plow inverting; FM = fine mixing; CM = coarse mixing; DH = disc trench hinge; DF = disc trench furrow; BW = burned windrows; VC = vegetation control; UC = untreated control.*

TABLE 6 *Year 25 damage to white spruce at Inga Lake*[a]

		Proportion of live trees damaged (%)[b]							
Damage presence	**Damage type**	**PI**	**FM**	**CM**	**DH**	**DF**	**VC**	**UC**	**BW**
No recorded damage		64	56	57	66	51	52	75	51
Damage recorded		36	44	43	34	49	48	25	49
	Hare browse	0	0	0	0	2	0	0	0
	Broken stem or top/dead top	1	1	4	1	7	0	2	1
	Fork (above 1.3 m height)	17	17	21	11	19	24	6	28
	Multiple stems (fork below 1.3 m height)	0	3	1	0	1	2	0	2
	Multiple tops	13	22	14	12	16	19	10	15
	Crook or sweep	0	1	2	1	2	1	2	2
	Pissodes terminal damage	0	0	0	0	0	0	0	0
	Frost crack	1	0	0	0	0	1	0	1
	Rubbing or scarring	3	4	4	9	9	1	5	3
	Snowpress	1	0	0	0	0	1	1	1
	Sirococcus tip blight	1	1	1	1	0	1	1	1

a PI = plow inverting; FM = fine mixing; CM = coarse mixing; DH = disc trench hinge; DF = disc trench furrow; VC = vegetation control; UC = untreated control; BW = burned windrow.

b Differences between the overall proportion of trees reported as damaged and the summed total of all damage types are due to the rounding of values to the nearest whole number.

below a height of 1.3 m), 0–7% had broken stems or tops or dead tops, 0–2% had sweeps or crooks, and 1–9% had rubbing or scarring damage. Assessors could not identify specific causes of stem deformity and damage to stems and tops, but subjective observations over nearly three decades suggest that contributing factors included frost heave during the establishment period, early snow- or vegetation-press, frost damage or winter kill, whipping damage from adjacent broadleaf trees, and breakage caused by adjacent broadleaves that were bent over during early, heavy snow events that occurred before foli-

age was shed. Hare browse, *Sirococcus* tip blight (*Sirococcus strobilinus*), frost cracks, and snowpress damage were present on ≤ 2% of surviving trees. Although minor amounts of terminal damage caused by *Pissodes strobi* were recorded, it affected < 0.5% of trees in individual treatments, and appears as "0" in Table 6.

3.1.2 Spruce growth at Inga Lake There were strongly significant treatment effects ($p < 0.01$) on all attributes of spruce growth in years 5, 10, and 25 (Table 7). In year 5, spruce were significantly taller in the plow inverting treatment than in the untreated control. None of the other treatments showed significant height increases relative to the control, but spruce in the disc trench furrow treatment were significantly shorter than those in the untreated control. In years 10 and 25, spruce in all treatments except disc trench hinge and disc trench furrow were significantly taller than those in the untreated control. At age 25, spruce in the fine mixing, plow inverting, and vegetation control treatments were, on average, more than 4 m (2.0–2.1 times) taller than spruce in the untreated control (Figure 6a). Mean spruce height in the coarse mixing and disc trench hinge treatments was 1.8 times and 1.2 times greater than in the untreated control, respectively, while trees in the disc trench furrow treatment were shorter, with a mean height that was 0.8 times that of untreated control spruce. White spruce GLD was significantly larger in the plow inverting and fine mixing treatments than in the untreated control in year 5, and in years 10 and 25, spruce in all treatments except disc trench hinge and disc trench furrow had a significantly larger mean diameter than those in the untreated control (Table 7). At age 25, spruce in the coarse mixing, plow inverting, fine mixing, and vegetation control treatments had a mean dbh that was 2.2–3.0 times larger than that of untreated control spruce (Figure 6b). The mean diameter of spruce in the disc trench hinge treatments was only 1.3 times larger than that of untreated control spruce, while disc trench furrow spruce were smaller, with a mean diameter that was 0.9 times that of untreated control spruce. Spruce in the plow inverting and fine mixing treatments had significantly greater individual stem volume than spruce in the untreated control in all measurement years, and by year 10, mean volume was also significantly greater in the vegetation control treatment than in the untreated control (Table 7). In year 25, stem volume in all treatments except disc trench hinge and disc trench furrow was significantly greater than in the untreated control. By age 25, spruce in the vegetation control treatment had significantly larger stem volume than spruce in any of the other site preparation treatments. At age 25, spruce in the vegetation control treatment had a mean stem volume that was 9.3 times greater than that of untreated control spruce, while mean stem volume in the fine mixing, plow inverting, and coarse mixing treatments was 7.6, 6.5, and 5.0 times larger than that of untreated control spruce, respectively (Figure 6c). Spruce in the disc trench hinge treatment had twice the stem volume of control spruce, while disc trench furrow trees were smaller, with 0.9 times the volume of control trees. Spruce in the fine mixing and vegetation control treatments had significantly lower HDR than untreated control spruce in years 5, 10, and 25 (Table 7). Spruce HDR in the plow inverting treatment was also significantly lower than that of the untreated control in year 5. By year 25, HDR in all treatments except disc trench hinge and disc trench furrow was significantly lower than in the untreated control.

TABLE 7 *Treatment effect[a,b] on white spruce growth in years 5 (1992), 10 (1997), and 25 (2012) at Inga Lake*

Variable	Year	PI (1483 stems/ha)[c]	FM (1432 stems/ha)	CM (1316 stems/ha)	DH (1097 stems/ha)	DF (1446 stems/ha)	VC (1331 stems/ha)	UC (1434 stems/ha)	*p*-value
Height (cm)	5	90 ± 2 a	78 ± 3 ab	79 ± 2 ab	72 ± 5 bc	54 ± 3 d	63 ± 3 cd	69 ± 4 bc	**< 0.01**
	10	250 ± 12 a	217 ± 12 ab	213 ± 7 ab	165 ± 23 bc	118 ± 10 c	214 ± 12 ab	148 ± 13 c	**< 0.01**
	25	870 ± 21 a	848 ± 46 ab	763 ± 13 ab	516 ± 113 bc	351 ± 80 c	891 ± 30 a	422 ± 63 c	**< 0.01**
Diameter (cm)[d]	5	1.5 ± 0.05 a	1.5 ± 0.08 a	1.1 ± 0.03 b	1.0 ± 0.07 bc	0.9 ± 0.03 c	1.1 ± 0.07 b	1.0 ± 0.04 bc	**< 0.01**
	10	4.0 ± 0.10 ab	4.2 ± 0.10 a	3.2 ± 0.10 b	2.4 ± 0.30 c	1.8 ± 0.10 c	4.4 ± 0.20 a	2.1 ± 0.20 c	**< 0.01**
	25	11.0 ± 0.30 ab	12.0 ± 0.60 ab	9.8 ± 0.30 b	5.9 ± 1.30 c	4.2 ± 0.90 c	13.5 ± 0.30 a	4.5 ± 0.70 c	**< 0.01**
HDR (cm/cm)[d]	5	59 ± 1 bc	52 ± 2 c	71 ± 1 a	72 ± 3 a	63 ± 3 ab	56 ± 3 bc	72 ± 3 a	**< 0.01**
	10	63 ± 1 a	51 ± 2 b	68 ± 1 a	69 ± 3 a	65 ± 2 a	49 ± 1 b	69 ± 1 a	**< 0.01**
	25	82 ± 2 bc	74 ± 1 c	85 ± 2 bc	104 ± 7 ab	112 ± 13 a	68 ± 1 c	116 ± 6 a	**< 0.01**
Volume (cm^3)[d]	5	63 ± 5 a	55 ± 8 a	31 ± 2 b	23 ± 4 b	11 ± 1 b	25 ± 3 b	19 ± 3 b	**< 0.01**
	10	1184 ± 76 a	1170 ± 111 ab	700 ± 76 bc	322 ± 90 cd	123 ± 26 d	1231 ± 158 a	235 ± 49 cd	**< 0.01**
	25	41 705 ± 3267 b	48 966 ± 3997 b	32 156 ± 2047 b	12 706 ± 5735 c	5502 ± 2427 c	59 910 ± 4607 a	6459 ± 2340 c	**< 0.01**

a Values are presented as the mean of block means ± 1 standard error. *P*-values are based on the ANOVA *F* test for a treatment effect (homogeneous variance model), and those in bold are significant at $p \leq 0.05$. Means assigned the same letter do not differ significantly according to the Bonferroni test.

b PI = plow inverting; FM = fine mixing; CM = coarse mixing; DH = disc trench hinge; DF = disc trench furrow; VC = vegetation control; UC = untreated control.

c Values in parentheses are planting densities per hectare (the average of density values calculated for individual plots based on measured plot area).

d Stem diameter was measured as ground-level diameter (GLD) in years 5 and 10, and as diameter at breast height (dbh) (1.3 m height) in year 25. Height-to-diameter ratio (HDR) and tree volume were calculated using GLD in years 5 and 10, and using dbh in year 25. Volume was calculated using the formula for a cone in years 5 and 10, and using a taper equation (Kozak 1988) in year 25.

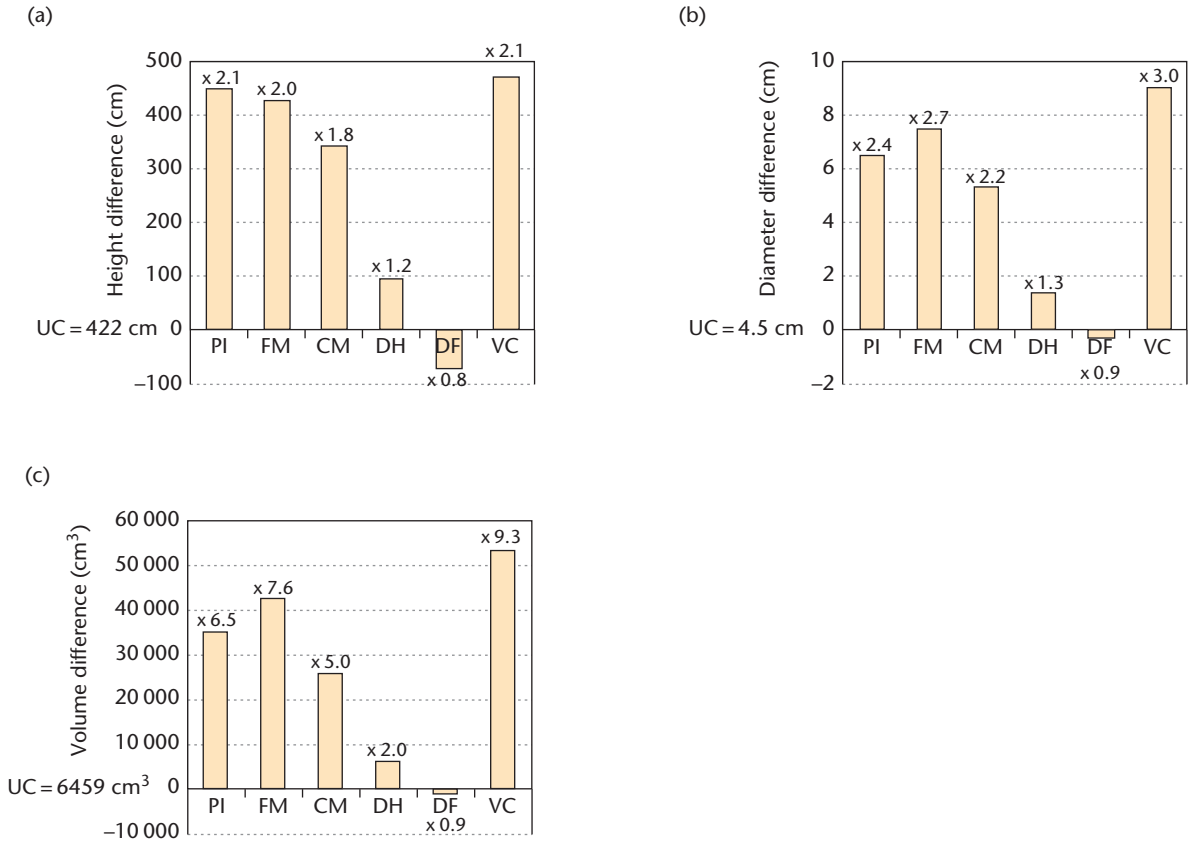

FIGURE 6 *Inga Lake year 25 (2012) changes in white spruce (a) height, (b) diameter, and (c) individual tree volume in the plow inverting (PI), fine mixing (FM), coarse mixing (CM), disc trench hinge (DH), disc trench furrow (DF), and vegetation control (VC) treatments relative to the untreated control (UC). The mean for the untreated control is represented by "0" on the y-axis. Values above or below individual bars are the ratio of the treatment mean to the untreated control.*

According to the unadjusted *t* tests that compared the treatment means, white spruce in the burned windrow treatment were significantly taller and had significantly larger stem diameter and significantly greater stem volume than those in the untreated control in years 5, 10, and 25 (Figure 7). In all assessment years, spruce in the burned windrow treatment also had significantly lower HDR than untreated control spruce.

3.1.3 Stand-level spruce volume at Inga Lake There were significant treatment effects on stand-level white spruce volume at Inga Lake in years 19, 24, and 25 (Table 8). In those assessment years, spruce stand volume in the vegetation control, fine mixing, plow inverting, and coarse mixing treatments was significantly greater than in the untreated control, but there were no significant stand-level volume gains in the disc trench hinge treatment relative to the untreated control. The disc trench furrow treatment was not assessed in year 19, but in years 24 and 25, it did not show significant stand-level volume gains over the untreated control. Stand-level spruce volume in the vegetation control and fine mixing treatments was significantly greater than that of the coarse mixing and disc trench hinge treatments in all assessment years, and

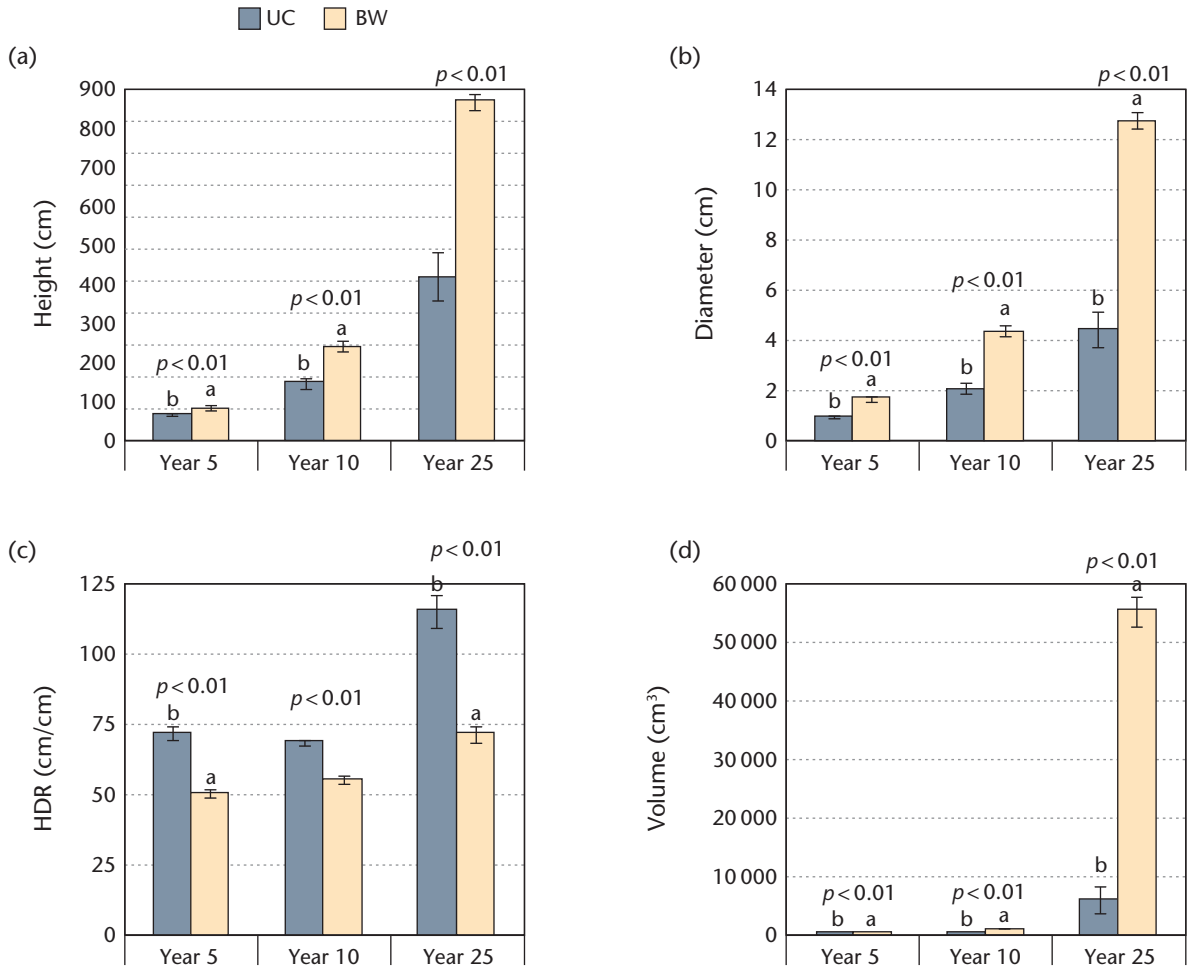

FIGURE 7 t *test comparisons between the untreated control (UC) and burned windrow (BW) treatments at Inga Lake for white spruce (a) height, (b) diameter, (c) height-to-diameter ratio (HDR), and (d) individual stem volume in year 5 (1992), year 10 (1997), and year 25 (2012). Error bars are ± 1 standard error (ANOVA model with homogeneous variances), and means with different letters differ significantly at α = 0.05 (*p *is the* p*-value).*

was greater than that of the disc trench furrow treatment in years 24 and 25. At age 25, the relative magnitude of stand volume in the various treatments approximately reflected the magnitude of individual tree volume. By age 25, mean stand volume in the vegetation control treatment was 10.5 times greater than that of the untreated control stand, where overtopped spruce had small stature. Stand-level volume increments for years 19–24 and years 24–25 were significantly larger in the vegetation control, fine mixing, and plow inverting treatments than in the untreated control (Table 8; Figure 8). The coarse mixing treatment had significantly larger volume gains than the untreated control for the year 19–24 interval but not for the 24–25 interval (Table 8).

Site index in the vegetation control treatment at Inga Lake was estimated to be 23.6 m at age 25 (Table 5), and TIPSY projected that spruce in this treatment would meet a target merchantable volume[4] of 250 m^3/ha at age 47 years (Figure 9).

4 A typical target merchantable volume is considered to be 250 m^3/ha, based on information provided by Canadian Forest Products Ltd., Fort St. John.

TABLE 8 *Treatment effect[a,b] on stand-level white spruce volume and volume increment from years 19 (2006) to 25 (2012) at Inga Lake*

Variable	Year	PI (1453 stems/ha)[c]	FM (1361 stems/ha)	CM (1250 stems/ha)	DH (911 stems/ha)	DF (1171 stems/ha)	VC (1180 stems/ha)	UC (1105 stems/ha)	*p*-value
Stand volume (m^3/ha)	19	23.8 ± 1.2 ab	26.6 ± 3.4 a	14.5 ± 2.2 b	4.1 ± 1.8 c	–	25.6 ± 2.4 a	2.2 ± 0.7 c	**< 0.01**
	24	52.4 ± 1.8 ab	59.8 ± 6.8 a	35.7 ± 4.2 b	10.5 ± 4.9 c	6.2 ± 3.6 c	64.0 ± 5.2 a	5.7 ± 2.1 c	**< 0.01**
	25	58.5 ± 2.1 ab	66.2 ± 8.0 a	40.8 ± 4.6 b	12.5 ± 5.9 c	7.4 ± 4.4 c	71.1 ± 5.9 a	6.8 ± 2.5 c	**< 0.01**
Stand volume	19–24	28.6 ± 1.5 ab	33.2 ± 3.6 a	21.2 ± 2.0 a	6.4 ± 3.1 c	–	38.4 ± 3.0 a	3.5 ± 1.4 c	**< 0.01**
increment (m^3/ha)	24–25	6.1 ± 1.4 abc	6.4 ± 1.4 ab	5.2 ± 0.9 abcd	2.0 ± 1.0 bcd	1.2 ± 0.8 cd	7.1 ± 1.4 a	1.1 ± 0.4 d	**< 0.01**

a Values are presented as the mean of block means ± 1 standard error. *P*-values are based on the ANOVA *F* test for a treatment effect (homogeneous variance model), and those in bold are significant at $p \leq 0.05$. Means assigned the same letter do not differ significantly according to the Bonferroni test.

b PI = plow inverting; FM = fine mixing; CM = coarse mixing; DH = disc trench hinge; DF = disc trench furrow; VC = vegetation control; UC = untreated control.

c Values in parentheses are the density of live target spruce at age 25, calculated as average planting density (across all blocks) multiplied by average year 25 survival.

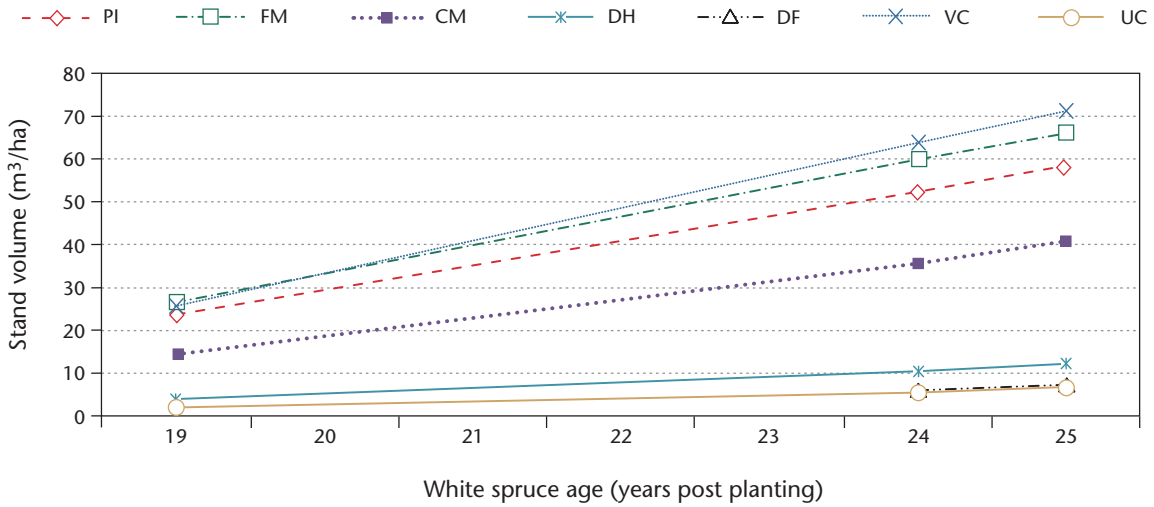

FIGURE 8 *Inga Lake stand-level white spruce volume from year 19 (2006) to year 25 (2012) in the plow inverting (PI), fine mixing (FM), coarse mixing (CM), disc trench hinge (DH), disc trench furrow (DF), vegetation control (VC), and untreated control (UC) treatments.*

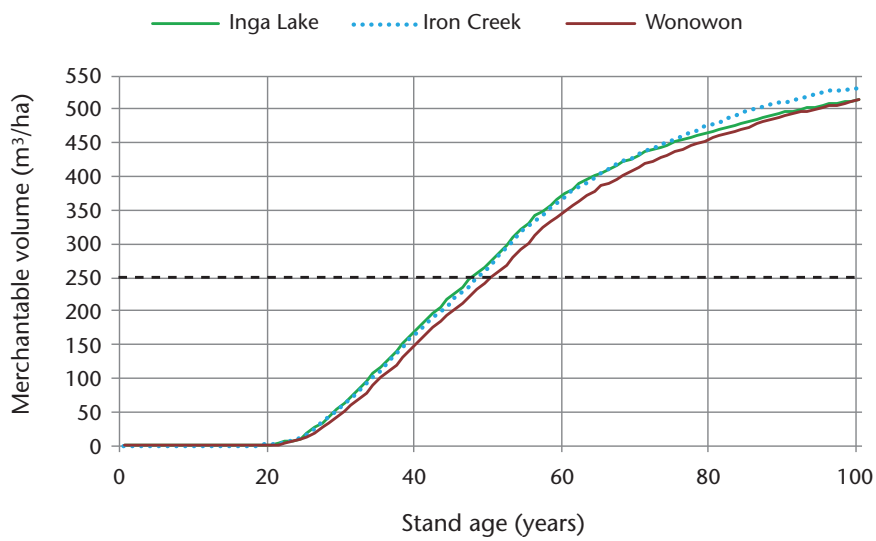

FIGURE 9 *TIPSY projections of merchantable white spruce volume to stand age 100 years for the vegetation control treatments at Inga Lake and Wonowon and the chemical site preparation treatment at Iron Creek (using default operational adjustment factors OAF1 = 0.85 and OAF2 = 0.95). The horizontal dashed line represents a typical operational merchantable volume target of 250 m³/ha.*

3.1.4 Year 25 overtopping and competing vegetation In year 25, the proportion of overtopped spruce at Inga Lake ranged from 0% in the vegetation control treatment to 91% in the untreated control (Table 9). On average, overtopped trees in all treatments (except vegetation control where none were overtopped) had between three and four occupied quadrants within a 1-m radius. Species that commonly overtopped spruce at Inga Lake were aspen, willow, and alder, while overtopping balsam poplar and paper birch had scattered presence. The distribution and average height of these species is presented in Table 9.

TABLE 9 *Characteristics of overtopping vegetation at Inga Lake in year 25 (2012)*

		Overtopping vegetation characteristics		Overtopping vegetation presence in 1-m radius cylinder	
Treatment[a]	**Species**	**Average canopy height (m)[b]**	**Distribution and number of treatment plots (of 5) where recorded**	**Proportion of overtopped spruce (%)**	**Average number of occupied quadrants for spruce with overtopping vegetation**
PI	Aspen	8.3	Scattered (3 of 5)	10	3.4
	Willow	7.6	Scattered to continuous (5 of 5)		
FM	Aspen	8.2	Scattered (1 of 5)	9	3.4
	Balsam poplar	8.1	Scattered (2 of 5)		
	Willow	7.0	Continuous to patchy (2 of 5)		
	Alder	4.6	Continuous (2 of 5)		
CM	Aspen	8.8	Scattered (3 of 5)	32	3.4
	Willow	7.9	Continuous (5 of 5)		
DH	Aspen	9.0	Scattered (1 of 5)	78	3.6
	Balsam poplar	10.3	Scattered to patchy (1 of 5)		
	Willow	8.3	Continuous to patchy (4 of 5)		
	Alder	4.0	Patchy (1 of 5)		
DF	Aspen	8.3	Scattered to patchy (2 of 5)	86	3.7
	Birch	6.4	Scattered (1 of 5)		
	Willow	8.1	Continuous to scattered (4 of 5)		
	Alder	5.0	No data (1 of 5)		
VC	Alder	3.1	Continuous (1 of 5)	0	n/a
UC	Aspen	9.3	Patchy to scattered (3 of 5)	91	3.8
	Willow	8.5	Continuous to patchy (4 of 5)		

a PI = plow inverting; FM = fine mixing; CM = coarse mixing; DH = disc trench hinge; DF = disc trench furrow; VC = vegetation control; UC = untreated control.

b Canopy height in each treatment plot was determined by visually identifying and measuring a stem that was judged to be representative of the average canopy height. Values presented are the average of estimates for individual plots.

3.2 Iron Creek

3.2.1 Spruce and lodgepole pine survival and year 26 damage at Iron Creek After 26 years, spruce survival at Iron Creek was high (92–95%) in the plow inverting, mounding, and chemical site preparation treatments, compared with 75% in the untreated control, where there had been ongoing, gradual mortality (Figure 10). The patch scarification treatment was not assessed after year 20, but trends to that point were identical to those of the untreated control. The survival of lodgepole pine planted in untreated ground declined steadily from the time of planting to 37% in year 20 (after which it was not assessed). Pine mortality was attributed mainly to repeat browsing by hares and light competition from the heavy cover of aspen and green alder.

In year 26, damage was recorded on 29% of surviving spruce in the untreated control, and 31–45% of surviving spruce in other treatments (Table 10). Forking (above 1.3 m height) and multiple tops were the most common types of damage recorded in year 26; forking was recorded on 4–15% of trees, and multiple tops were recorded on 12–21%. Multiple stems (i.e., forks that occurred below 1.3 m height) were present on 2–9% of live spruce. Broken stems, sweeps, and rubbing or scarring damage were also present on ≤ 2% of trees. As described for Inga Lake, a variety of factors may have contributed to stem and top damage. *Pissodes* terminal damage was observed on an average of 1–2% of live spruce at age 26. Frost cracks, snowpress, and *Sirococcus* tip blight also affected ≤ 4% of spruce in the various treatments.

TABLE 10 *Year 26 damage to white spruce at Iron Creek*[a]

Damage presence	Damage type	Proportion of live trees damaged (%)[b]			
		PI	MND	CSP	UC
No recorded damage		69	57	55	71
Damage recorded		31	43	45	29
	Woodpecker damage	0	0	1	0
	Broken stem	1	1	0	0
	Fork (above 1.3 m height)	15	11	14	4
	Multiple stems (fork below 1.3 m height)	2	9	7	2
	Multiple tops	12	17	21	15
	Sweep	0	0	0	1
	Pissodes terminal damage	1	1	2	2
	Frost crack	1	0	2	1
	Rubbing or scarring	0	1	0	2
	Snowpress	0	3	0	4
	Sirococcus tip blight	1	1	0	0

a PI = plow inverting; MND = mounding; CSP = chemical site preparation; UC = untreated control.

b Differences between the overall proportion of trees reported as damaged and the summed total of all damage types are due to the rounding of values to the nearest whole number.

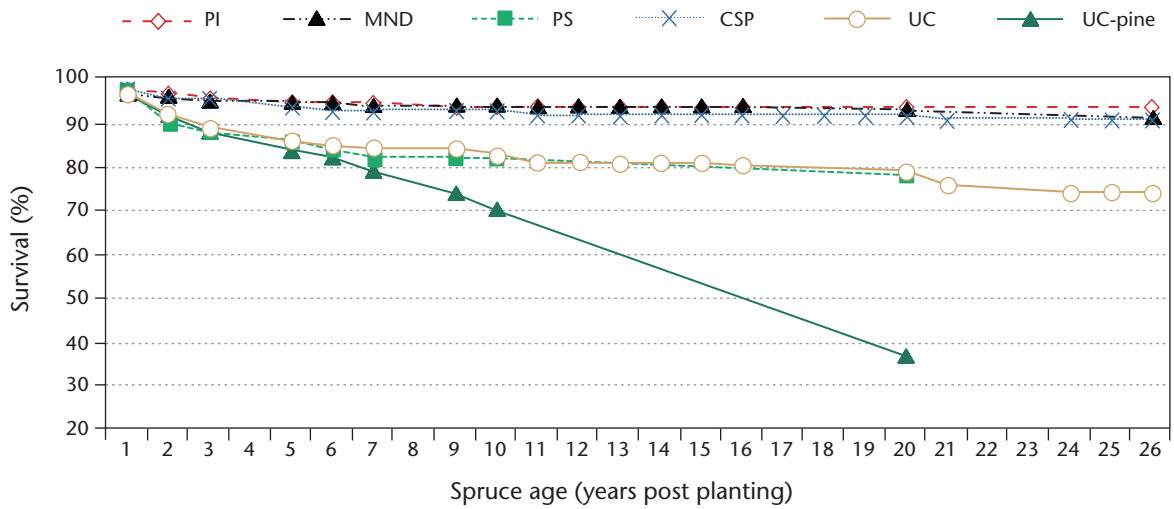

FIGURE 10 *White spruce and lodgepole pine survival at Iron Creek from 1987 (year 1) to 2012 (year 26). PI = plow inverting; MND = mounding; PS = patch scarification; CSP = chemical site preparation; UC = untreated control; UC-pine = lodgepole pine planted into untreated ground.*

3.2.2 Spruce and lodgepole pine growth at Iron Creek Site preparation had a significant effect ($p < 0.01$) on white spruce height, diameter, and stem volume in years 5, 10, and 26, but had a significant effect on HDR only in year 26 (Table 11). Spruce in the plow inverting treatment were significantly taller than those in the untreated control in all assessment years, and by year 26, spruce in the chemical site preparation treatment were also significantly taller than those in the untreated control. At age 26, the mean height of spruce in the

TABLE 11 *Treatment effect[a,b] on white spruce growth in years 5 (1991), 10 (1996), and 26 (2012), and untreated lodgepole pine growth in years 5 (1991) and 10 (1996), at Iron Creek*

Variable	Year	PI (947 stems/ha)[c]	MND (1105 stems/ha)	PS (1091 stems/ha)	CSP (971 stems/ha)	UC (1133 stems/ha)	*p*-value	UC-pine (1045 stems/ha)
Height (cm)	5	81 ± 2 a	68 ± 4 ab	47 ± 3 c	69 ± 8 ab	54 ± 5 bc	**< 0.01**	68 ± 6
	10	230 ± 8 a	197 ± 9 ab	127 ± 12 c	201 ± 19 ab	151 ± 17 bc	**< 0.01**	173 ± 26
	26	979 ± 27 a	771 ± 47 ab	–	918 ± 52 a	620 ± 16 b	**< 0.01**	–
Diameter (cm)[d]	5	1.3 ± 0.08 a	1.1 ± 0.07 ab	0.7 ± 0.03 c	1.1 ± 0.08 a	0.8 ± 0.03 bc	**< 0.01**	1.0 ± 0.07
	10	3.8 ± 0.00 a	3.2 ± 0.30 a	1.9 ± 0.10 b	3.5 ± 0.20 a	2.3 ± 0.20 b	**< 0.01**	2.9 ± 0.4
	26	13.0 ± 1.20 ab	9.6 ± 0.90 bc	–	13.5 ± 1.00 a	7.2 ± 0.30 c	**< 0.01**	–
HDR (cm/cm)[d]	5	67 ± 3	67 ± 3	70 ± 3	62 ± 3	69 ± 5	0.31	68 ± 4
	10	61 ± 2	64 ± 5	67 ± 4	60 ± 4	66 ± 4	0.36	61 ± 3
	26	80 ± 4 bc	89 ± 3 ab	–	72 ± 2 c	99 ± 4 a	**< 0.01**	–
Volume (cm^3)[d]	5	40 ± 5 a	26 ± 3 abc	8 ± 1 c	29 ± 8 ab	11 ± 2 bc	**< 0.01**	28 ± 6
	10	1050 ± 24 a	756 ± 108 ab	198 ± 40 c	839 ± 183 a	315 ± 61 bc	**< 0.01**	608 ± 155
	26	65 710 ± 13 446 ab	35 079 ± 6573 ab	–	67 093 ± 12 472 a	19 570 ± 2081 b	**< 0.01**	–

a Values are presented as the mean of block means ± 1 standard error. *P*-values are based on the ANOVA *F* test for a treatment effect (homogeneous variance model), and those in bold are significant at $p \leq 0.05$. Means assigned the same letter do not differ significantly according to the Bonferroni test.

b PI = plow inverting; MND = mounding; PS = patch scarification; CSP = chemical site preparation; UC = untreated control; UC-pine = lodgepole pine planted into untreated ground.

c Values in parentheses are planting densities per hectare (the average of density values calculated for individual plots based on measured plot area).

d Stem diameter was measured as ground-level diameter (GLD) in years 5 and 10, and as diameter at breast height (dbh) (1.3 m height) in year 26. Height-to-diameter ratio (HDR) and tree volume were calculated using GLD in years 5 and 10, and using dbh in year 26. Volume was calculated using the formula for a cone in years 5 and 10, and using a taper equation (Kozak 1988) in year 26.

plow inverting, chemical site preparation, and mounding treatments was 1.6, 1.5, and 1.2 times greater than that in the untreated control, respectively (Figure 11a). The patch scarification treatment was assessed only in years 5 and 10, and in both years, it had a slightly negative (non-significant) effect on spruce height relative to the control (Table 11). In years 5, 10, and 26, spruce in the plow inverting and chemical site preparation treatments had significantly larger stem diameter than untreated control spruce. Spruce in the mounding treatment had significantly larger diameter than those in the untreated control in year 10 but not in years 5 or 26. As of year 26, the mean diameter of spruce in the chemical site preparation, plow inverting, and mounding treatments was 1.9, 1.8, and 1.3 times larger than that in the untreated control, respectively (Figure 11b). The patch scarification treatment resulted in a slight (non-significant) trend in reduced diameter relative to the untreated control in years 5 and 10; the treatment was not assessed in year 26 (Table 11). At age 5, only the plow inverting treatment was associated with significant gains in individual spruce stem volume relative to the untreated control, whereas in year 10, spruce in both the plow inverting and chemical site preparation treatments had significantly greater stem volume than those in the untreated control (Table 11). Spruce in the chemical site preparation treatment continued to have significantly larger volume than those in the untreated control in year 26, whereas the difference between the plow inverting and untreated control

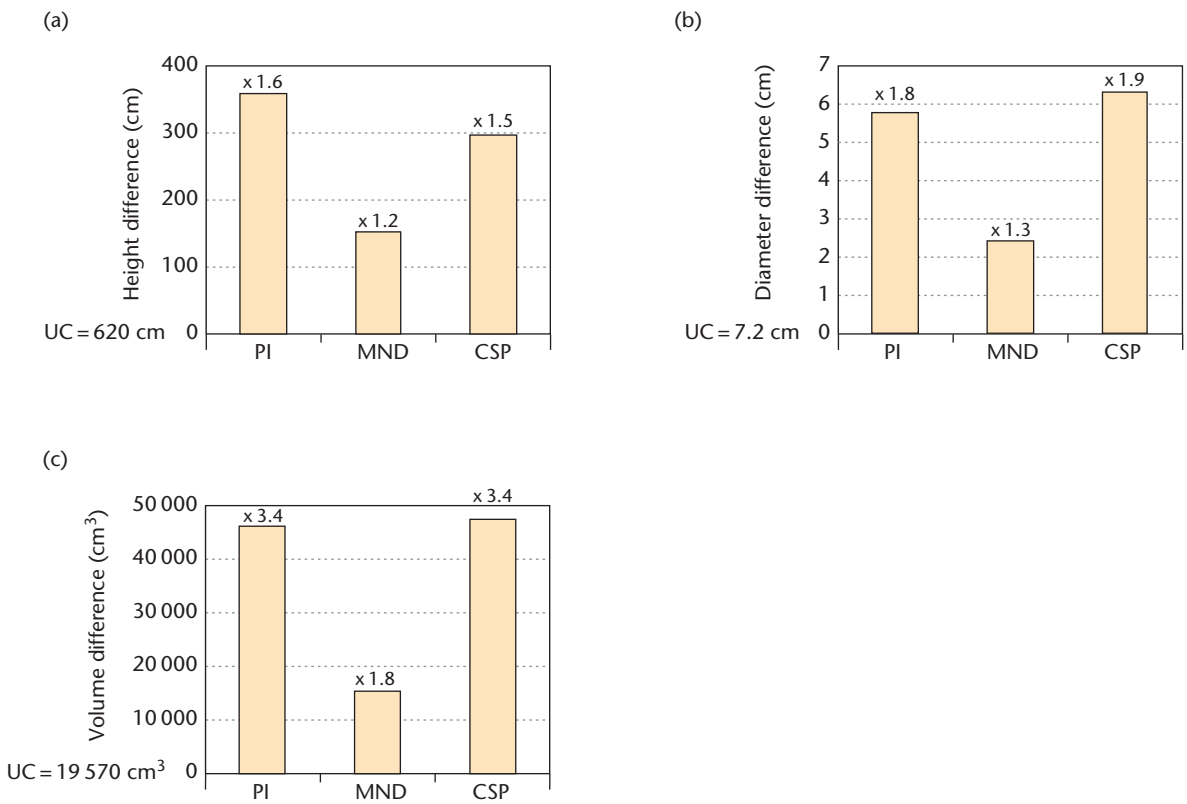

FIGURE 11 *Iron Creek year 26 (2012) changes in white spruce (a) height, (b) diameter, and (c) individual tree volume in the plow inverting (PI), mounding (MND), and chemical site preparation (CSP) treatments relative to the untreated control (UC). The mean for the untreated control is represented by "0" on the y-axis. Values above or below individual bars are the ratio of the treatment mean to the untreated control.*

treatments was no longer significant. In year 26, the mean stem volume of spruce in the chemical site preparation and plow inverting treatments was 3.4 times greater than that in the untreated control, and spruce in the mounding treatment had a 1.8 times greater mean volume (Figure 11c). The stem volume of spruce in the patch scarification treatment did not differ significantly from that of the untreated control spruce in year 5 or year 10 (Table 11). There were no significant treatment effects on white spruce HDR in years 5 or 10, but in year 26, spruce in the plow inverting and chemical site preparation treatments had significantly lower HDR than those in the untreated control (Table 11).

Lodgepole pine planted into untreated ground was not compared statistically to spruce, but mean height, diameter, HDR, and stem volume for years 5 and 10 are presented in Table 11.

3.2.3 Stand-level spruce volume at Iron Creek In year 20, when all treatments, including patch scarification, were assessed, stand volume was significantly higher in the plow inverting and chemical site preparation treatments than in the untreated control (Table 12). Although mean stand volume in the mounding treatment was more than twice that of the untreated control in year 20, the difference was not statistically significant. The patch scarification stand had less volume than that of the untreated control in year 20, but the difference was not significant. In year 25, when only the chemical site preparation and untreated control treatments were assessed, stand volume was significantly larger in the chemical site preparation treatment ($p < 0.01$). In year 26, stand volume was significantly greater in the plow inverting and chemical site preparation treatments than in the untreated control, but the difference between mounding and untreated control stands continued to be non-significant. In year 26, both plow inverting and chemical site preparation stands had mean volumes that were 3.6 times greater than that in the untreated control, and the spruce stand volume increment from year 20 to 26 was significantly greater in the plow inverting and chemical site preparation treatments than in the untreated control (Table 12). During this period, the increases in spruce volume in the plow inverting and chemical site preparation treatments were 3.4 and 3.6 times that of the untreated control,

TABLE 12 *Treatment effect[a,b] on stand-level white spruce volume and volume increment from years 20 (2006) to 26 (2012), and stand-level untreated lodgepole pine volume in year 20, at Iron Creek*

Variable	Year	PI (906 stems/ha)[c]	MND (1017 stems/ha)	PS	CSP (894 stems/ha)	UC (855 stems/ha)	*p*-value	UC-pine
Stand volume (m^3/ha)	20	22.4 ± 4.1 a	12.6 ± 1.8 ab	4.2 ± 1.1 b	19.9 ± 4.8 a	5.6 ± 0.7 b	**< 0.01**	3.7 ± 1.4
	25	–	–	–	49.4 ± 9.1 a	13.5 ± 0.7 b	**< 0.01**	–
	26	58.7 ± 12.8 a	34.1 ± 5.3 ab	–	58.1 ± 10.4 a	16.2 ± 1.3 b	**< 0.01**	–
Stand volume increment (m^3/ha)	20–26	36.2 ± 8.8 a	21.6 ± 3.5 ab	–	38.2 ± 5.7 a	10.6 ± 1.1 b	**< 0.01**	–
	25–26	–	–	–	8.7 ± 1.5 a	2.7 ± 0.6 b	**< 0.01**	–

a Values are presented as the mean of block means ± 1 standard error. *P*-values are based on the ANOVA *F* test for a treatment effect (homogeneous variance model), and those in bold are significant at $p \leq 0.05$. Means assigned the same letter do not differ significantly according to the Bonferroni test.

b PI = plow inverting; MND = mounding; PS = patch scarification; CSP = chemical site preparation; UC = untreated control; UC-pine = lodgepole pine planted into untreated ground.

c Values in parentheses are the density of live target spruce at age 26, calculated as average planting density (across all blocks) multiplied by average year 26 survival. Densities are not presented for the PS and UC-pine treatments because survival in these treatments was not assessed at age 26.

respectively (Figure 12). The year 25–26 stand volume increment could be calculated only for the chemical site preparation and untreated control treatments, but the difference between the two was significant: during this 1-year period, the increase in spruce volume in the chemical site preparation treatment was 3.2 times that in the untreated control (Table 12).

Site index in the chemical site preparation treatment at Iron Creek was estimated to be 24.0 m at age 26 (Table 5), and TIPSY projected that spruce in this treatment would meet a target merchantable volume[5] of 250 m^3/ha at age 48 years (Figure 9).

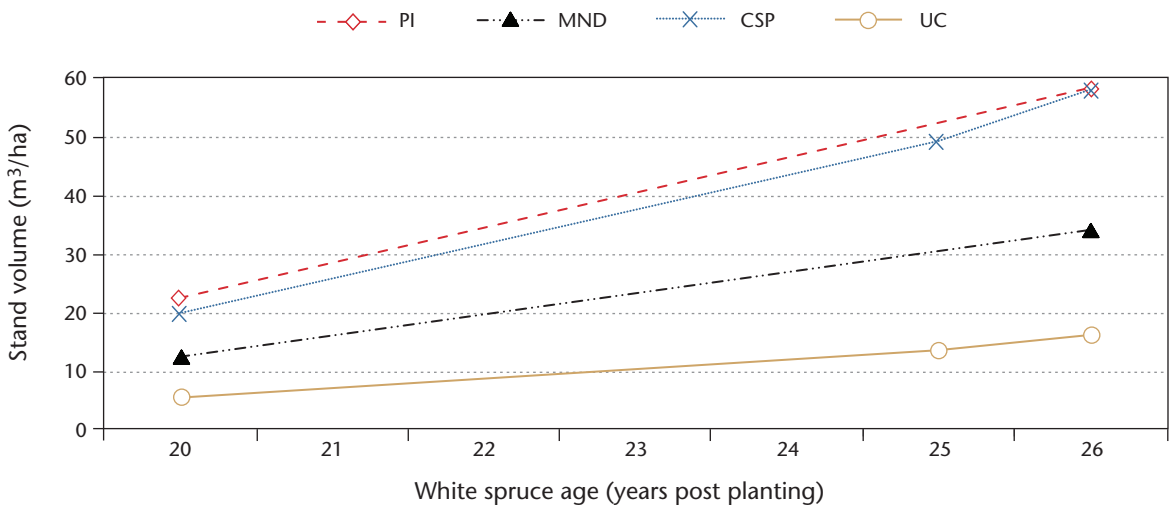

FIGURE 12 *Iron Creek stand-level white spruce volume from year 20 (2006) to year 26 (2012) in the plow inverting (PI), mounding (MND), chemical site preparation (CSP), and untreated control (UC) treatments.*

3.2.4 Year 26 overtopping and competing vegetation The proportion of spruce that were overtopped in year 26 at Iron Creek ranged from 2% in the chemical site preparation treatment to 71% in the untreated control (Table 13). On average, the few overtopped trees in the chemical site preparation treatment had 2.8 occupied quadrants within a 1-m cylinder, whereas in all other treatments, overtopped trees had between three and four occupied quadrants. Species that commonly overtopped spruce at Iron Creek were aspen, balsam poplar, and alder. The distribution and average height of these species is presented in Table 13.

3.3 Wonowon

3.3.1 Spruce survival and year 25 damage at Wonowon At Wonowon, 20–43% of bareroot spruce died within 4 months of planting (Figure 13). After the first growing season, survival was highest in the mounding treatment (80%), followed by the vegetation control and untreated control treatments (74%). First-year survival was lowest in the patch scarification (62%) and blade scarification (57%) treatments. Survival in the mounding and vegetation control treatments continued to decline steeply between years 1 and 2, after which it stabilized at approximately 70%. In year 25, spruce survival was 67% and 60% in the mounding and vegetation control treatments, respec-

5 A typical target merchantable volume is considered to be 250 m^3/ha, based on information provided by Canadian Forest Products Ltd., Fort St. John.

TABLE 13 *Characteristics of overtopping vegetation at Iron Creek in year 26 (2012)*

		Overtopping vegetation characteristics		Overtopping vegetation presence in 1-m radius cylinder	
Treatment[a]	**Species**	**Average canopy height (m)[b]**	**Distribution and number of treatment plots (of 5 [or 4])[c] where recorded**	**Proportion of overtopped spruce (%)**	**Average number of occupied quadrants for spruce with overtopping vegetation**
PI	Aspen	12.7	Patchy to continuous (2 of 4)	31	3.3
	Balsam poplar	13.3	Scattered (2 of 4)		
MND	Aspen	13.2	Scattered to continuous (3 of 5)	65	3.6
	Balsam poplar	13.3	Scattered to continuous (4 of 5)		
	Alder	7.4	Scattered to patchy (2 of 5)		
CSP	Alder	6.2	Scattered (1 of 5)	2	2.8
UC	Aspen	11.6	Scattered to continuous (3 of 5)	71	3.6
	Balsam poplar	12.2	Scattered to continuous (3 of 5)		
	Alder	6.6	Scattered to continuous (3 of 5)		

a PI = plow inverting; MND = mounding; CSP = chemical site preparation; UC = untreated control.

b Canopy height in each treatment plot was determined by visually identifying and measuring a stem that was judged to be representative of the average canopy height. Values presented are the average of estimates for individual plots.

c There were only four treatment plots in the PI treatment (see Methods).

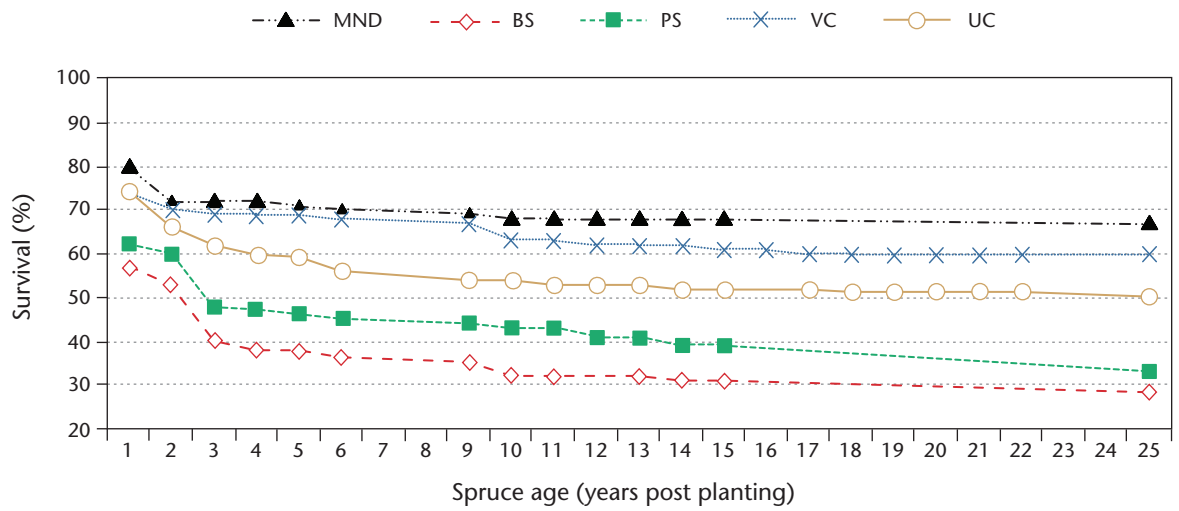

FIGURE 13 *White spruce survival at Wonowon from 1984 (year 1) to 2008 (year 25). MND = mounding; BS = blade scarification; PS = patch scarification; VC = vegetation control; UC = untreated control.*

tively. In the blade scarification and patch scarification treatments, survival declined steeply until year 3, when it was 40% and 48%, respectively. After year 3, survival declines in those treatments were gradual but continuous, and only 28% and 33% of the original planted seedlings survived to year 25, respectively. Survival of untreated control spruce declined to 56% between years 1 and 6, and then more gradually to 50% in year 25.

In year 25, damage was recorded on 6% and 7% of spruce in the vegetation control treatment and the untreated control, respectively, versus 32–53% in the other treatments (Table 14). Crooks did not affect spruce in the vegetation control treatment or the untreated control but were recorded on 16–26% of surviving white spruce in the patch scarification, blade scarification, and

TABLE 14 *Year 25 (2008) damage to white spruce at Wonowon*[a]

Damage presence	Damage type	Proportion of live trees damaged (%)[b]				
		MND	BS	PS	VC	UC
No recorded damage		47	57	68	94	93
Damage recorded		53	43	32	6	7
	Broken or dead top	1	3	4	0	1
	Fork (above 1.3 m height)	15	12	5	0	1
	Multiple stems (fork below 1.3 m height)	7	2	3	2	2
	Multiple tops	1	0	0	0	0
	Crook	26	21	16	0	0
	Pissodes terminal damage	0	0	0	0	0
	Frost crack	1	0	0	1	0
	Defoliated leader	1	1	0	0	0
	Snowpress	1	2	6	0	1
	Vegetation-related physical damage	0	0	3	0	4

a MND = mounding; BS = blade scarification; PS = patch scarification; VC = vegetation control; UC = untreated control.

b Differences between the overall proportion of trees reported as damaged and the summed total of all damage types are due to the rounding of values to the nearest whole number.

mounding treatments. Forks were recorded on 12% and 15% of surviving spruce in the blade scarification and mounding treatments, respectively, compared with 5% in the patch scarification treatment and 1% in the untreated control. None of the spruce in the vegetation control treatment had forks. Multiple stems were recorded on 2–7% of spruce in the various treatments. Spruce terminal weevil (*Pissodes*) damage was not observed at the Wonowon site, and frost cracks were rare. Snowpress affected 6% of spruce in the patch scarification treatment but was otherwise rare, while vegetation-related physical damage caused by naturally regenerated lodgepole pine or grass affected 3–4% of surviving spruce in the untreated control and patch scarification treatments.

3.3.2 Spruce growth at Wonowon There were strongly significant treatment effects ($p < 0.01$) on all attributes of spruce growth in years 5, 9, and 25 (Table 15). In all assessment years, spruce in the mounding and vegetation control treatments were significantly taller than those in the untreated control. Spruce in the vegetation control treatment also had significantly larger diameter than those in the control in years 5, 9, and 25, while those in the mounding treatment had significantly larger diameter than control spruce in years 5 and 9, but not in year 25. In contrast, spruce in the blade scarification and patch scarification treatments did not differ significantly in height or diameter from untreated control spruce in years 5, 9, or 25. At age 25, spruce in the vegetation control treatment had a mean height that was 1.4 times greater and a mean stem diameter that was 1.9 times larger than the untreated control spruce, while spruce in the mounding treatment had a mean height that was 1.3 times greater and a mean diameter that was 1.4 times larger than the untreated control spruce (Figure 14a, b). Spruce in the blade scarification treatment were only 1.04 times as tall as those in the untreated control, but they had 1.2 times greater diameter. Spruce in the patch scarification treat-

TABLE 15 *Treatment effect[a,b] on white spruce growth in years 5 (1988), 9 (1992), and 25 (2008) at Wonowon*

Variable	Year	MND (1442 stems/ha)[c]	BS (1756 stems/ha)	PS (1677 stems/ha)	VC (1679 stems/ha)	UC (1605 stems/ha)	*p*-value
Height (cm)	5	51 ± 1 a	44 ± 1 ab	41 ± 2 b	55 ± 1 a	43 ± 1 b	**< 0.01**
	9	142 ± 3 a	106 ± 3 b	88 ± 7 b	152 ± 2 a	96 ± 3 b	**< 0.01**
	25	746 ± 27 ab	612 ± 39 bc	557 ± 36 c	844 ± 19 a	587 ± 17 c	**< 0.01**
Diameter (cm)[d]	5	0.9 ± 0.03 a	0.8 ± 0.03 b	0.7 ± 0.03 b	0.9 ± 0.02 a	0.7 ± 0.02 b	**< 0.01**
	9	2.0 ± 0.10 a	1.6 ± 0.10 b	1.3 ± 0.10 b	2.2 ± 0.10 a	1.3 ± 0.00 b	**< 0.01**
	25	10.5 ± 1.00 ab	9.0 ± 0.90 b	7.3 ± 0.90 b	14.0 ± 0.60 a	7.5 ± 0.90 b	**< 0.01**
HDR (cm/cm)[d]	5	59 ± 1 bc	56 ± 1 c	58 ± 1 bc	62 ± 1 ab	63 ± 1 a	**< 0.01**
	9	71 ± 1 b	68 ± 2 b	71 ± 2 b	70 ± 1 b	77 ± 2 a	**< 0.01**
	25	80 ± 7 b	83 ± 12 ab	96 ± 11 ab	63 ± 4 b	113 ± 9 a	**< 0.01**
Volume (cm^3)[d]	5	12 ± 1 a	8 ± 1 b	6 ± 1 b	14 ± 1 a	6 ± 0 b	**< 0.01**
	9	199 ± 15 b	91 ± 12 c	50 ± 14 c	256 ± 21 a	55 ± 1 c	**< 0.01**
	25	36 594 ± 6352 b	25 309 ± 3411 bc	15 7810 ± 3608 c	62 689 ± 4451 a	19 447 ± 3646 bc	**< 0.01**

a Values are presented as the mean of block means ± 1 standard error. *P*-values are based on the ANOVA *F* test for a treatment effect (homogeneous variance model), and those in bold are significant at $p \leq 0.05$. Means assigned the same letter do not differ significantly according to the Bonferroni test.

b MND = mounding; BS = blade scarification; PS = patch scarification; VC = vegetation control; UC = untreated control.

c Values in parentheses are planting densities per hectare (the average of density values calculated for individual plots based on measured plot area).

d Stem diameter was measured as ground-level diameter (GLD) in years 5 and 9, and as diameter at breast height (dbh) (1.3 m height) in year 25. Height-to-diameter ratio (HDR) and tree volume were calculated using GLD in years 5 and 9, and using dbh in year 25. Volume was calculated using the formula for a cone in years 5 and 9, and using a taper equation (Kozak 1988) in year 25.

ment were approximately the same size as those in the untreated control; they were 0.95 times as tall with 0.97 times the diameter (Figure 14a, b). In years 5 and 9, spruce in the vegetation control and mounding treatments had larger stem volume than those in the untreated control, but by age 25, only spruce in the vegetation control treatment continued to be associated with significant stem volume gains over the untreated control (Table 15). At age 25, spruce in the vegetation control treatment had a mean stem volume that was 3.2 times greater than that of untreated control spruce, while mean stem volumes in the mounding and blade scarification treatments were 1.9 and 1.3 times larger, respectively (Figure 14c). Spruce in the patch scarification treatment were slightly smaller than those in the untreated control: mean stem volume was 0.81 times that of the untreated control mean. In year 5, spruce HDR was significantly lower in the mounding, blade scarification, and patch scarification treatments than in the untreated control (Table 15). In year 9, HDR was significantly lower in all treatments than in the untreated control, but by year 25 (when HDR was based on dbh), only trees in the mounding and vegetation control treatments had significantly lower HDR than untreated control spruce.

3.3.3 Stand-level spruce volume at Wonowon In year 25, the vegetation control treatment had significantly greater stand volume than any of the other treatments (Table 16). In that year, the mean stand volume of spruce in the vegetation control and mounding treatments was 4.8 and 2.7 times greater than that in the untreated control, respectively. Stand volume was also more variable in the mounding treatment than in the vegetation control

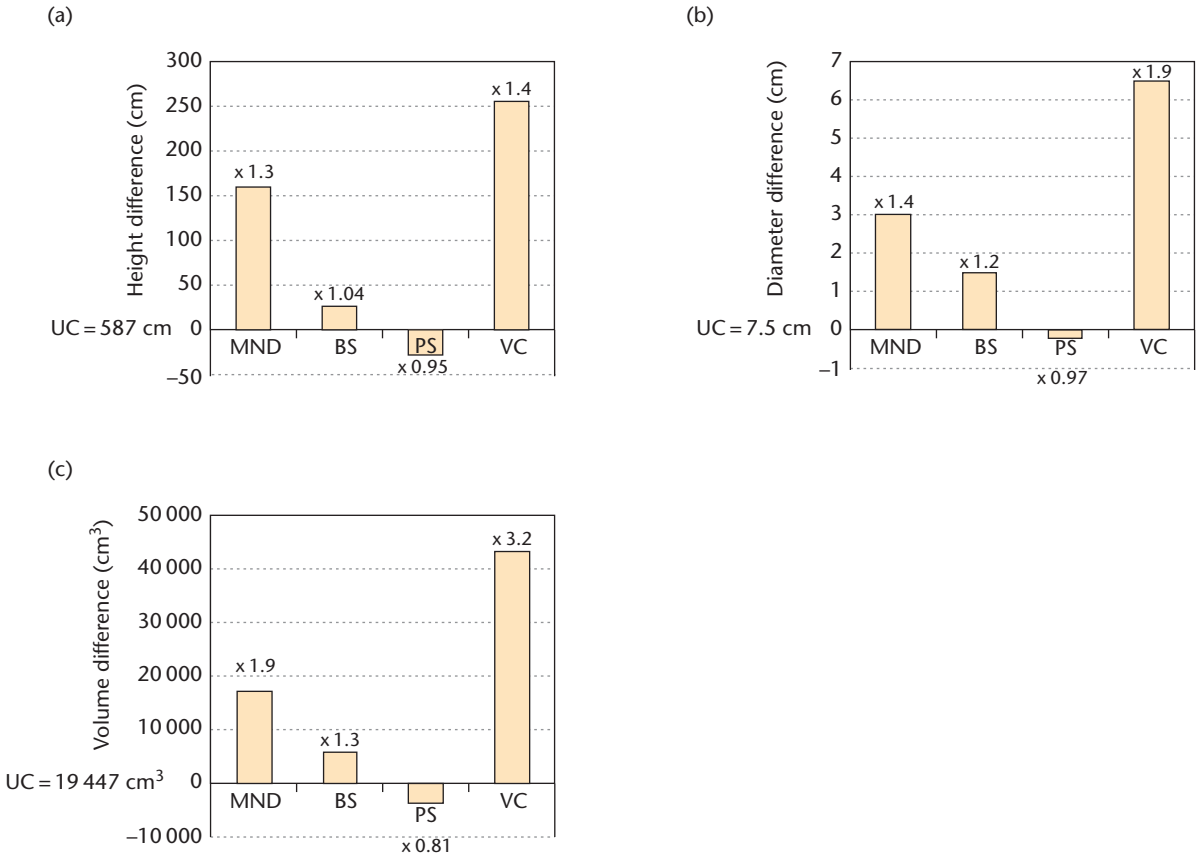

FIGURE 14 *Wonowon year 25 (2008) changes in white spruce (a) height, (b) diameter, and (c) individual tree volume in the mounding (MND), blade scarification (BS), patch scarification (PS), and vegetation control (VC) treatments relative to the untreated control (UC). The mean for the untreated control is represented by "0" on the y-axis. Values above or below individual bars are the ratio of the treatment mean to the untreated control.*

treatment. The vegetation control treatment and the untreated control were assessed again in year 29 (2012) and the difference in stand volume between these treatments continued to be statistically significant (Table 16). In the year 29 assessment, stand volume in the vegetation control treatment was 4.2 times that of the control. Between years 25 and 29, the vegetation control stand increased in volume by 40.5 m^3/ha while the untreated control stand increased by 11.3 m^3/ha, and this difference was also statistically significant. Site index in the vegetation control treatment at Wonowon was estimated to be 23.0 m at age 25 (Table 5), and TIPSY projected that spruce in that treatment would meet a target merchantable volume[6] of 250 m^3/ha at age 50 years (Figure 9).

3.3.4 Year 25 overtopping and competing vegetation In year 25, the proportion of white spruce that were overtopped at Wonowon ranged from 0% in the vegetation control treatment to 67% in the untreated control (Table 17). Trees that were overtopped had, on average, between three and four occupied

6 A typical target merchantable volume is considered to be 250 m^3/ha, based on information provided by Canadian Forest Products Ltd., Fort St. John.

quadrants within a 1-m cylinder. Data for Wonowon were not collected in a way that allowed the presence of overtopping vegetation to be quantified by species, but notes recorded during data collection indicated that the main overtopping species were aspen, birch, and green alder.

TABLE 16 *Treatment effect[a,b] on stand-level white spruce volume and volume increment from years 25 (2008) to 29 (2012) at Wonowon*

Variable	Year	MND (966 stems/ha)[c]	BS (492 stems/ha)	PS (553 stems/ha)	VC (1008 stems/ha)	UC (803 stems/ha)	*p*-value
Stand volume (m^3/ha)	25	35.3 ± 7.5 b	12.8 ± 4.3 c	9.7 ± 5.3 c	64.4 ± 3.3 a	13.3 ± 0.9 bc	**< 0.01**
	29	–	–	–	105.0 ± 4.7 a	24.9 ± 3.1 b	**< 0.01**
Stand volume increment (m^3/ha)	25–29	–	–	–	40.5 ± 1.8 a	11.3 ± 2.3 b	**< 0.01**

a Values are presented as the mean of block means ± 1 standard error. *P*-values are based on the ANOVA *F* test for a treatment effect (homogeneous variance model), and those in bold are significant at $p \leq 0.05$. Means assigned the same letter do not differ significantly according to the Bonferroni test.

b MND = mounding; BS = blade scarification; PS = patch scarification; VC = vegetation control; UC = untreated control.

c Values in parentheses are the density of live target spruce at age 25, calculated as average planting density (across all blocks) multiplied by average year 25 survival.

TABLE 17 *Overtopping at Wonowon in year 25 (2008)*

	Overtopping vegetation presence in 1-m radius cylinder	
Treatment[a]	Proportion of overtopped spruce (%)	Average number of occupied quadrants for spruce having overtopping vegetation
MND	37	3.4
BS	47	3.5
PS	59	3.3
VC	0	n/a
UC	67	3.3

a MND = mounding; BS = blade scarification; PS = patch scarification; VC = vegetation control; UC = untreated control.

4 DISCUSSION

The Inga Lake, Iron Creek, and Wonowon experiments examined white spruce responses to site preparation on backlog sites in the BWBSmw, where the limitations to seedling establishment and early growth were far greater than they are on more recently harvested sites. Under current management approaches, harvested sites are regenerated promptly, and where necessary, competing vegetation is proactively managed. From the perspective of operational management, our results are most applicable to situations where rehabilitation is required following plantation failure, or to other scenarios where there is a desire to establish conifer seedlings on sites with well-developed vegetation.

4.1 Survival

Survival over the 25–26-year assessment period was considerably better at Inga Lake and Iron Creek than at Wonowon, a finding that we attribute to differences in vegetation development at the time of treatment installation and to differences in the type of planting stock that was used. At Wonowon, treatments were applied through a well-developed layer of bluejoint-dominated vegetation, whereas at Inga Lake and Iron Creek, the tall shrub and broadleaf-dominated vegetation had been sheared and piled prior to treatment installation. This difference in initial conditions resulted in considerably lower vegetation abundance immediately following planting at Inga Lake (Bedford and MacKinnon 1996), and presumably also at Iron Creek, than at Wonowon. Stocktype differences were also important; at Wonowon, which is the oldest of the three experiments, bareroot stock was used because container stock had not yet come into common use in northern British Columbia. In contrast, by 1987–1988, the use of better performing container stock (B.C. Ministry of Forests 1998; Thiffault et al. 2003) had become the provincial norm, and that stocktype was used in the Inga Lake and Iron Creek experiments.

At Inga Lake and Iron Creek, at least 89% of container-grown white spruce survived to year 3 in all treatments, including the untreated controls, which suggested at this early stage that beyond shearing and piling, site preparation was not necessary to achieve initial establishment goals. Beyond year 3, however, there was ongoing attrition of poorly growing seedlings in the untreated control and in the low-severity scalping and trenching treatments that exposed little mineral soil. In contrast, survival over 25–26 years was at least 90% in the higher-severity mechanical treatments that created extensive mineral soil exposure, as well as in the chemical site preparation and vegetation control treatments that removed or prevented the re-development of overtopping vegetation. In the low-severity treatments where vegetation recovered rapidly following pre-treatment shearing and site preparation (Bedford and MacKinnon 1996; Haeussler et al. 1999; Boateng et al. 2000), we attribute the gradual ongoing mortality primarily to competition for light. Tall shrub and broadleaf-dominated communities, such as those that dominated the Inga Lake and Iron Creek sites, are highly competitive (Boateng and Comeau 1997b), as was illustrated by data collected at Iron Creek in year 12, when Comeau (2002) recorded understorey (at a height of 1.5 m) light levels as low as 12% in control plots. Although white spruce can survive long periods of reduced light availability (Wright et al. 2000), prolonged exposure to deep shade and the resulting slow growth gradually increases the likelihood of death (Waring 1987; Ruel et al. 2000). It appears that the abundant willow in untreated control plots at Inga Lake also competed with spruce for soil moisture; unpublished microclimate data indicate growing-season soil moisture deficits in some years, which likely compounded the competitive effects on untreated spruce. Repeated clipping damage by hares also contributed to mortality in some treatments at Inga Lake, with damage incidence generally increasing with the abundance of surrounding vegetation. Hare damage was especially prevalent in disc trenches, which the animals apparently used as travel routes (Figure 15). Cyclical hare damage is common where vegetation cover is high enough to provide suitable habitat (Harper et al. 1997; Sullivan 1997; Henigman et al. 2001), and is a frequent management concern in northeastern British Columbia.

In contrast to the good early survival of container stock at Inga Lake and Iron Creek, bareroot spruce at Wonowon sustained extensive mortality within

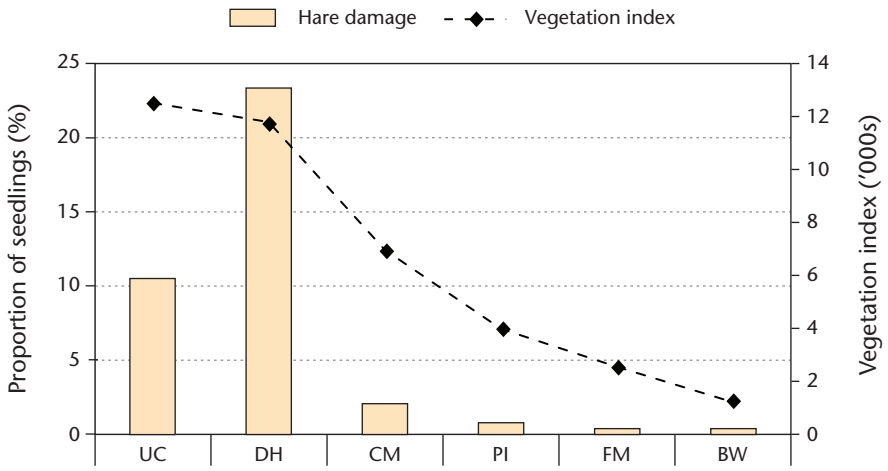

FIGURE 15 *Proportion of live white spruce damaged by hares versus the vegetation index (calculated as described in Appendix 4) at Inga Lake in 1992. UC = untreated control; DH = disc trench hinge; CM = coarse mixing; PI = plow inverting; FM = fine mixing; BW = burned windrows. (The competition index is not presented for the vegetation control treatment because vegetation presence was in flux following glyphosate application.)*

4 months of planting, regardless of site preparation treatment. We ascribe the planting-season losses primarily to the sensitivity of bareroot stock to planting shock and drought (Nilsson and Örlander 1995). Competition from dense bluejoint-dominated vegetation no doubt contributed to these problems in the untreated control and in the vegetation control treatment where glyphosate was not applied until after the first growing season. Beyond year 2, spruce survival stabilized in the vegetation control treatment but continued to decline in the untreated control. This illustrates the importance of reducing vegetation abundance during the establishment period and suggests that, where vegetation is well-developed at the time of planting, glyphosate application may be more effective as site preparation than as a post-planting brushing treatment. Vegetation competition was not the only factor that played a role in early mortality at Wonowon, however, since nearly as many white spruce seedlings died on mounds, where there was good early vegetation control, as died in the untreated control. Mounded soils are subject to drying (Spittlehouse and Stathers 1990), and we suspect that this may have increased stress levels for the drought-sensitive bareroot stock. Other studies have also attributed early mortality of low-vigour spruce planted in mounds to drought, even where the periods of soil moisture deficit were brief (Newsome et al. 2016). Anecdotal comments suggest that poor planting may also have contributed to the mortality of mound seedlings at Wonowon; planters had difficulty penetrating the mineral soil–organic interface in mounds, which resulted in seedling root systems being placed in a curved rather than vertical configuration during planting (known as J-rooting). In the patch scarification treatment at Wonowon, where fewer than half the seedlings survived to year 3, the dry condition of the planting substrate is assumed to have played a role in early mortality. Seedlings in this treatment were planted into

accumulated forest floor material at the edge of the exposed mineral soil patches—the intention was to position them above the moisture-collecting region at the scalp bottoms and to provide developing root systems with access to nutrient-rich humus material; however, the organic material was fragmented and subject to rapid drying. The practice of planting into forest floor accumulations at scalp edges is common where this treatment is used on boreal sites with adequate moisture (Bassman 1989; von der Gönna 1992), but it was apparently unsuitable at Wonowon where the forest floor was thin (4–6 cm) and little organic material was gathered by the machine. Of all the treatments at Wonowon, survival was lowest in the blade scarification treatment; early mortality in this treatment was attributed mainly to severe frost heaving, and in localized areas, to poorly drained conditions, both of which are common problems on northern sites with fine-textured soil (Örlander et al. 1990). Beyond year 2, bareroot spruce survival at Wonowon was relatively stable in the mounding and vegetation control treatments, which substantially reduced the abundance of overtopping vegetation. In contrast, there were ongoing, gradual losses until at least year 10 in the untreated control, as well as in the blade and patch scarification treatments where vegetation overhung the scalp edges. Green alder regenerated abundantly from seed in the exposed mineral soil of the blade scarification treatment (Appendix 4), eventually creating a dense overstorey that likely exacerbated survival problems.

Lodgepole pine is a recommended regeneration species for zonal sites in the BWBSmw (B.C. Ministry of Forests 2000), but it was not the focus of these experiments. It was examined only on untreated plots at the Iron Creek site, and even there, its inclusion was primarily for demonstration purposes related to concerns about the amount of lodgepole pine that was currently (late 1980s) being planted without site preparation in the BWBS zone. Pine planted into untreated ground at Iron Creek exhibited slow, steady declines in survival over the 20 years they were assessed, which we attribute to a combination of early hare damage and light competition from the heavy cover of aspen and green alder.

4.2 Growth

During the 1980s, when the Inga Lake, Iron Creek, and Wonowon experiments were initiated, there was considerable interest in microclimatic effects on seedling growth. Other studies in boreal regions were demonstrating that mechanical site preparation could relieve cold, wet soil conditions, reduce bulk density, improve soil nutrient status, and improve the above-ground thermal regime at seedling height (Coates and Haeussler 1990; Örlander et al. 1990; Stathers and Spittlehouse 1990). Vegetation control was also an important consideration in early studies, but the focus was on treatment effects during the establishment period rather than effects that persisted over the long term (Biring et al. 1996). During the first 10 years of our experiments, results were consistent with the expectation that enhancing growing conditions through mechanical disruption of soil in the rooting zone would enhance white spruce growth. By year 15, however, it was apparent that lasting reduction in the abundance of overtopping vegetation was also an important consideration, and that growth responses in the chemical site preparation or vegetation control treatments where soil had not been disrupted were at least as good as those in the most aggressive mechanical treatments (Macadam and Kabzems 2006). White spruce is moderately

shade-tolerant (Klinka et al. 2000), but growth rates, especially in diameter, generally increase with increasing light availability (Coates et al. 1994). In our studies, there was an obvious inverse relationship between mean spruce stem volume in the various treatments and the proportion of trees that were overtopped at age 25–26 (Figure 16). This strongly suggests that lasting vegetation control was a more important factor at these backlog sites than early microsite manipulation. This is particularly true of the Inga Lake site, where vegetation dominated by willow quickly overtopped planted spruce in the untreated control (Appendix 4), and continued to do so in year 25.

At Inga Lake and Iron Creek, plow inverting, fine mixing, and coarse mixing treatments that disturbed nearly 100% of the soil surface were associated with significant gains in spruce height and diameter relative to the untreated controls as early as year 5. At Inga Lake, early spruce growth responses in these treatments were associated with reductions in soil bulk

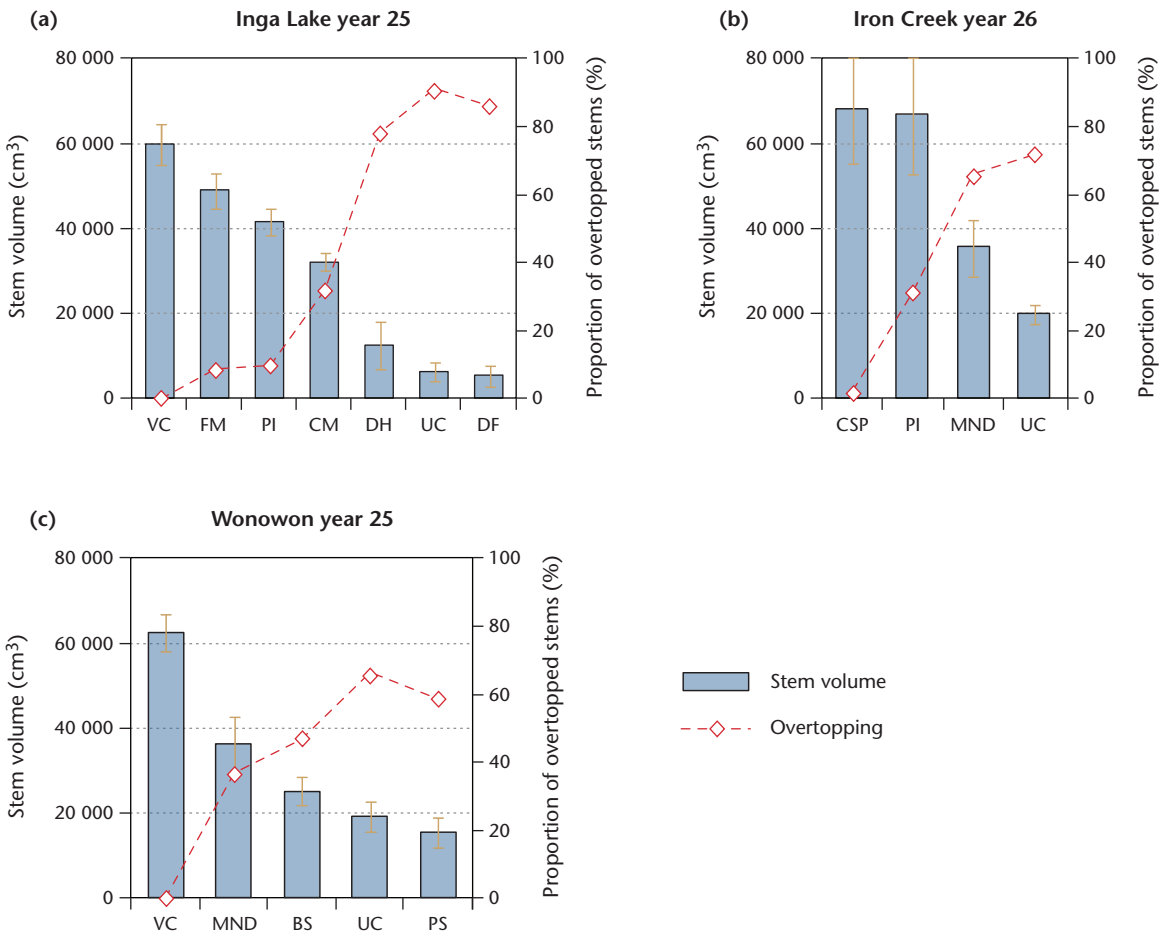

FIGURE 16 *White spruce stem volume and proportion of overtopped stems in (a) year 25 (2012) at Inga Lake, (b) year 26 (2012) at Iron Creek, and (c) year 25 (2008) at Wonowon. Treatments are arranged in order of decreasing stem volume. Error bars are ± 1 standard error. VC = vegetation control; FM = fine mixing; PI = plow inverting; CM = coarse mixing; DH = disc trench hinge; UC = untreated control; DF = disc trench furrow; CSP = chemical site preparation; MND = mounding; BS = blade scarification; PS = patch scarification.*

density and improvements in soil nutrient status (Macadam and Kabzems 2006). Warmer, better drained conditions in the rooting zone (Stathers and Spittlehouse 1990) no doubt also contributed to the ability of spruce seedlings in these treatments to respond in advance of seedlings planted into undisturbed soil in the chemical site preparation or vegetation control treatments. To varying degrees, the mechanical site preparation treatments also exerted lasting control over competing vegetation, which reduced the proportion of white spruce that were overtopped in year 25–26. Fine mixing and plow inverting accomplished this to a greater extent than coarse mixing, probably because they were more effective at reducing willow and alder presence (Appendix 4). At Inga Lake, where almost all untreated spruce continued to be overtopped at age 25 by willow that was, on average, 3–4 m taller, the fine mixing, plow inverting, and coarse mixing treatments were associated with 8-fold, 7-fold, and 5-fold gains in stem volume, respectively. At Iron Creek, where about three-quarters of untreated spruce continued to be overtopped at age 26, the plow inverting treatment was associated with a 3-fold increase in stem volume (fine mixing and coarse mixing treatments were not applied at Iron Creek).

Mounding, which is a less aggressive treatment than mixing or plowing, was associated with 2-fold gains in stem volume relative to untreated 26- and 25-year-old spruce at Iron Creek and Wonowon, respectively. The size of spruce growing on mounds was highly variable, however, and the gains were not statistically significant in any of the assessment years at Iron Creek, and not past year 9 at Wonowon. Mounding disturbs 10–30% of the surface area (von der Gönna 1992), thereby combining localized vegetation control with improved conditions for root growth (Draper et al. 1985; Örlander et al. 1990; Hallsby 1995). In our studies, responses to mounding appeared to decline as root systems extended beyond the area affected by the treatment and as vegetation that surrounded mounds increased in stature. At age 26, approximately two-thirds of the spruce trees in the mounding treatment at Iron Creek were overtopped by tall shrubs and broadleaf trees, while only one-third of the 25-year-old mound-planted spruce at Wonowon were overtopped, mainly by the birch, aspen, and alder that grew in scattered patches throughout the grass-dominated community. It has generally been supposed that large mounds are more effective than small mounds, particularly on sites with a high water table (von der Gönna 1992) and where vegetation competition is very limiting (McMinn and Hedin 1990). However, an earlier analysis of the Wonowon data that included a larger range of mounding treatments (described in Appendix 1) than we included in this report showed that, while all sizes of mounds tended to be associated with spruce growth increases relative to the untreated control, statistically significant growth differences between large and small mounds were no longer evident by year 20 (Boateng et al. 2006).

In contrast to mounding, plowing, and mixing, low-intensity mechanical treatments, such as trenching and patch scarification, did not appear to improve spruce growth in the short or longer term. These treatments apparently had little positive effect on the rooting zone micro-environment and did not exert lasting control over tall shrub-dominated vegetation at Inga Lake or bluejoint-dominated vegetation at Wonowon (Figure 16); the patch scarification treatment at Iron Creek was not assessed in year 26, but surviving spruce

were subjectively observed to be heavily overtopped. In fact, spruce in the patch scarification and disc trench furrow treatments that were variously carried out at the three sites showed (non-significant) trends in reduced growth relative to the untreated controls for the first 5 years after planting. Although blade scarification is a high-severity form of site preparation, it did not improve growth relative to the untreated control at Wonowon; poor seedling growth in exposed fine-textured mineral soil could be related to high soil density, poor aeration, frost heaving, or inadequate drainage effects on root egress. In year 12, Heineman et al. (1999) reported that most of the main lateral roots on spruce trees in the untreated control at Wonowon were growing in forest floor material, with fewer than half of them penetrating upper mineral soil horizons. Thiffault et al. (2003) likewise reported neutral to slightly negative effects as a result of scalping, and noted that on boreal sites, scarification is mainly intended to increase soil temperature and is most effective on sites that have a thick humus layer, which was not the case at our research sites.

Vegetation control, whether conducted as chemical site preparation (Iron Creek) or post-planting brushing (Inga Lake and Wonowon), was associated with 25- to 26-year spruce growth responses that were at least as large as those resulting from the most effective mechanical treatments. We attribute this finding to the early elimination of overtopping vegetation and the longevity of this effect (Figure 16). Sutton (1995) similarly reported that vegetation control had positive effects on white spruce growth that persisted for up to three decades, and other shorter-term studies have also demonstrated that early vegetation control is necessary for optimizing spruce growth on boreal sites (e.g., Harper et al. 1997; Cole et al. 1999). In our studies, growth gains of spruce in the chemical site preparation or vegetation control treatments relative to those in the untreated controls were largest at Inga Lake, where there was an approximate 9-fold increase in mean stem volume at age 25. The large gains at that site were realized even though brushing did not occur until after the third growing season. According to Wagner et al. (1999), vegetation control during the first 3 years after planting is critical to achieving good growth, which suggests that growth gains relative to the untreated control at Inga Lake may have been even larger if brushing had been done sooner. The small size of 5-year-old spruce in the vegetation control treatment at Inga Lake, along with anecdotal comments regarding their poor condition prior to brushing, supports that assumption. Chemical site preparation at Iron Creek and chemical brushing after the first growing season at Wonowon both provided earlier control of vegetation than occurred at Inga Lake, and were more consistent with the recommendations of Wagner et al. (1999).

The initial chemical brushing treatment applied at Inga Lake had low efficacy because willow had been defoliated by insects in the year of application; to compensate for this, follow-up manual cutting treatments were applied to simulate a highly effective chemical brushing treatment. Our experiments were not designed to allow for statistical comparison of spruce growth responses to chemical site preparation versus post-planting chemical brushing across the three sites, so we cannot comment on whether glyphosate, when it has high efficacy, is more effective as site preparation or as brushing. However, in another study that was conducted using hybrid spruce on high-elevation sites in south-central British Columbia, the two approaches produced nearly the same spruce growth responses (Newsome

7 B.C. Ministry of Forests, Lands and Natural Resource Operations RESULTS database (May 2014).

et al. 2016). In contrast, Wood and von Althen (1993) concluded that glyphosate controlled vegetation more effectively when it was used for site preparation rather than for post-planting vegetation control. Differences in the outcomes could be related to differences in the stage of development of the plant communities or to the autecology of the particular plant species. In spite of its positive effects on spruce growth, chemical site preparation has been used on only about 2% as much area in the BWBS zone of British Columbia as has been treated by mechanical methods.[7]

4.3 Stand-level Growth Response

In all three of our experiments, vegetation control, whether it was achieved through chemical site preparation or post-planting brushing, was associated with significant gains in total white spruce volume per hectare at age 25–26 compared with the corresponding untreated controls. Gains in stand volume relative to controls generally reflected individual tree volume responses and were largest (approximately 10-fold) at Inga Lake where the control trees continued to be suppressed by the dense overtopping canopy of willow and scattered aspen. At Iron Creek and Wonowon, where a lesser proportion of untreated control spruce were overtopped (Figure 16), chemical site preparation and post-planting vegetation control resulted in 4- to 5-fold gains over the untreated controls, respectively. Plow inverting and fine mixing at Inga Lake resulted in relative stand volume gains over the untreated control that were of similar magnitude to the vegetation control treatment, whereas gains associated with coarse mixing were somewhat smaller. At both Iron Creek and Wonowon, stands resulting from the mounding treatments had, after 25–26 years, approximately twice the volume of the corresponding untreated control stands. In our studies, individual tree volume and density differences arising from variable planting density and differing survival responses contributed to stand volume outcomes. Ideally, in growth and yield studies, treatments would include density as an independent variable or a controlled design factor. Although there was an intention to have homogeneous density across the treatment plots in our experiments, it proved impossible to adequately control this factor because of the operational restrictions associated with treatment application, the spatial configuration of different treatments, and the difficulty of adjusting planting spacing to accommodate those factors. Treatment effects on survival may have made a small contribution to 25- to 26-year stand volume outcomes at Inga Lake and Iron Creek, but were more important at Wonowon, where high mortality during the establishment period resulted in year 25 densities that were as low as 553 stems/ha.

Site index, when determined from the growth of healthy, unimpeded trees, is a measure of potential site productivity (Stearns-Smith 2001). The site index values of 23–24 m that were estimated for our study sites, based on spruce growth to age 25 or 26 in the unimpeded chemical site preparation or vegetation control treatments, are somewhat higher than the average estimate of 21 m for zonal sites in the BWBSmw as a whole (B.C. Ministry of Forests, Lands and Natural Resource Operations 2013b). The TIPSY projections suggest that white spruce in these treatments will meet a target merchantable volume of 250 m^3/ha at age 47–50 years (Figure 9), which implies that they would be suitable to harvest in about 2034—approximately when the mid-term timber supply shortage is predicted to begin (B.C. Ministry of Forests, Lands and Natural Resource Operations 2012). We chose not

7 B.C. Ministry of Forests, Lands and Natural Resource Operations RESULTS database (May 2014).

to present growth projections for impeded spruce in the other treatments because TASS and TIPSY are not designed to model the growth of suppressed trees. In an earlier (year 19) attempt to address this limitation, a customized TASS run used the assumption that control spruce at the Inga Lake site would continue to increase in height at their current (year 19) rate and would outgrow willow at age 26 (Boateng et al. 2009). This supposition was clearly incorrect since, after 25 years, the 7- to 8-m tall willow continued to overtop white spruce by approximately 3 m. We now estimate that if untreated control spruce continue to increase in height at the rate expressed in year 25 (data not presented), they will grow through the willow canopy, on average, at age 37 years.

4.4 Intense-burn Effects

Localized pile and burn treatments, of which burned windrows are an example, potentially affect about 4% of BWBS zone area that has been harvested and regenerated to spruce since 1980.[8] At Inga Lake, burned windrows occupied about 10% of the cutblock. Spruce planted into the burned swathes consistently had significantly greater height and diameter than those in the untreated control, which translated into an almost 9-fold increase in individual tree stem volume at age 25. Such growth responses are likely related to the lasting effects that the intense burn had on soil characteristics. In particular, burned windrow soils at Inga Lake had significantly higher pH than control soils for at least 15 years (Macadam and Kabzems 2006). In a related study, Boateng et al. (2010) similarly reported increases in soil pH and the availability of calcium, potassium, and boron, which persisted in burned windrows for at least two decades. It is important to remember that the intense-burn effects of localized pile and burn treatments are different from those produced by broadcast burning. Even where broadcast burning is severe, it results in relatively minor long-term increases in soil pH and nutrient availability on sub-boreal sites (Kranabetter and Macadam 1998). From a management perspective, the rapid, prolonged growth response of spruce in burned windrows at Inga Lake suggests that careful management of localized areas affected by intense burning can positively contribute to long-term stand volume.

4.5 Management Implications and Conclusions

When the Inga Lake, Iron Creek, and Wonowon studies were established in the 1980s, the Province of British Columbia was in the process of switching from bareroot to container stock as the operational norm. Our finding that far better survival was achieved with the container stock used at Inga Lake and Iron Creek than the bareroot stock used at Wonowon supports that transition. Year 5 survival rates at Inga Lake and Iron Creek demonstrate that container-grown white spruce is easily established on zonal sites in the BWBSmw, even without site preparation. Despite the gradual mortality that subsequently occurred up to year 25–26 in the control, the current target stocking of 1200 stems/ha (B.C. Ministry of Forests 2000) could have been met by increasing the planting density to 1600 stems/ha at those sites. Nevertheless, free-growing objectives would not have been met without either high-severity site preparation or post-planting brushing. Free-growing surveys are generally conducted when trees are about 10–12 years old, and although spruce were well above the 1-m minimum height (B.C. Ministry of Forests 2000) at that age, vegetation data (collected at Inga Lake, as de-

8 B.C. Ministry of Forests, Lands and Natural Resource Operations RESULTS database (May 2014).

scribed in Appendix 4) suggest that most untreated spruce would not have met the competing vegetation criterion of 150% conifer:brush ratio. At Wonowon, due to the early steep survival declines of bareroot stock, it is doubtful that even minimum stocking requirements could have consistently been met by any of the treatments.

White spruce in chemical site preparation, vegetation control, or high-severity mechanical site preparation treatments at Inga Lake, Iron Creek, and Wonowon exhibited large increases in growth relative to controls; however, when relating these results to current practice, it is important to bear in mind that these were backlog NSR sites with greater potential for vegetation competition than is likely to be encountered on newly harvested sites. It should also be remembered that mixing and plowing treatments that disturb nearly 100% of the ground surface cannot be used on operationally harvested sites with mature tree stumps. Use of these treatments was possible at the Inga Lake and Iron Creek sites only because existing vegetation, including immature broadleaf and coniferous trees, had previously been sheared and piled. This procedure left small-diameter, relatively shallow stumps that were not an impediment to the machinery used for mixing and plowing. Nonetheless, mixing and plowing treatments were worth considering during the era when reducing the backlog of NSR sites had high priority, and they may still be appropriate in situations where site rehabilitation is required.

For zonal BWBSmw sites with well-developed vegetation, where improving conifer growth is the objective, we recommend mounding over other commonly available mechanical techniques, such as disc trenching or scalping. The low-intensity disc trenching and patch scarification treatments were ineffective at enhancing white spruce establishment and growth under the backlog conditions at our research sites; however, these treatments are commonly used in the BWBS zone on sites that are regenerated promptly following harvest,[9] and they are considered to be effective under these conditions. Although higher-severity mixing and plowing treatments produced larger growth responses than mounding in our studies, as we describe above, these treatments are not suitable for use on operationally harvested sites. Glyphosate applied as either a site preparation or post-planting vegetation control treatment was also highly effective, and depending on site characteristics, may be a more cost-effective option than mechanical preparation. Where the use of glyphosate is considered for current sites, applying it as a brushing treatment rather than as site preparation is likely the more judicious approach because it allows the extent of vegetation development to be assessed prior to treatment, thereby avoiding the risk of unnecessary herbicide application.

The backlog conditions that were an important forest management issue when the Inga Lake, Iron Creek, and Wonowon experiments were initiated have, for the most part, been addressed. To a large degree, this was accomplished through the use of site preparation treatments such as those described in this report. Furthermore, since aspen is now an important timber supply species under mixedwood management scenarios in boreal regions of British Columbia, a site such as Iron Creek would not require rehabilitation under current approaches to forest management. Although several of the treatments we report on have limited applicability under current management conditions, the data have other potential uses. For example, as growth and yield modelling tools that are commonly used in

9 B.C. Ministry of Forests, Lands and Natural Resource Operations RESULTS database (May 2014).

British Columbia become more sophisticated in their ability to model the development of overtopped and mixedwood stands, these long-term data sets will potentially be useful for calibration and verification work. It is also important that we can accurately predict the effects that various damaging agents have on future forest yield and wood quality. Damage to white spruce tops and stems was common at our research sites, but most trees appeared to recover over time; ongoing assessment of these sites will allow us to quantify the effects that various damage types have on long-term growth and to refine the way these defects are incorporated into growth and yield modelling tools. The challenges facing forest managers are constantly changing, and well-designed and maintained experimental projects such as those described in this report can be adapted to address a wide range of issues.

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APPENDIX 1 Treatments that were tested in the Inga Lake, Iron Creek, and Wonowon experiments but not included in this report

Additional treatments at Inga lake

Treatment	Treatment type	Machinery	Description (all mechanical treatments were conducted in September 1987, and planting was done in spring 1988)
Single tuttle plow	Plowing	WIT divider plow (modified breaking plow on which the plow shares were extended to allow furrow slices to slide off onto adjacent soil—developed by Wayne and Iva Tuttle [WIT])	Single furrow slices were deposited onto the undisturbed forest floor adjacent to a single side of each trench. The furrow slices were approximately 30-cm wide with a 15-cm deep capping of mineral soil. White spruce were deeply planted to 5 cm above the root collar.
Double tuttle plow	Plowing	As above	Furrow slices were placed on either side of each trench by running machine lines sufficiently close that, on the return pass, a second furrow slice could be deposited next to the slice that had been deposited on the outward pass. This resulted in "side-by-side" slices, each of which was approximately 30-cm wide with a 15-cm deep mineral soil cap. White spruce were deeply planted to 5 cm above the root collar.
Mineral mound	Mounding	None	Mineral mounds were hand-constructed in the centre of furrows made by the TTS Delta trencher. Approximately 20 L of mineral soil from the furrow were used to fill a 40 × 40 cm frame to a depth of 14 cm. The result was mineral soil mounds overlying mineral soil. White spruce seedlings were planted slightly below the root collar in the centre of the mounds.

Additional treatments at Iron Creek

Treatment	Treatment type	Machinery	Description (all mechanical treatments were conducted in July 1986, and planting was done in spring 1987)
Bräcke mound	Mounding	Bräcke mounder with a 3-tined mattock wheel	Mounds averaged 29 cm wide × 29 cm long × 29 cm high. The depth of mineral capping ranged from < 3 cm to 6 cm. White spruce seedlings were planted to the root collar.
Bräcke patch + fertilizer	Scalping	Bräcke scarifier with a 3-tined mattock wheel	Patches of exposed mineral soil averaged 60–80 cm long. White spruce seedlings were planted to the root collar in mineral soil, just below the hinge of accumulated forest floor material at the scalp edge. Seedlings were immediately fertilized with 30 g of 26-week 18-6-10 Osmocote®.
Sinkkila mound	Mounding	Sinkkila HMF scarifier mounted on a John Deere 740A line-skidder	Mounds were prepared in a single pass operation; 24% of the mounds were capped by 3–5 cm of mineral soil, 26% by 6–9 cm of mineral soil, 18% by 10–13 cm of mineral soil, and 14% by 5 cm or more of well-decomposed organic matter; the other mounds were more thinly capped. White spruce seedlings were planted on the sloped side of each mound.
Sinkkila mound + fertilizer	Mounding	As above	Mounds were prepared as described above for the Sinkkila mounding treatment and had similar characteristics. Seedlings were planted on the sloped side of each mound and were immediately fertilized within a 15-cm radius with 30 g of 26-week 18-6-10 Osmocote®.

Additional treatments at Wonowon

Treatment	Treatment type	Machinery	Description (all mechanical treatments were conducted in August 1983, and planting was done in June 1984)
Bräcke mound + 2-cm (or Plus 2)	Mounding	Bräcke mounder with a 4-tined mattock wheel towed by a D7 crawler	The Bräcke mounder created mounds with an average of 1–2 cm mineral soil capping. There was no mineral soil supplementation. Seedlings were planted in the mound centre, to a depth that allowed root systems to have contact with organic material beneath the mineral cap.
Bräcke mound + 6-cm (or Plus 6)	Mounding	As above	Bräcke mounds were manually supplemented with mineral soil to create a 6-cm deep mineral soil cap. Seedlings were planted in the mound centre, to a depth that allowed root systems to have contact with organic material beneath the mineral cap.
Bräcke mound + 20-cm (or Plus 20)	Mounding	As above	Bräcke mounds were manually supplemented with mineral soil to create a 20-cm deep mineral soil cap. Seedlings were planted in the mound centre, to a depth that allowed root systems to have contact with organic material beneath the mineral cap.
Large stock	None	None	No site preparation and no soil disturbance. Container white spruce stock that had been grown in the nursery for 1 year and then transplanted to nursery beds where it was grown for an additional 2 years (PBR 1+2) was used. Whereas the standard bareroot stock used in the rest of the study was typically 30–50 cm tall with 5–8 mm diameter, this stocktype was typically 40–60 cm tall with 6–12 mm diameter. Seedlings were planted to the root collar without screefing.

APPENDIX 2 Plot size determination at Inga Lake, Iron Creek, and Wonowon

Plot sizes were determined in 2006 for all three sites. At Inga Lake and Iron Creek, distance was measured along each side of the shape that enclosed the inner 48 (measurement) target trees. The area inside the shape was calculated using basic geometric principles. Each set of inner 48 trees was assumed to also occupy a 1.5-m wide area around the shape (on the assumption that tree rows were, on average, 3 m apart); 1.5 × 1.5 m was added for each of the corner areas. Therefore, this perimeter area was calculated as the perimeter length multiplied by 1.5 m plus a 1.5 × 1.5 m area for each outer corner. If the shape involved inner corners, a 1.5 × 1.5 m area for each inner corner was subtracted from the total area.

At Wonowon, the same approach was used to determine plot areas, except that measured areas included all 80 planted trees in each plot. For the vegetation control treatment, where only the inner 48 trees were measured (those that received post-planting spot glyphosate application), a multiplier of 0.6 (48 trees/80 trees) was applied to the calculated area.

Inga Creek plot areas and numbers of inner trees

		Block A			Block B			Block C			Block D			Block E		
Treatment	**Alternate treatment name[a]**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**
Plow inverting	Breaking plow	A7	0.032	48	B5	0.030	48	C7	0.046	48	D8	0.038	48	E3	0.026	48
Fine mixing	Madge	A8	0.033	48	B4	0.037	48	C1	0.035	48	D6	0.028	48	E5	0.037	48
Coarse mixing	Bedding plow	A6	0.033	48	B8	0.032	48	C3	0.046	48	D3	0.039	48	E2	0.036	48
Disc trench hinge	Delta hinge	A1	0.042	48	B6	0.044	48	C4	0.044	48	D7	0.052	48	E4	0.039	48
Disc trench furrow	Delta furrow	A5	0.036	48	B3	0.039	48	C6	0.023	48	D5	0.038	48	E6	0.037	48
Vegetation control	Herbicide	A2	0.040	48	B1	0.035	48	C5	0.038	48	D4	0.025	48	E1	0.036	48
Burned windrow	Fire	AF	0.041	48	BF	0.043	48	CF	0.041	48	DF	0.041	48	EF	0.038	48
Untreated control	Untreated	A3	0.032	48	B7	0.028	48	C8	0.041	48	D1	0.036	48	E7	0.034	48
	Single tuttle plow	A4	0.033	48	B2	0.031	48	C2	0.031	48	D2	0.031	48	E8	0.036	48
	Double tuttle plow	A4	0.044	60	B2	0.048	60	C2	0.047	60	D2	0.014	30	E8	0.017	30
	Mineral mound[b]	(A5)	–	–	(B3)	–	–	(C6)	–	–	(D5)	–	–	(E6)	–	–

a Treatment name commonly used in analysis output and older reports.

b Mineral mounds were constructed in furrow bottoms of Delta trenches that were adjacent to (not within) the Delta furrow plot in each block.

Iron Creek plot areas and numbers of inner trees

		Block A			Block B			Block C			Block D			Block E		
Treatment	**Alternate treatment name[a]**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**
Plow inverting	Breaking plow	A1	0.061	48	–	–	–	–	–	–	D4	0.054	48	–	–	–
		A2	0.044	48	–	–	–	–	–	–	D5	0.047	48	–	–	–
Mounding	Ministry mound	A10	0.053	48	B9	0.043	48	C9	0.048	48	D7	0.036	48	E1	0.041	48
Patch scarification	Bräcke patch	A9	0.049	48	B3	0.041	48	C5	0.043	48	D1	0.042	48	E4	0.046	48
Chemical site preparation	Herbicide	A8	0.049	48	B2	0.052	48	C11	0.039	48	D3	0.060	48	E11	0.052	48
Untreated control	Untreated	A11	0.042	48	B5	0.046	48	C8	0.037	48	D11	0.043	48	E3	0.045	48
Untreated control with lodgepole pine	Alternate stock	A3	0.056	48	B1	0.043	48	C10	0.046	48	D10	0.044	48	E7	0.043	48
	Bräcke mound	A6	0.045	48	B6	0.047	48	C3	0.052	48	D6	0.039	48	E8	0.045	48
	Bräcke patch + fertilizer	A7	0.053	48	B4	0.042	48	C4	0.042	48	D2	0.050	48	E2	0.047	48
	Sinkkila mound[b]	A5	–	–	B10	–	–	C1	–	–	D9	–	–	E10	–	–
	Sinkkila mound + fertilizer	A4	–	–	B11	–	–	C2	–	–	D8	–	–	E9	–	–

a Treatment name commonly used in analysis output and older reports.

b Referred to as Sinkkila patch in some documents, but the reason for this is not clear.

Wonowon plot areas and numbers of inner trees

		Block A			Block B			Block C			Block D			Block E		
Treatment	**Alternate treatment name[a]**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**	**Plot**	**Area (ha)**	**Inner trees**
Mounding	Bräcke mound + 14-cm (or plus 14)	A3	0.058	80	–	–	–	C3	0.046	80	D3	0.058	80	E3	0.063	80
Blade scarification	Blade	A5	0.041	80	–	–	–	C5	0.049	80	D5	0.060	80	E5	0.038	80
Patch scarification	Bräcke patch (or Hinge)	A4	0.039	80	–	–	–	C4	0.051	80	D4	0.049	80	E4	0.055	80
Vegetation control[b]	Herbicide	A9	0.048	48	–	–	–	C9	0.044	48	D9	0.055	48	E9	0.045	48
Untreated control	Untreated	A7	0.047	80	–	–	–	C7	0.057	80	D7	0.045	80	E7	0.052	80
	Bräcke mound + 2-cm (or plus 2)	A2	0.047	80	–	–	–	C2	0.053	80	D2	0.051	80	E2	0.038	80
	Bräcke mound + 6-cm (or plus 6)	A1	0.038	80	–	–	–	C1	0.054	80	D1	0.047	80	E1	0.052	80
	Bräcke mound + 20-cm (or plus 20)	A6	0.043	80	–	–	–	C6	0.038	80	D6	0.052	80	E6	0.060	80
	Untreated large stock	A8	0.049	81	–	–	–	C8	0.049	80	D8	0.046	80	E8	0.045	80

a Treatment name commonly used in analysis output and older reports.

b The area measured for the vegetation control plots was for 80 trees (48 measured trees + 32 buffer trees). When area-based volume calculations were made for this treatment, a multiplier of 0.6 (48/80) was applied to the measured area.

Complete record of height and diameter[a] measurements at Inga Lake

Treatment	Block	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Year after planting[b]		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Plow inverting	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
Fine mixing	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
Coarse mixing	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x					x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x					x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x					x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x					x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x					x	x
Disc trench hinge	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x	x
Disc trench furrow	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
Vegetation control	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
Burned windrow	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x			x	x	x
Untreated Control	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x	x	x	x	x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x	x	x	x	x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x	x	x	x	x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x	x	x	x	x	x

Table continues

Complete record of height and diameter measurements at Inga Lake (continued)

Treatment	Block	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Year after planting		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Single tuttle plow	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					x				x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					x				x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					x				x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					x				x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					x				x	
Double tuttle plow	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
Mineral mound	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	C	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x
	E	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									x	x

a Diameter was measured at ground-level (GLD) from 1988 to 2006, and at a height of 1.3 m (diameter at breast height [dbh]) from 2006 to 2012 (both were measured in 2006).

b Seedlings were planted in spring 1988, so year 1 growth was also considered to have occurred in 1988.

Complete record of height and diameter[a] measurements at Iron Creek

Treatment	Block	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Year after planting[b]		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Plow inverting	A	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x						x
	D	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x						x
Mounding	A	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x						x
	B	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x						x
	C	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x						x
	D	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x						x
	E	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x						x
Patch scarification	A	x	x	x		x	x	x		x	x										x						
	B	x	x	x		x	x	x		x	x										x						
	C	x	x	x		x	x	x		x	x										x						
	D	x	x	x		x	x	x		x	x										x						
	E	x	x	x		x	x	x		x	x										x						
Chemical site preperation	A	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x	x		x	x			x	x	x
	B	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x	x		x	x			x	x	x
	C	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x	x		x	x			x	x	x
	D	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x	x		x	x			x	x	x
	E	x	x	x		x	x	x		x	x	x	x	x	x	x	x	x	x		x	x			x	x	x
Untreated control	A	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x	x			x	x	x
	B	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x	x			x	x	x
	C	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x	x			x	x	x
	D	x	x	x		x	x	x		x	x	x	x	x	x	x	x				x	x			x	x	x
	E	x	x	x		x	x	x		x	x	x	x	x	x	x	x		x		x	x			x	x	x
Untreated control with lodgepole pine	A	x	x	x		x	x	x		x	x										x						
	B	x	x	x		x	x	x		x	x										x						
	C	x	x	x		x	x	x		x	x										x						
	D	x	x	x		x	x	x		x	x										x						
	E	x	x	x		x	x	x		x	x										x						
Bräcke mound	A	x	x	x		x	x	x		x	x										x						
	B	x	x	x		x	x	x		x	x										x						
	C	x	x	x		x	x	x		x	x										x						
	D	x	x	x		x	x	x		x	x										x						
	E	x	x	x		x	x	x		x	x										x						
Bräcke patch + fertilizer	A	x	x	x		x	x	x		x	x										x						
	B	x	x	x		x	x	x		x	x										x						
	C	x	x	x		x	x	x		x	x										x						
	D	x	x	x		x	x	x		x	x										x						
	E	x	x	x		x	x	x		x	x										x						

Table continues

Complete record of height and diameter measurements at Iron Creek (continued)

Treatment	Block	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Year after planting		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Sinkkila mound + fertilizer	A	x	x	x		x	x	x		x	x																
	B	x	x	x		x	x	x		x	x																
	C	x	x	x		x	x	x		x	x																
	D	x	x	x		x	x	x		x	x																
	E	x	x	x		x	x	x		x	x																
Sinkkila mound	A	x	x	x		x	x	x		x	x																
	B	x	x	x		x	x	x		x	x																
	C	x	x	x		x	x	x		x	x																
	D	x	x	x		x	x	x		x	x																
	E	x	x	x		x	x	x		x	x																

a Diameter was measured at ground-level (GLD) from 1987 to 2006, and at a height of 1.3 m (diameter at breast height [dbh]) from 2006 to 2012 (both were measured in 2006). Grey-shaded cells indicate years in which diameter was not assessed.

b Seedlings were planted in spring 1987, so year 1 growth was also considered to have taken place in 1987.

Complete record of height and diameter[a] measurements at Wonowon

Treatment	Block	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Year after planting[b]		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Mounding (aka Bräcke mound + 14-cm mineral cap)	A	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	C	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	D	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	E	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
Blade scarification	A	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	C	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	D	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	E	x	x	x	x	x	x			x	x	x		x	x	x										x				
Patch scarification	A	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	C	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	D	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	E	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
Vegetation control	A	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x
	C	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x
	E	x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x
Untreated control	A	x	x	x	x	x	x			x	x	x	x	x	x	x		x	x	x	x	x	x			x			x	x
	C	x	x	x	x	x	x			x	x	x	x	x	x	x		x	x	x	x	x	x			x			x	x
	D	x	x	x	x	x	x			x	x	x	x	x	x	x		x	x	x	x	x	x			x			x	
	E	x	x	x	x	x	x			x	x	x	x	x	x	x		x	x	x	x	x	x			x			x	x
Bräcke mound + 2-cm mineral cap	A	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	C	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	D	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	E	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
Bräcke mound + 6-cm mineral cap	A	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	C	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	D	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	E	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
Bräcke mound + 20-cm mineral cap	A	x	x	x	x	x	x			x	x	x	x	x	x	x		x								x				
	C	x	x	x	x	x	x			x	x	x	x	x	x	x		x								x				
	D	x	x	x	x	x	x			x	x	x	x	x	x	x		x								x				
	E	x	x	x	x	x	x			x	x	x	x	x	x	x		x								x				
Large stock	A	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	C	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	D	x	x	x	x	x	x			x	x	x	x	x	x	x										x				
	E	x	x	x	x	x	x			x	x	x	x	x	x	x										x				

a Diameter was measured at ground-level (GLD) from 1984 to 2005, and at a height of 1.3 m (diameter at breast height [dbh]) from 2008 to 2012. Grey-shaded cells indicate years in which diameter was not assessed.

b Seedlings were planted in spring 1984, so year 1 growth was also considered to have taken place in 1984.

Methods

Initial vegetation sampling focussed on leading plant species within 1- to 1.26-m radius subplots centred around 10 randomly selected planted spruce seedlings; the relative frequency of the three dominant species on 50 subplots per treatment was tallied each year from 1988 to 1997. Seven of the Inga Lake treatments were monitored in this way from 1988 to 1997 (in order of treatment severity): (1) untreated control (winter sheared only), (2) disc trench hinge, (3) coarse mixing, (4) plow inverting, (5) fine mixing, (6) burned windrows, and (7) vegetation control (refer to Table 2 for treatment descriptions). In 1997, 2002, 2007, and 2011, a complete survey of vascular plants, forest floor bryophytes, and macrolichens was conducted within three randomly located sets of subplots on five replicate plots in each of the treatments. Nested subplots measured 25 m^2 for trees and tall shrubs > 2 m height, 9 m^2 for low shrubs < 2 m height, 3 m^2 for herbs, and 1 m^2 for bryophytes and macrolichens. Not all treatments were measured at each date. In 2011, five mature forest plots located adjacent to the Inga Lake trial were also sampled, and more in-depth sampling of mixotrophic plants and epiphytic lichens and bryophytes growing on white spruce was conducted (results not presented in this appendix).

For each year, a vegetation index (VI) was calculated as the product of percent vegetation cover and vegetation height. The VI was calculated slightly differently in early than in later years due to differences in the approach used for data collection: from 1988 to 1993, VI = total vegetation % cover × mean vegetation top height, while from 1997 to 2011, VI = $\sum$ (% cover × modal height) for individual species.

Results and Discussion

Due to a history of fires at the Inga Lake site, seral vegetation was well established prior to treatment and is not representative of vegetation that would develop after conventional logging of a mature conifer stand. Alder, willows, aspen, and most understorey plants resprouted vigorously following winter shearing on the "untreated" plots, which created severe competition for newly planted white spruce. Additional mechanical site preparation or vegetation control treatments provided varying levels of competition control, ranging from very little (disc trench hinge) to almost complete suppression of woody plants in the earliest years (fine mixing), to almost complete suppression in the middle years (vegetation control treatment).

Changes in plant community composition from 1988 (year 1) to 2011 (year 24)

Untreated control

In the untreated control, winter shearing alone caused little damage to existing vegetation. Most species quickly resprouted, and the original plant community recovered within a few years. Willows, alder, and aspen were dominant after the first year, and this continued through year 24 (Figure A4-1, Figure A4-2), which created heavy competition for planted white spruce.

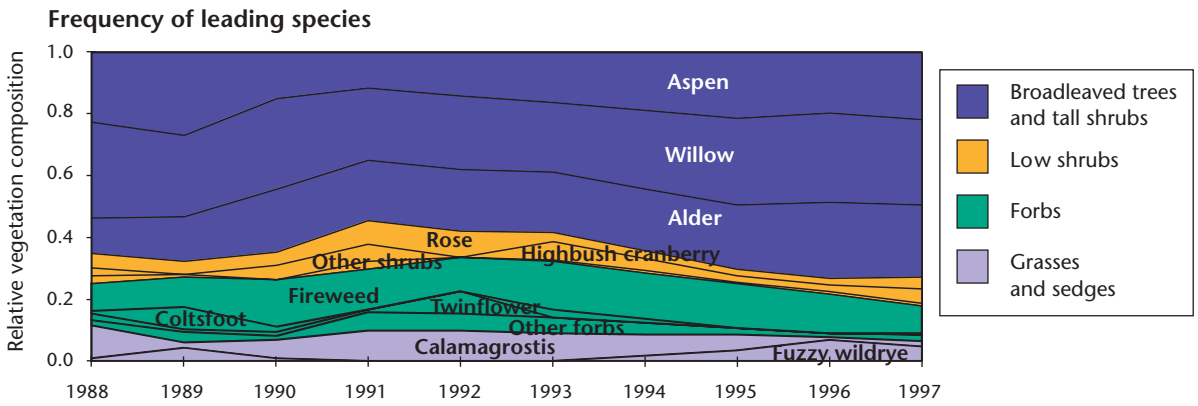


FIGURE A4-1 *Changes in plant community composition in the untreated control from 1988 (year 1) to 1997 (year 10).*

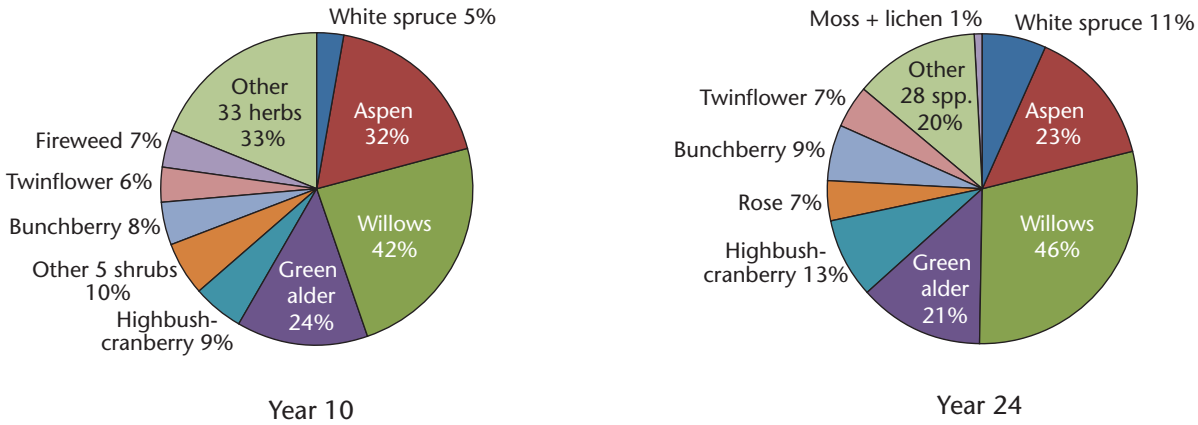


FIGURE A4-2 *Percent cover of dominant vegetation species in the untreated control in year 10 (1997) and year 24 (2011).*

Disc trench hinge

In the disc trench hinge treatment, trenching provided little control of re-sprouting willow, alder, and aspen; the dominance of these species increased during the first 10 years (Figure A4-3). In years 10 and 24, the plant community was essentially the same as on untreated plots (Figure A4-4).

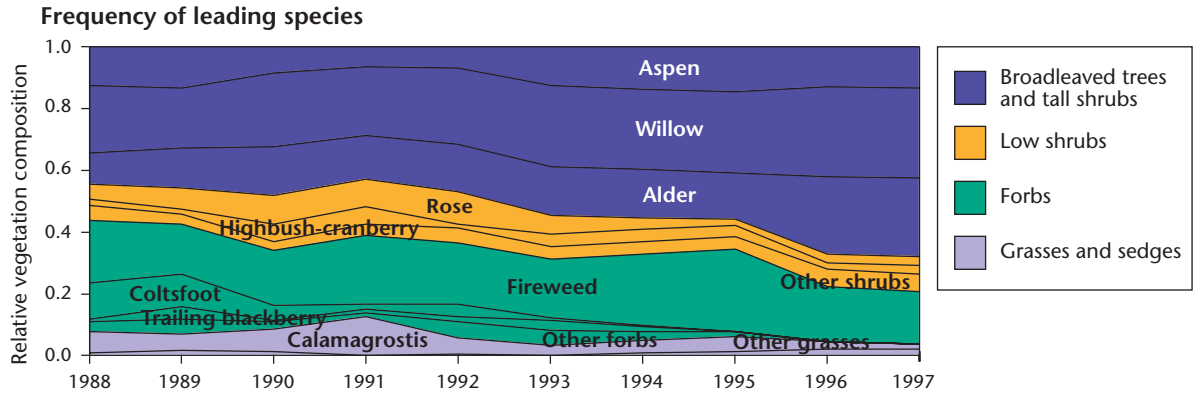


FIGURE A4-3 *Changes in plant community composition in the disc trench hinge treatment from 1988 (year 1) to 1997 (year 10).*

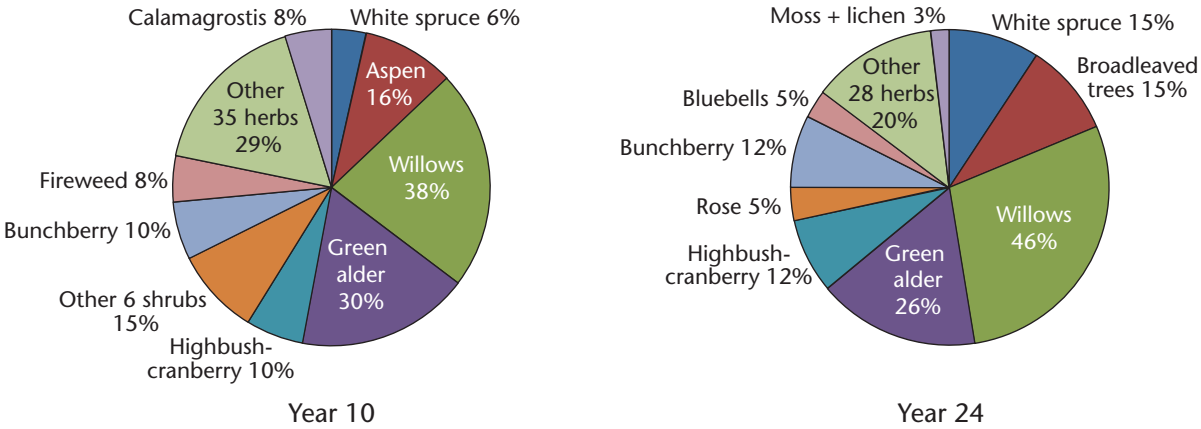


FIGURE A4-4 *Percent cover of dominant vegetation species in the disc trench hinge treatment in year 10 (1997) and year 24 (2011).*

Coarse mixing

In the coarse mixing treatment, early vegetation control was short-lived because there was prolific resprouting of woody species along the berm (Figure A4-5, Figure A4-6). Green alder also seeded heavily within the trenches.

Vegetation abundance, diversity, and composition were intermediate compared to lightly and heavily disturbed treatments, but the linear pattern imposed by the trenches increased overall homogeneity.

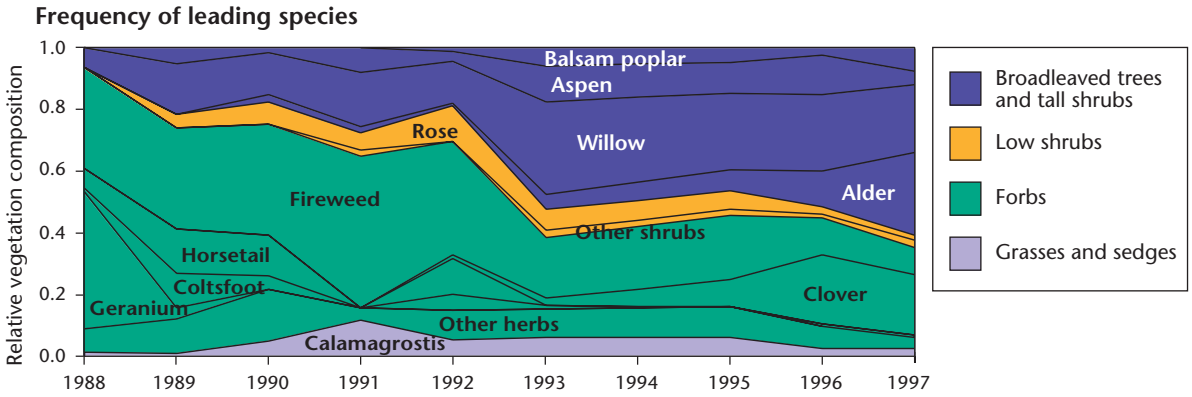


FIGURE A4-5 *Changes in plant community composition in the coarse mixing treatment from 1988 (year 1) to 1997 (year 10).*

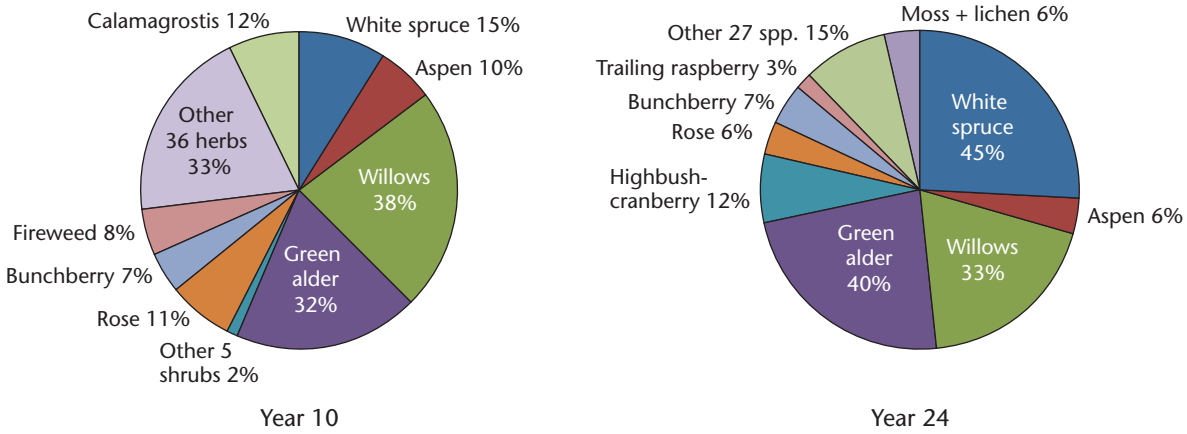


FIGURE A4-6 *Percent cover of dominant vegetation species in the coarse mixing treatment in year 10 (1997) and year 24 (2011).*

Plow inverting

The overturned sod provided strong early control of resprouting willows, alder, and aspen; because the plow left no trenches, woody plants resprouted only where the sod was not fully turned over. The presence of willow, alder, and aspen gradually increased from year 1 to year 10 (Figure A4-7), and remained relatively constant from year 10 to year 24 (Figure A4-8). At 10 years, this treatment had the highest species diversity, but at 24 years, it had the lowest species diversity, apparently because there was little microsite heterogeneity.

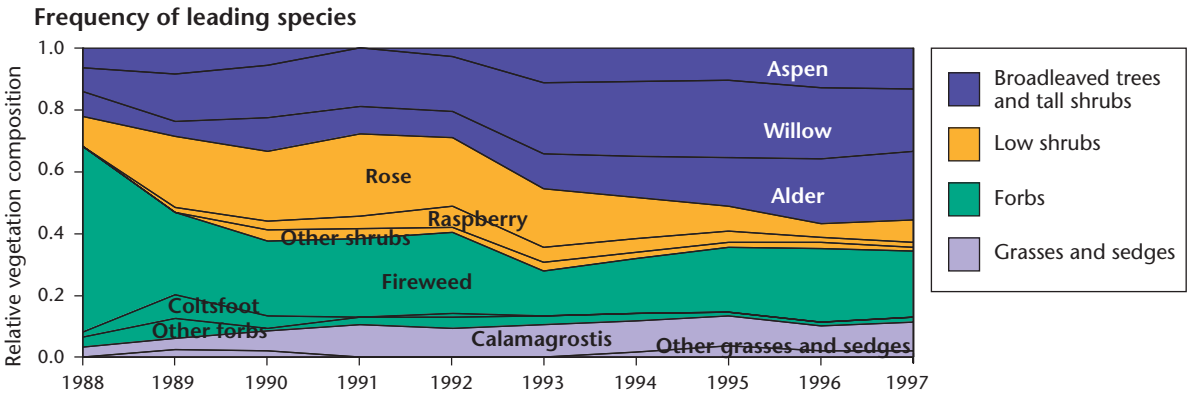


FIGURE A4-7 *Changes in plant community composition in the plow inverting treatment from 1988 (year 1) to 1997 (year 10).*

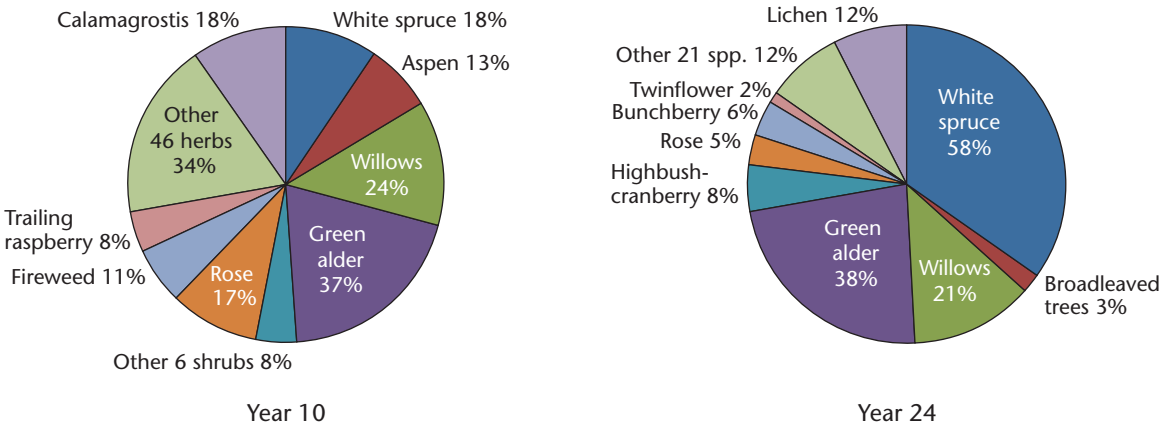


FIGURE A4-8 *Percent cover of dominant vegetation species in the plow inverting treatment in year 10 (1997) and year 24 (2011).*

Fine mixing

High-speed mixing virtually eliminated woody species and promoted abundant growth of grasses and forbs, including non-native clovers and dandelion (Figure A4-9). Over the first 10 years, woody species gradually re-established from seed. Woody regrowth was slowest on moist, fine-textured areas where the grass competition was most intense (Figure A4-10).

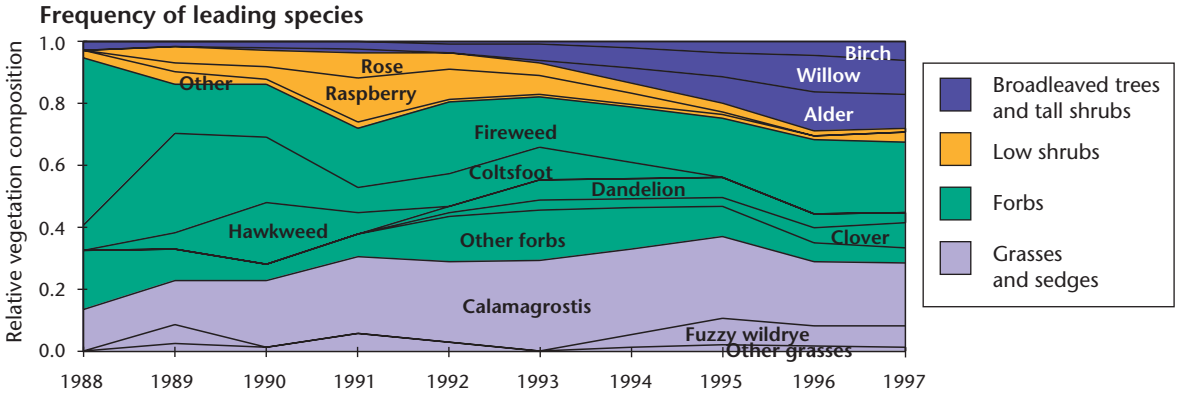
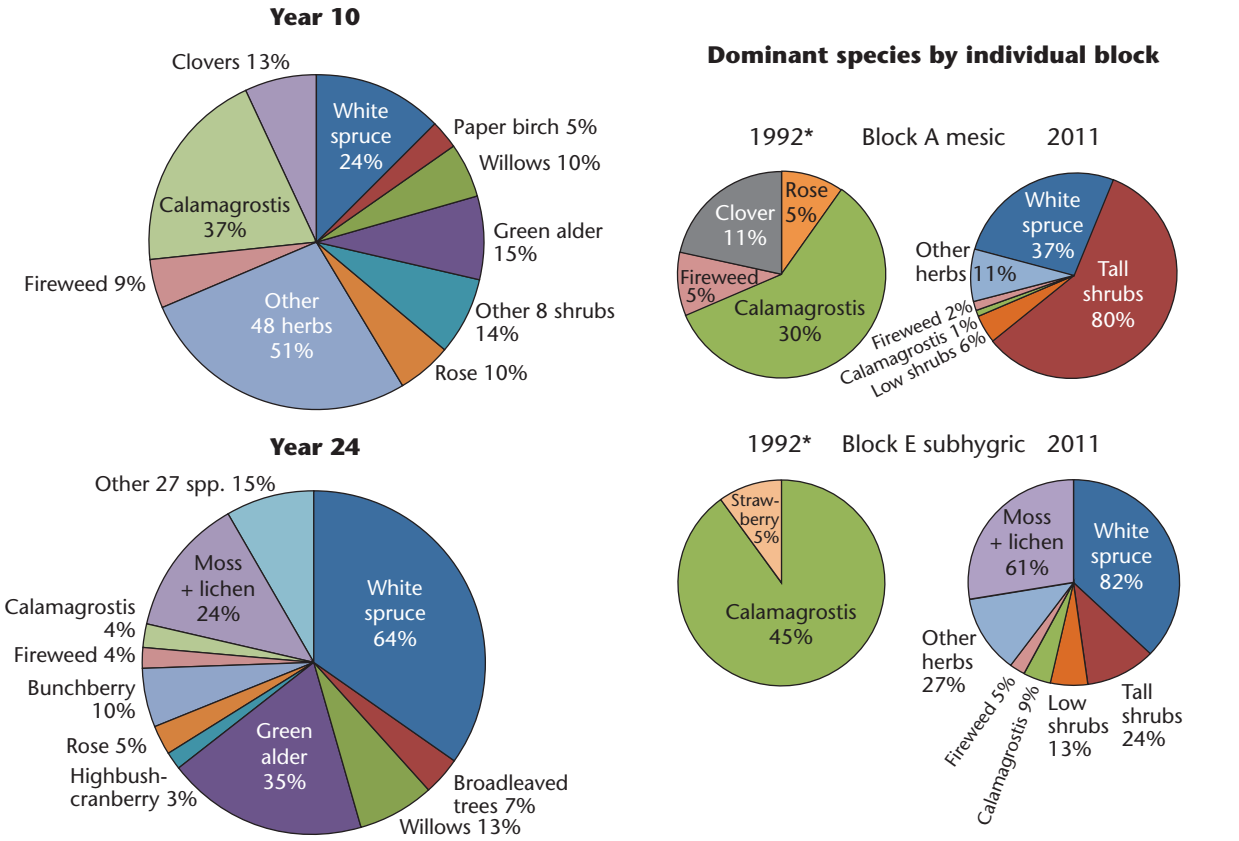


FIGURE A4-9 *Changes in plant community composition in the fine mixing treatment from 1988 (year 1) to 1997 (year 10).*

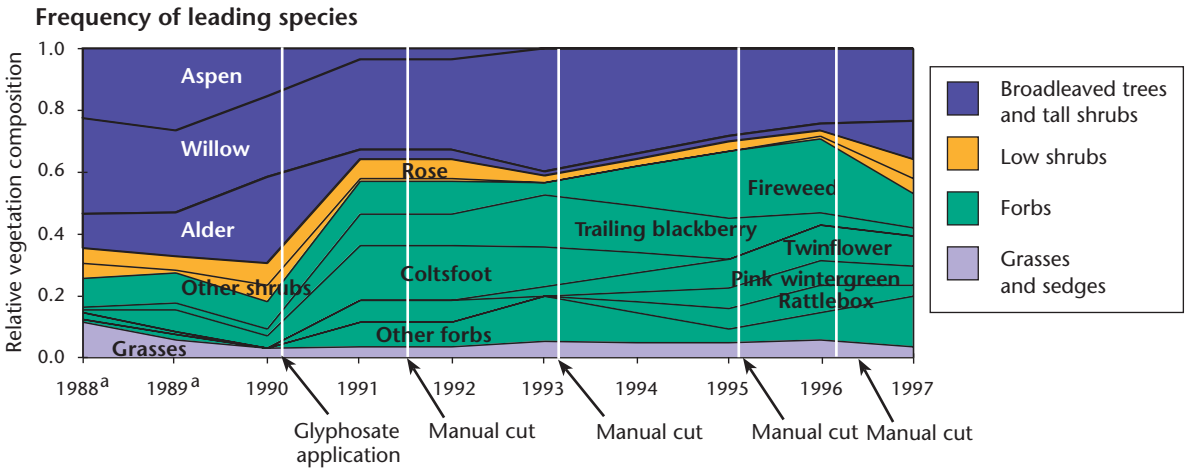


*Based on dominant plant species on 50 tree-centred subplots per plot.

FIGURE A4-10 *Percent cover of dominant vegetation species in the fine mixing treatment in year 10 (1997) and year 24 (2011), and a comparison of the dominant vegetation species growing in the mesic soil moisture conditions of block A versus the subhygric conditions of block E in years 5 (1992) and 24 (2011).*

Vegetation control

In the vegetation control treatment, glyphosate application followed by repeated manual brushing minimized woody cover (Figure A4-11). Moose concentrated on these plots when browse on other treatments became too tall, and they kept the tall shrubs from overtopping the spruce after manual brushing was discontinued. Due to glyphosate application, *Calamagrostis* (bluejoint) never became dominant, which allowed smaller plants to flourish. The understorey was a diverse mix of herbs, mosses, and lichens that gradually shifted to feathermosses as the spruce canopy closed (Figure A4-12).



a Data for 1988 and 1989 (prior to glyphosate application) are taken from untreated plots.

FIGURE A4-11 *Changes in plant community composition in the vegetation control treatment from 1988 (year 1) to 1997 (year 10).*

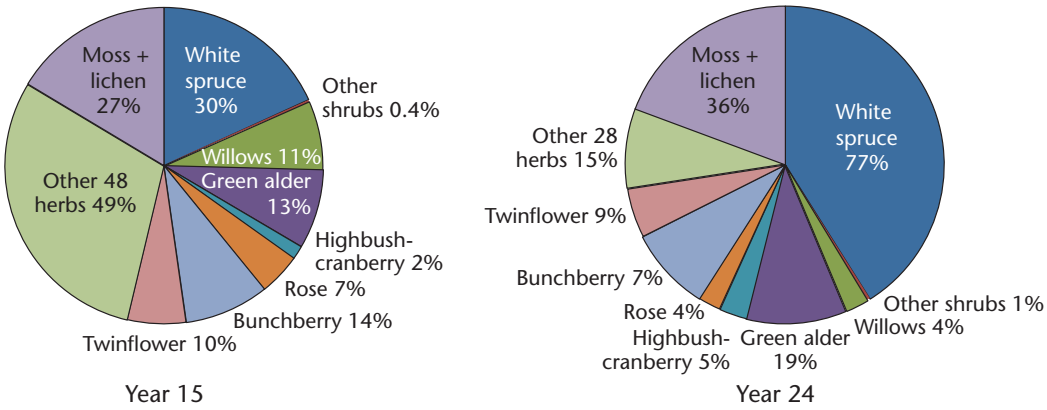


FIGURE A4-12 *Percent cover of dominant vegetation species in the vegetation control treatment in year 15 (2002) and year 24 (2011).*

Burned windrow

The intense heat generated by windrow burning eliminated on-site vegetation. Regrowth was from seeds and spores, which created low competition levels in the early years. Bicknell's geranium, fire moss, balsam poplar, and willow seedlings were characteristic pioneers after the severe fire (Figure A4-13). At 10 years, the plant community was still very different from the untreated plots and had the highest cover of non-native clovers and grasses. At 24 years, the burned windrow plots had converged with other treatments but retained significantly higher species richness (Figure A4-14).

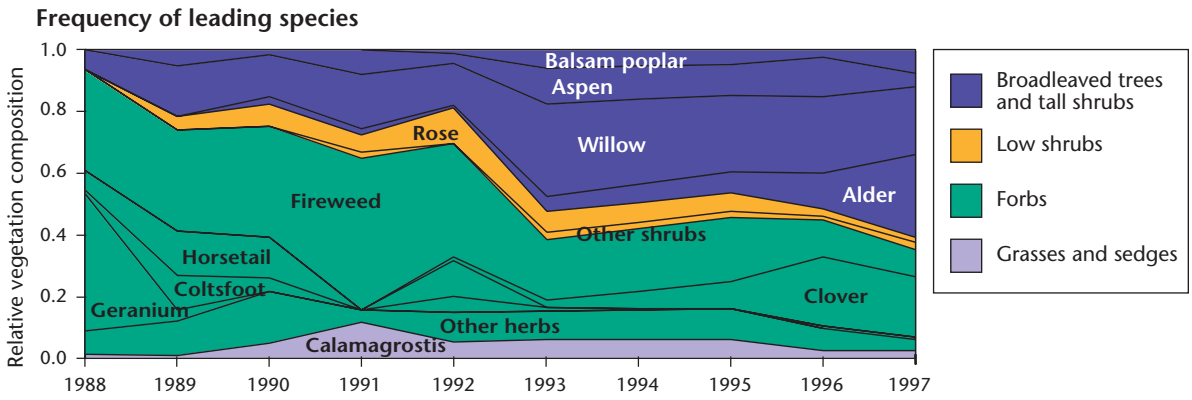


FIGURE A4-13 *Changes in plant community composition in the burned windrow treatment from 1988 (year 1) to 1997 (year 10).*

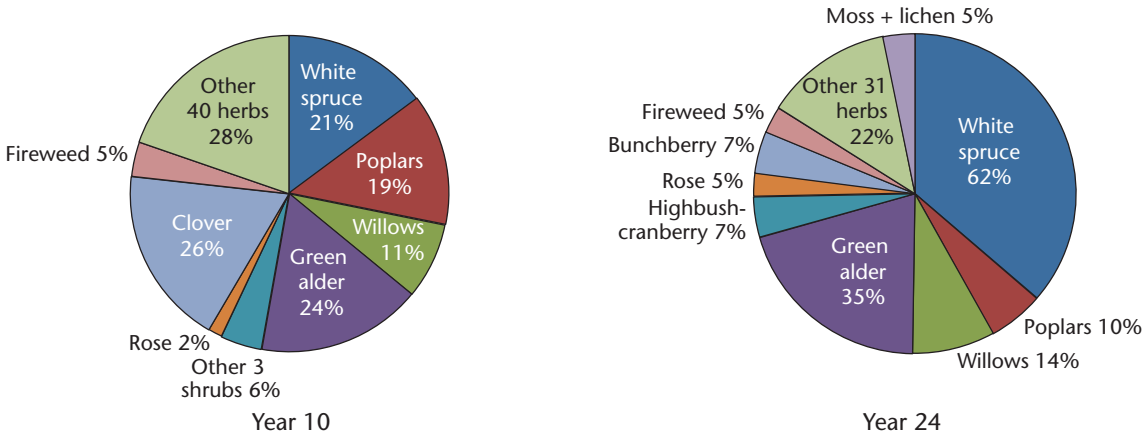


FIGURE A4-14 *Percent cover of dominant vegetation species in the burned windrow treatment in year 10 (1997) and year 24 (2011).*

Treatment effects on competition levels

Site preparation was generally successful at improving spruce growth to the extent that it controlled woody species, and vegetation indices for individual treatments reflect this (Figure A4-15). Willow, alder, and aspen were common to extremely dense on all treatments except vegetation control, where they were selectively removed during the six manual brushing entries that followed brushing with glyphosate. On the fine mixing and burned windrow treatments, broadleaved species regenerated from seed rather than resprouting, and thus took 5–10 years to overtop the planted white spruce. These treatments had more balsam poplar and birch than the less severe disc trenching, plow inverting, and coarse mixing treatments. On wetter soils, fine mixing stimulated dense regrowth of *Calamagrostis*, which inhibited shrub and tree regeneration. Glyphosate application (as part of the vegetation control treatment) and high-intensity windrow burning both successfully reduced *Calamagrostis*, while on plow inverting, coarse mixing, disc trench hinge, and untreated plots, *Calamagrostis* was somewhat inhibited by shade from alders, willows, and aspen.

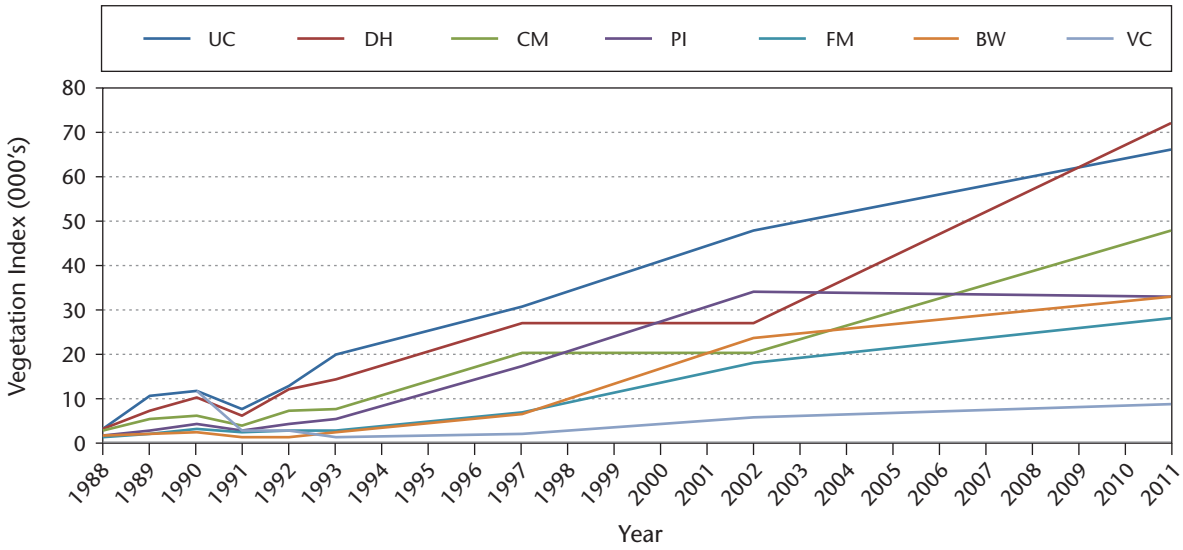


FIGURE A4-15 *Vegetation index in site preparation treatments at Inga Lake from 1988 (year 1) to 2011 (year 24). UC = untreated control; DH = disc trench hinge; CM = coarse mixing; PI = plow inverting; FM = fine mixing; BW = burned windrows; VC = vegetation control.*

Moose and snowshoe hares were abundant at Inga Lake and interacted with mechanical site preparation treatments to influence vegetation abundance and composition. Moose prefer birch, balsam poplar, and willow that are < 2 m tall, plus highbush-cranberry, and rarely browse green alder. On less severe treatments, moose exerted little control because shrubs were hyper-abundant, but on fine mixing and vegetation control plots, moose kept broadleaves from overtopping the spruce. Snowshoe hares devour understorey vegetation during peaks in their ~10-year cycle (e.g., 2011), and consume smaller-diameter woody plants in winter and apparently favour fireweed in summer. After the spruce canopy closes, hare feeding speeds the shift to a mossy understorey. Together, moose and hares appear to act as a feedback mechanism that intensifies differences in vegetation composition among treatments.

Treatment effects on species diversity, richness, and evenness

Plant species diversity peaked at ~15 years (Figure A4-16), and declined rapidly as the tree canopy closed. Severe treatments had low diversity in the first few years (data not shown) but higher diversity after 10 years when competitive exclusion by dominant species became more important than the killing effect of the treatment. *Calamagrostis*, willows, and green alder were dominant competitors in the first 15 years, and planted white spruce became dominant thereafter. Herbs, bryophytes, and lichens flourished on vegetation control plots between 10 and 20 years because glyphosate killed *Calamagrostis*, while manual cutting removed the dominant shrubs. These species-rich plots are becoming less diverse as the white spruce become larger. The burned windrows have high diversity because fire created plenty of opportunities for seeding in, and remnant piles of decaying wood are now acting as hubs of plant diversity. Plowing initially created microtopographic diversity for bryophytes and herbs, but these treatments are now the most homogeneous. At 24 years, the Inga Lake plots had greater species richness than nearby mature forest (mean of 20 species per plot) because early successional species were present, but they had fewer late successional plants, such as myco/mixotrophic forest herbs (small plants that get their food through mycorrhizal connections to trees), as well as lichens and bryophytes that grow on stems, twigs, and decaying wood. Twenty-four years of study at Inga Lake illustrated the tremendously dynamic nature of boreal mixedwood plant communities, and indicated that there is no one-size-fits-all solution for maintaining plant biodiversity. We need to learn more about how plants and animals interact in these forests to address significant concerns about the cumulative effects of human development in this landscape.

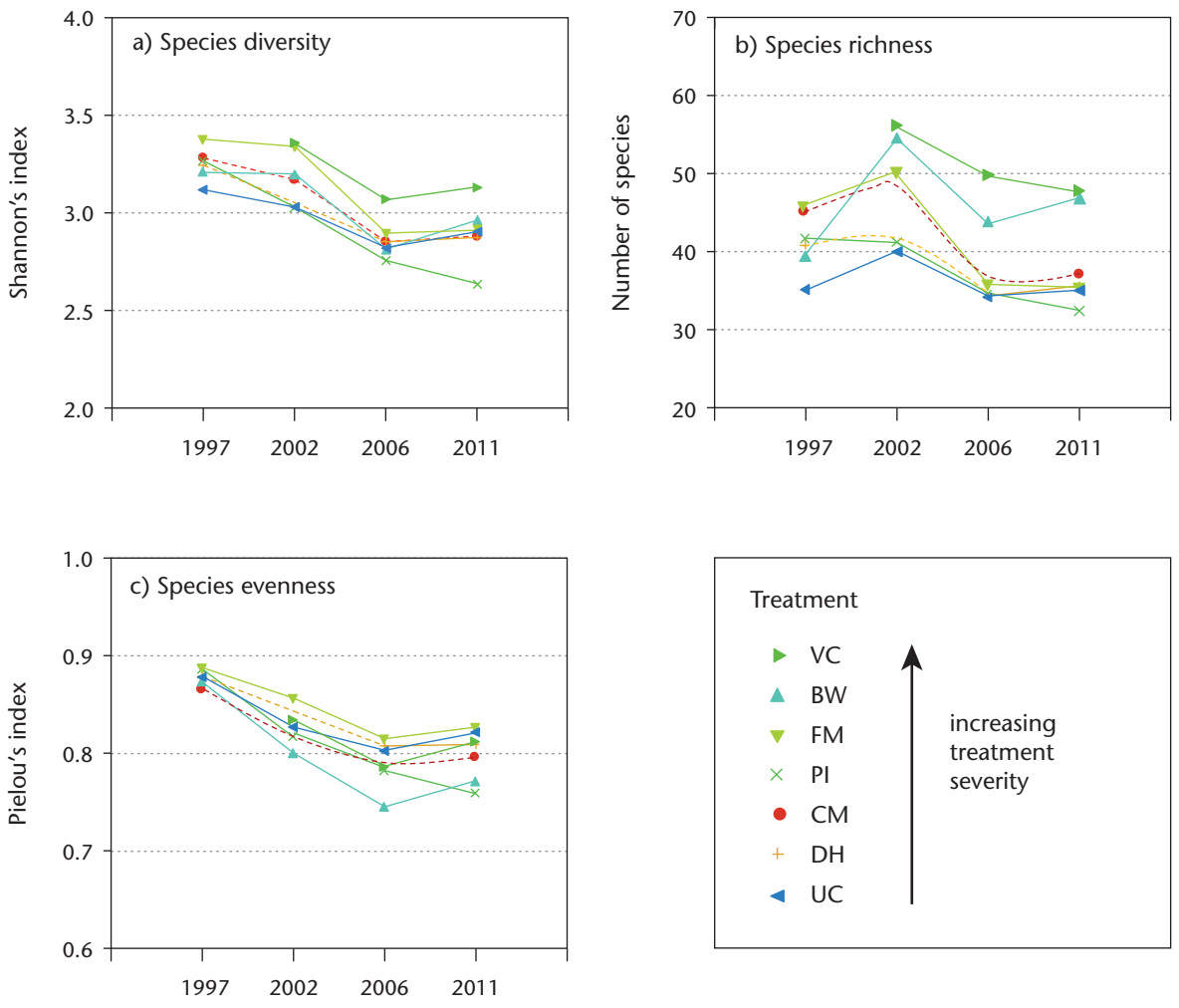


FIGURE A4-16 *Total species (all vegetation layers) (a) diversity, (b) richness, and (c) evenness 10–24 years after treatment. VC = vegetation control; BW = burned windrows; FM = fine mixing; PI = plow inverting; CM = coarse mixing; DH = disc trench hinge; UC = untreated control.*