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ARTICLE

A partial deciduous canopy, coupled with site preparation, produces excellent growth of planted white spruce

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Abstract: Survival and growth of planted white spruce (*Picea glauca* (Moench) Voss) were assessed at year 15 in boreal mixedwood stands of northern Alberta, Canada, in stands that were deciduous-dominated prior to logging or were conifer-dominated. Three overstory retention levels (0%, 50%, and 75% retention) and four site preparation treatments (mound, high speed mix, scalp, and no treatment) were evaluated. In deciduous-dominated stands, planted spruce performed best in the 50% retention; here, stem volume was at least double that of any other retention treatment after 15 years. In contrast, spruce had reduced growth in coniferous-dominated stands in both 50% and 75% retention treatments compared with the 0% retention. Survival of planted spruce was unaffected by level of retention, but survival was lower in coniferous-dominated stands than in deciduous-dominated stands; in the coniferous-dominated stands, survival was better with mounding and mixing and lowest with scalp treatments. All height variables tended to be greater in the mix and mound site preparation treatments. Finally, the best estimates of future total growth (regenerated spruce and deciduous combined) in the coniferous-dominated stands were in the clearcut treatment. In terms of regenerated spruce growth, the best estimates occurred in the deciduous-dominated – 50% retention stand planted with soil mixing–mounding treatments, where projected growth of spruce was comparable with that of open-grown and tended stands in Alberta's boreal forests.

Key words: boreal mixedwood, shelterwood, site preparation, survival, partial harvest, planted, variable retention, white spruce.

Résumé : La survie et la croissance de plants d'épinette blanche (*Picea glauca* (Moench) Voss) ont été évaluées à l'âge de 15 ans dans des peuplements mixtes boréaux du nord de l'Alberta, au Canada, sur des stations dominées avant la coupe par des feuillus ou par des conifères. Nous avons évalué trois niveaux de rétention du couvert dominant (0, 50 et 75 % de rétention) et quatre traitements de préparation de terrain (monticules, mélange du sol à grande vitesse, scalpage et témoin non traité). Dans les peuplements dominés par des feuillus, les plants d'épinette croissaient mieux à 50 % de rétention du couvert dominant. Dans ce cas, le volume des tiges était au moins le double de celui observé dans les autres traitements de rétention après 15 ans. En revanche, une croissance réduite de l'épinette a été observée dans les peuplements dominés par des conifères avec 50 et 75 % de rétention comparativement à 0 % de rétention. La survie des plants d'épinette n'a pas été influencée par le niveau de rétention, mais elle était plus faible dans les peuplements dominés par des conifères que dans ceux dominés par des feuillus. Dans les peuplements dominés par des conifères, la survie était meilleure dans les traitements par monticules et par mélange et était la plus faible dans le traitement de scalpage. Toutes les variables de hauteur avaient tendance à être supérieures dans les traitements de préparation de terrain par mélange et par monticules. Finalement, la meilleure estimation de la croissance totale future (régénération d'épinette et de feuillus combinée) des peuplements dominés par des conifères a été observée dans la coupe à blanc. En ce qui concerne la croissance de la régénération d'épinette, la meilleure croissance a été observée avec 50 % de rétention du couvert feuillu et les préparations de terrain par mélange du sol et par monticules, où la croissance projetée de l'épinette était comparable à celle de peuplements libres de croître et éduqués de la forêt boréale de l'Alberta. [Traduit par la Rédaction]

Mots-clés : peuplement mixte boréal, coupe progressive, préparation de terrain, survie, coupe partielle, plants, rétention variable, épinette blanche.

Introduction

Mixedwood forests of aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench.) Voss) cover extensive areas of the boreal region of Canada, ranging from the Yukon to western Quebec. After clearcut logging, aspen and balsam poplar (*Populus balsamifera* L.) usually regenerate prolifically, whereas white spruce is typically much slower to establish naturally because of its more irregular seed supply and need for mineral or decomposed organic seedbeds (Gärtner et al. 2011). Also, as spruce has slow juvenile growth, it typically remains under dense young deciduous trees for decades; therefore, plantation techniques, including site preparation, planting, and vegetation control with herbicides are often prescribed to accelerate spruce regeneration after harvest (e.g., Pitt et al. 2010). Site preparation is well-documented to benefit growth of white spruce after clearcutting (Bedford et al. 2000; Hallsby and Örlander 2004; Hawkins et al. 2006; Boateng et al. 2009).

Over the past few decades, sustaining biodiversity has become a cornerstone of sustainable forest management (Canadian Council of Forest Ministers 2005) and partial harvesting, i.e., retaining

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Table 1. Precut stand basal area and postcut stem density for mature trees. The density of deciduous regeneration at year 15 is presented in the last column.

	Precut basal area (1998)		Postcut density (1999)		Density (2014)		
Retention (%)	Conifer ($m^2 \cdot ha^{-1}$)	Deciduous ($m^2 \cdot ha^{-1}$)	Conifer ($stems \cdot ha^{-1}$)	Deciduous ($stems \cdot ha^{-1}$)	Conifer ($stems \cdot ha^{-1}$)	Deciduous ($stems \cdot ha^{-1}$)	Deciduous regeneration density ($stems \cdot ha^{-1}$)
Stand composition: CDOM							
0	33.0	1.8					2214
50	34.6	0	326	0	231	0	389
75	31.5	3.6	479	89	337	84	132
Stand composition: DDOM							
0	11.8	36.7					3025
50	14.2	36.4	90	343	62	163	576
75	8.4	36.9	89	510	41	441	118

Note: Precut basal area was determined in six 2 × 40 m plots established across the machine trails in each of the cutting units for this experiment (Solarik et al. 2012). The number of postcut stems per hectare ($stems \cdot ha^{-1}$) was estimated by the target cutting density in the various retention plots. The 15-year density of residual trees was projected by multiplying this density by the mortality rate of conifer and deciduous stems in these plots, up to year 15, in each of the cutting units. Regeneration density of deciduous stems greater than 4.9 cm diameter at breast height (1.3 m) was tallied in the elongated plots at year 15.

overstory forest structure in variable retention (VR) harvests has been listed as a critical step in sustaining biodiversity (Guay-Picard et al. 2015). While there have been increasing efforts to investigate the release of trees and establishment of new regeneration following partial harvest (e.g., Gendreau-Berthiaume et al. 2012; Hébert et al. 2013), far less effort has focused on growth and survival performance in VR systems. In a recent review, Urli et al. (2017) emphasized a greater need to better understand the relationship(s) between the growth responses of spruce in ecosystem management vs. intensive management systems. Classic shelterwood cuts promote natural regeneration of Norway spruce (Erefur et al. 2008) and other conifers (Man et al. 2009; Bose et al. 2014), presumably because the canopy moderates light, daytime heating, and nighttime frosts (Man and Lieffers 1999; Prévost and Raymond 2012). Most studies indicate that moderate shade from shelter trees has little negative influence on height growth of spruce (e.g., Lieffers and Stadt 1994; Erefur et al. 2008), although it has been shown to reduce diameter growth (Groot 1999). The greatest volume growth following clearcutting, however, has usually been reported to be with complete vegetation removal (e.g., Boateng et al. 2009; Pitt et al. 2010).

While VR has been widely adopted in western Canada, Fennoscandia, and the United States, there have been relatively few long-term studies focused on the growth response of planted conifers under forests of different composition, different harvesting intensities, and different site preparation conditions (but see Granhus et al. 2003; Man et al. 2009) Our study provides an unique opportunity to examine the effectiveness of different levels of canopy retentions (0%, 50%, and 75% residuals) in forests of different composition (conifer- and deciduous-dominated) and different mechanical site preparation treatments (mounding, mixing, scalping, and control) that are currently being used to establish spruce without use of herbicides (Thiffault and Roy 2011).

This study reports on the growth and survival of planted white spruce 15 years after harvest within a portion of the Ecosystem Management Emulating Natural Disturbance (EMEND) experiment (Spence and Volney 1999). We also project stand growth, as year 15 is considered to be an appropriate time to begin projection of stand growth (Nigh and Martin 2001; Alberta Environment and Sustainable Resource Development 2014).

Methods

Site description

Study sites are part of the EMEND experiment located northwest of Peace River in Alberta, Canada (56°46′13″N, 118°22′28″W) in the Lower Foothills Ecoregion of Alberta. Elevation ranged from 677 to 880 m a.s.l., mean annual temperature is 1.2 °C, and mean annual precipitation is 431 mm (mostly falling in June and July) (Environment Canada 2018). The majority of the forest is on well-drained sites on fine-textured glacial till and lacustrine deposits (Kishchuk et al. 2014). Soils are clay and clay-loam Orthic Gray Luvisol and Dark Grey Luvisol with Humimor and Mullmoder humus form (Kishchuk et al. 2016). The mixedwoods forests of our study area were either deciduous-dominated (aspen, sometimes intermixed with balsam poplar (*Populus balsamifera* L.)), or coniferous-dominated (white spruce, with some occasional black spruce (*Picea mariana* (Mill.) B.S.P)). Deciduous-dominated areas were ~80 years old at the time of harvest, while coniferous-dominated stands were ~125 years old. Mature deciduous canopies were 25 m tall, whereas coniferous canopies were >30 m tall. Understorey species were predominantly low-bush cranberry (*Viburnum edule* (Michx.) Raf.), wild rose (*Rosa acicularis* Lindl.), fireweed (*Epilobium angustifolium* L.), and hairy wild rye (*Elymus innovatus* Beal) in the deciduous areas. The coniferous-dominated areas had lower densities of the same shrubs, but feather mosses were dominant at the ground level.

Experimental design and treatments

This study extends the year 7 report on the survival and growth of planted spruce under a range of site preparation and canopy retention treatments (Gradowski et al. 2008). Nine mature deciduous-dominated stands (DDOM, >70% deciduous), each of 5–10 ha, and nine coniferous-dominated (CDOM) stands were cut in the winter of 1998–1999. For both DDOM and CDOM compositions, three replicate stands were randomly assigned to each of three cutting intensities, where 0% (clearcut), 50%, or 75% of the overstory canopy was retained. Trees were selected for removal without bias towards species or size. The pre- and post-cut densities are presented in Table 1. Harvesting equipment, i.e., feller-buncher and grapple skidder, were confined to planned trails. In June of 1999, a uniform 50 × 50 m area was selected in each of the 18 stands and split into four 25 × 25 m subplots. A different site preparation treatment (mound, mix, scalp, or control) was assigned randomly to each subplot. Site preparation was done with a tracked excavator fitted with either a curved bucket for mounding (rolling up the organic layer and topping this with 8–15 cm of the mineral soil in an area ca. 0.8 m by 0.8 m) or scalping (pushing back the organic layer to expose mineral soil in a 1 m^2 area, using back strokes of the curved bucket). For the mixing treatment, a Meri-crusher horizontal drum mixer was fitted to the excavator to create 1 m^2 areas where the ca. 10 cm thick organic layer was mixed with an equal volume of mineral soil. The result was a fine mixture of soil and organic matter debris. Centers of prepared spots were ca. 2.5 m apart. In July 1999, 100 white spruce seedlings (summer stock, 1 + 0, grown in containers 4 cm wide and 15 cm deep) were planted, each on a prepared spot within each of the four subplots. In the control subplots, seedlings were planted into the organic layer with minimal disturbance. In total, 7200 white spruce seedlings were planted.

Trees were tagged, and their height and diameter were measured at the root collar or at 1.3 m (if the trees were taller than 1.3 m). Trees were re-measured in multiple years (2000, 2001, 2003, 2006, 2010, 2014), but in this study, we focused primarily on the growth measurements at years 11 (2010) and 15 (2014). Stem volume for trees less than 1.3 m tall were based on the volume of a cone, and for trees taller than 1.3 m, volume was calculated using a function with height and diameter at breast height (1.3 m) as independent variables (Honer et al. 1983). Mean annual height increment was based on the difference between heights at years 11 and 15 divided by 4. Top height was determined as the height of six undamaged trees with the greatest diameter within each of the subplots (i.e., thickest 100 trees·ha^{-1}). There was no control of vegetation in this experiment after the site preparation.

Data analysis

For height and volume variables, only trees alive at year 15 were considered for analysis. The experimental design was a split plot, where we chose to analyze stand composition (DDOM and CDOM) independently; this was done to ease interpretation by operational managers who must determine the best retention levels and site preparation separately for CDOM or DDOM stands. The main plots were harvest blocks, with nine harvest blocks per composition. For each composition, three harvest blocks were randomly assigned to one of the three retention levels. Subplots consisted of the four 100-tree units inside each harvest block to which the four site preparation methods were randomly assigned.

For each composition, height and volume variable averages were calculated for living trees in each of the 36 subplots per composition, and these 36 means were used for our 15th year analysis. Data were analyzed using PROC MIXED in SAS v.9.4 (SAS Institute Inc., Cary, North Carolina, U.S.A.). The following statistical model was used:

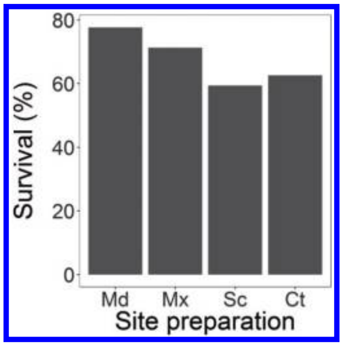
$$Y_{ikj} = \mu + R_i + B_k(R_i) + P_j + R_iP_j + e_{ijk}$$

where Y_{ijk} is the dependent variable corresponding to the overall mean (μ), retention level (R_i, $i = 1$ to 3), cut block nested within retention level ($B_k(R_i)$, $k = 1$ to 3), site preparation method (P_j, $j = 1$ to 4), retention by site preparation interaction (R_iP_j), and residual error (e_{ijk}).

Normality of residuals was evaluated by visual examination of conditional, studentized residuals (West et al. 2015). Potential heterogeneity of residual variance was addressed by comparing models with or without heterogeneous variances and selecting the best according to the Akaike information criterion (AIC). For both retention and site preparation, *t* tests, without a multiple comparison correction, were used to make pairwise comparisons among the different treatment combinations (Littell et al. 2006).

Survival was treated as a binary variable, based on the number of trees alive at year 15 in each subplot. SAS PROC GLIMMIX was used to perform logistic regression on survival using the same model above for height and volume variables except that the dependent variable was the log odds of survival and the model included an explicit random variable for subplot to account for the clustering of trees at that level. We also performed a supplementary analysis of survival using repeated measures ANOVA (results not shown); however, due to a high level of interplot variability, we chose to report only cumulative survival after 15 years.

Fig. 1. Survival of white spruce to age 15 in relation to mechanical site preparation (Md, mound; Mx, mix; Sc, scalp; Ct, control) for coniferous-dominated stands. The table shows the *P* values for the comparisons among site preparation methods based on two-tailed tests done without multiple comparison adjustments. *P* values less than 0.05 are shown in bold.



	Md	Mx	Sc
Mx	0.842		
Sc	***0.016***	***0.010***	
Ct	***0.049***	***0.032***	0.635

Stand projections

In terms of longer term predictions of growth, most growth models approved by regulators for public lands use site index (SI) as an important starting point in model prediction of forest yield (Bokalo et al. 2013; Alberta Environment and Sustainable Resource Development 2014). More specifically, SI is the mean height of the top 100 trees·ha^{-1} at a specific base age (typically identified at 50 years). The top height and density data of the regenerated white spruce in each stand at age 15 were used as input to estimate SI and mean annual increment (MAI) of the regenerated spruce up to rotation age, i.e., time of maximum MAI, using the Growth and Yield Projection System (GYPSY) (Alberta Environment and Sustainable Resource Development 2014). In Alberta, the top height of stands at surveys between 12 and 14 years are used to project yield (Alberta Agriculture and Forestry 2016). The density and top height of regenerated aspen and balsam poplar at this age were determined from a separate survey of each stand, measuring the density of regenerated deciduous trees in six 2 × 40 m plots established across the machine trails in each of the cutting units for this experiment (for plot descriptions, see Solarik et al. 2012). We used the model GYPSY (Huang et al. 2009) to project the growth of these plots to a single rotation age, i.e., the time of maximum MAI for spruce; such projections are used for estimating yield to determine timber supply. Rotation age was determined as the time of peak MAI. GYPSY projections used a regular spatial distribution of spruce and clumped distribution of poplars and summarized merchantable MAI, with minimum diameters of 15 cm at the log base and 10 cm for the top diameter and stump height of 10 cm.

Results

Survival

In conifer-dominated stands (CDOM), survival of spruce at year 15 was 68%. Site preparation significantly influenced spruce survival (P = 0.007), where spruce had much lower survival rates (62%) planted on the scalp treatment than on the mound and mix treatments (70%; Fig. 1). No differences in survival were found with retention intensity (P = 0.202). Most of the spruce mortality occurred in the first few years following planting (Appendix Figs. A1 and A2), where only a few of the individual plots were the main contributors to the relatively high average mortality rates, particularly for the scalp treatment (Appendix Fig. A2). We make these curves available for visual examination of the interplot variability. We chose to forego reporting this analysis in the paper as final survival is the main interest in this study.

In the deciduous-dominated stands (DDOM), survival of spruce was 82%, on average, 15 years after planting. Within the DDOM

Table 2. *P* values for the effects of retention, site preparation, and their interaction on planted white spruce survival, height, height increment (between years 11 and 15), top height, volume per tree, and volume per hectare for DDOM (deciduous-dominated) and CDOM (coniferous-dominated) stands.

Sources of variation	Height	Height increment	Top height	Volume per tree	Volume per hectare	Survival
Stand composition: CDOM						
Retention	**0.017**	0.055	**0.006**	**0.010**	**0.004**	0.202
Site prep	**0.001**	**0.008**	**0.001**	0.129	**0.023**	**0.007**
Retention × site prep	0.193	0.226	0.505	0.912	0.810	0.484
Stand composition: DDOM						
Retention	**0.043**	**0.050**	**0.034**	**0.001**	**0.021**	0.604
Site prep	**0.001**	**0.001**	**0.001**	**0.012**	**0.007**	0.267
Retention × site prep	0.143	0.186	0.266	0.358	0.197	0.332

Note: *P* values <0.05 are in bold.

stands, however, we found no difference in survival across either retention intensities ($P = 0.604$) or site preparation treatments ($P = 0.267$) (Table 2). Trees in some of the individual plots or even subplots of the DDOM had most of the mortality (Appendix Figs. A1 and A2), similar to the CDOM stands.

Growth

In CDOM stands, all growth measurements of regenerated spruce were influenced by retention intensity (Table 2); growth declined with increasing retention intensity, with the greatest growth occurring with the 0% retention treatments (Fig. 2). The regenerated spruce in the 0% retention had more than twice the volume at year 15 compared with the 75% retention (Fig. 2). Site preparation also greatly influenced sapling growth, where performance for all measurements was consistent with the following trend: mound > mix > control > scalp (Fig. 2).

In the DDOM sites, 50% retention produced the largest values for mean height, top height, stem volume, and stand volume (Table 1; Fig. 2); the same trend was also true for height increment. Site preparation also significantly influenced all growth variables (Table 1). More specifically, mixing and then mounding tended to have greater mean sapling size and growth than either the control or scalp treatments (Fig. 3).

Projection of growth

Firstly, the pattern of treatment effects on mean height increment between years 11 and 15 was very similar to the pattern of treatment effects on height at year 15 (Figs. 2 and 3), indicating that treatment differences had been maintained over the last 4 years. Secondly, the projection of growth using the GYPSY model indicates that the DDOM stands with 50% residual and mounding (Fig. 4; Appendix Table A1) had the highest estimate of spruce MAI (3.46 $m^3 \cdot year^{-1}$), with a rotation age of 92 years. This was followed closely by the mixing treatment. The lowest projections of spruce growth were noted in the DDOM sites with 0% residual and scalp treatments (1.34 $m^3 \cdot year^{-1}$) and in the CDOM sites with 75% residual and scalp treatments (1.51 $m^3 \cdot year^{-1}$). These two treatment combinations also had longer rotations of ~119 years. The greatest total MAI (spruce + poplar) was projected in the 0% retention in both CDOM and DDOM stands, although in the DDOM stands, the 50% retention had nearly the same total MAI (Fig. 4).

Discussion

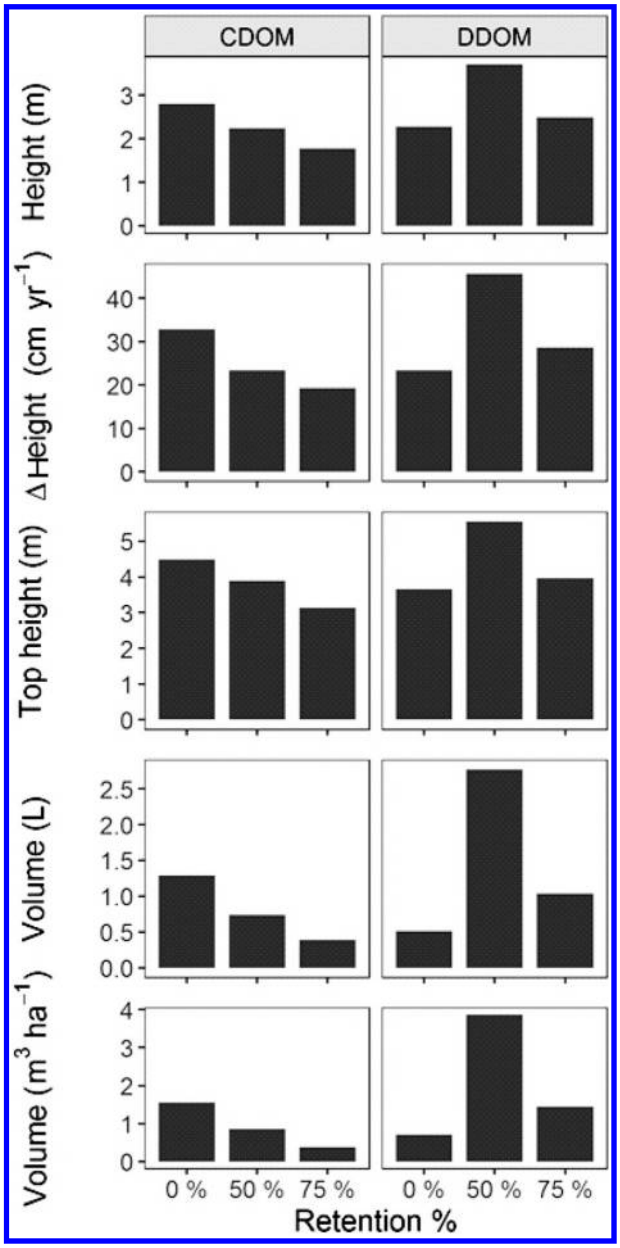
Our study shows that the amount of residual canopy and type of site preparation treatment used influences the growth of planted white spruce up to 15 years in both DDOM and CDOM stands. The DDOM stands with 50% residual canopy produced white spruce saplings with the greatest height and volume across the entire experiment (Fig. 2; Appendix Table A1). In shelterwood experiments in conifer-dominated sites, juvenile conifer growth typically increased with increasing stand openness (Granhus et al. 2003; Hanssen et al. 2003; Man et al. 2009), although Erefur et al. (2008) reported that 0% and 30% spruce canopy retention produced equal growth of regenerating spruce. It is likely that 50% cover of overstory aspen and balsam poplar provided the right combination of shelter from summer frosts (Man and Lieffers 1999; Prévost and Raymond 2012) and light transmission through the canopy. Light transmission in DDOM stands is also increased during the leaf-off periods of early spring and fall compared with summer (Constabel and Lieffers 1996; Prévost and Pothier 2003), which can lead to (*i*) early spring thaw of the soil (Chávez and Macdonald 2010), (*ii*) warmer soil temperatures (by up to 3 °C; Fenniak 2001), and (*iii*) earlier seasonal start and late season shutdown of photosynthesis (Man and Lieffers 1997). Pitt et al. (2015) confirmed that partial canopy deciduous trees can benefit juvenile spruce growth on sites with summer frosts and that there can also be a nutritional benefit of aspen and balsam poplar on growth of spruce for at least 20 years (Neufeld et al. 2014).

Planted spruce within the DDOM–0% retention treatment combination likely grew more slowly than within the 50% retention due to high density of aspen and balsam poplar regeneration; there were 33 000 $stems \cdot ha^{-1}$ at year 7 compared with 6000 $stems \cdot ha^{-1}$ following 50% retention in the same experimental units (Gradowski et al. 2008). Neufeld et al. (2014) indicated that juvenile deciduous trees can be a significant competitor with spruce, particularly at these earlier stages. The high densities of juvenile aspen and balsam poplar in 0% retention of the DDOM stands (Table 1) can produce higher leaf area indices and lower levels of mid-summer light than mature aspen canopies (Lieffers et al. 2002).

In the CDOM stands, aspen and balsam poplar regeneration at year 7 was 12 500 $stems \cdot ha^{-1}$ in the 0% retention and 3000 $stems \cdot ha^{-1}$ in the 50% retention (Gradowski et al. 2008). The slower growth of spruce in CDOM stands with 50% or 75% canopy retention was, therefore, likely related to the seasonally persistent and heavy canopy of the spruce. Spruce crowns are much longer than poplars and have fourfold higher leaf area density within their individual crowns compared with aspen (Stadt et al. 2005); therefore, they cast heavy shade. Furthermore, there might also be other unknown reason(s) for slower growth under spruce, perhaps associated with conifer litter, accompanying changes in soil conditions and mycorrhizal activity (Menkis et al. 2010) and lower soil pH and N concentration and lower base cations (Kishchuk et al. 2014).

Spruce growth varied greatly with mechanical site preparation, with the mix and mounding treatments generally being better than the control in both the DDOM and CDOM stands. The benefits of mounding for spruce establishment are well documented (e.g., Bedford et al. 2000; Hawkins et al. 2006; Boateng et al. 2009), but this study indicates that high-speed mixing and mounding produced approximately similar results over the range of growth variables (Fig. 3). We anticipate that both mixing and mounding resulted in rapid growth above the shrub layer or root access to

Fig. 2. Means for growth variables in relation to canopy retention for white spruce separately for the deciduous-dominated (DDOM) and coniferous-dominated (CDOM) compositions. The tables show the *P* values for the comparisons of different levels of retention based on two-tailed tests done without multiple comparison adjustments. Values on the left of the diagonal are for CDOM and those on the right are for DDOM, e.g., the *P* value comparing mean height between 0% and 50% retention in the CDOM is 0.063. *P* values less than 0.05 are shown in bold.



	0 %	50 %	75 %
0 %		**0.021**	0.670
50 %	0.063		**0.038**
75 %	**0.006**	0.106	

	0 %	50 %	75 %
0 %		**0.022**	0.502
50 %	0.059		0.057
75 %	**0.013**	0.309	

	0 %	50 %	75 %
0 %		**0.017**	0.606
50 %	0.063		**0.033**
75 %	**0.002**	**0.023**	

	0 %	50 %	75 %
0 %		**0.001**	0.108
50 %	0.114		**0.001**
75 %	**0.016**	**0.024**	

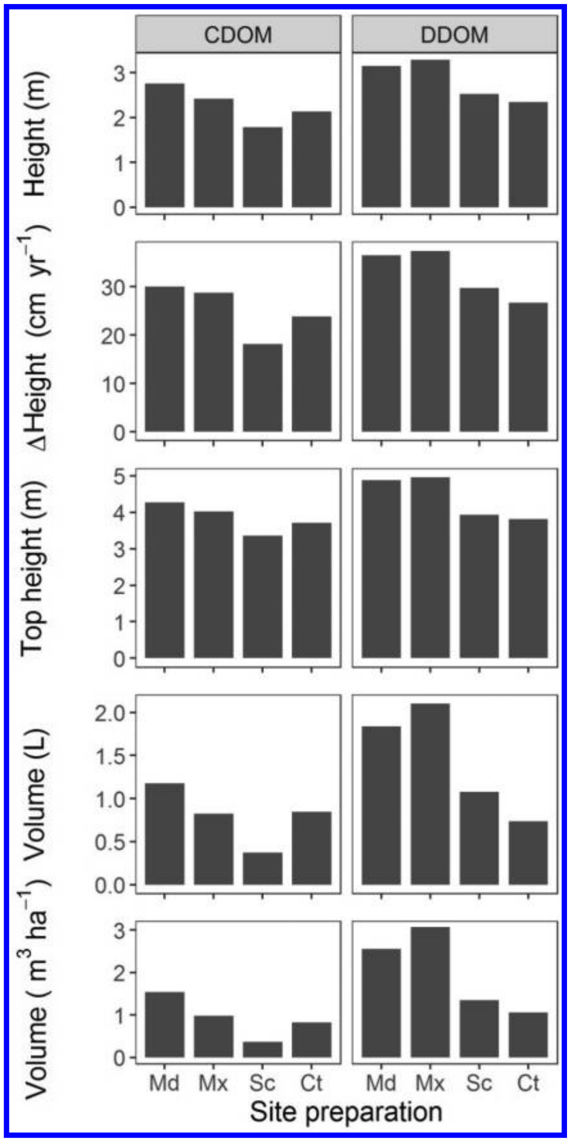
	0 %	50 %	75 %
0 %		**0.005**	0.289
50 %	0.062		**0.014**
75 %	**0.004**	**0.033**	

mineralization zones as a result of warmer soils or mixing of the organic layers (Neufeld et al. 2014). The scalp treatment tended to be better than the control for most performance variables in the DDOM sites, but it was worse than the control in the CDOM; the removal of the organic layer likely reduced nutrient availability (Gastaldello et al. 2007) that was sustained for a long period. The cold soils in the CDOM (Fenniak 2001) and the tendency for these locations to be wetter (and prone to flooding in the depressed scalps) might explain the poor performance of the scalp treatment here. There was a similar depression of growth of interior spruce with scalp treatment in sites that were prone to spring flooding (Sutton et al. 2001).

Projections forward

Our study indicates that the differences in cumulative size and volume for the spruce, for the various treatments at year 15, are likely to be sustained for some time into the future. This statement is supported by the fact for that means in height increment between years 11 and 15, the treatments sustained the same ranks as the cumulative data up to year 15 (Figs. 2 and 3). Hence, the differences among treatments are likely to be continued into the near future. In terms of the effects of mechanical site preparation, the height increment data suggest a long-term benefit of the mound and mixing treatments; however, as the roots of the planted trees should have expanded beyond the zone of soil treatment, the nutritional or thermal benefits of treatments on growth should be declining by this time. The apparent continued benefit of site preparation on growth of spruce beyond early establishment may be the result of placing these trees above competing vegetation and the mixing–mounding may also have increased mineralization (Gastaldello et al. 2007). There may also be other

Fig. 3. Means for growth variables for white spruce in relation to site preparation separately for the deciduous-dominated (DDOM) and coniferous-dominated (CDOM) compositions. The tables show the *P* values for the comparisons of different site preparation methods (Md, mound; Mx, mix; Sc, scalp; Ct, control) based on two-tailed tests done without multiple comparison adjustments. Values on the left of the diagonal are for CDOM and those on the right are for DDOM, e.g., the *P* value comparing mean height between mound and mix in the CDOM is 0.019. *P* values less than 0.05 are shown in bold.



	Md	Mx	Sc	Ct
Md		0.483	**0.005**	**0.001**
Mx	**0.019**		**0.001**	**<0.001**
Sc	**<0.001**	**<0.001**		0.361
Ct	**<0.001**	**0.046**	**0.015**	

	Md	Mx	Sc	Ct
Md		0.733	**0.018**	**0.002**
Mx	0.666		**0.008**	**0.001**
Sc	**0.002**	**0.004**		0.271
Ct	0.053	0.109	0.072	

	Md	Mx	Sc	Ct
Md		0.760	**0.002**	**0.001**
Mx	0.196		**0.001**	**<0.001**
Sc	**<0.001**	**0.003**		0.657
Ct	**0.009**	0.132	0.082	

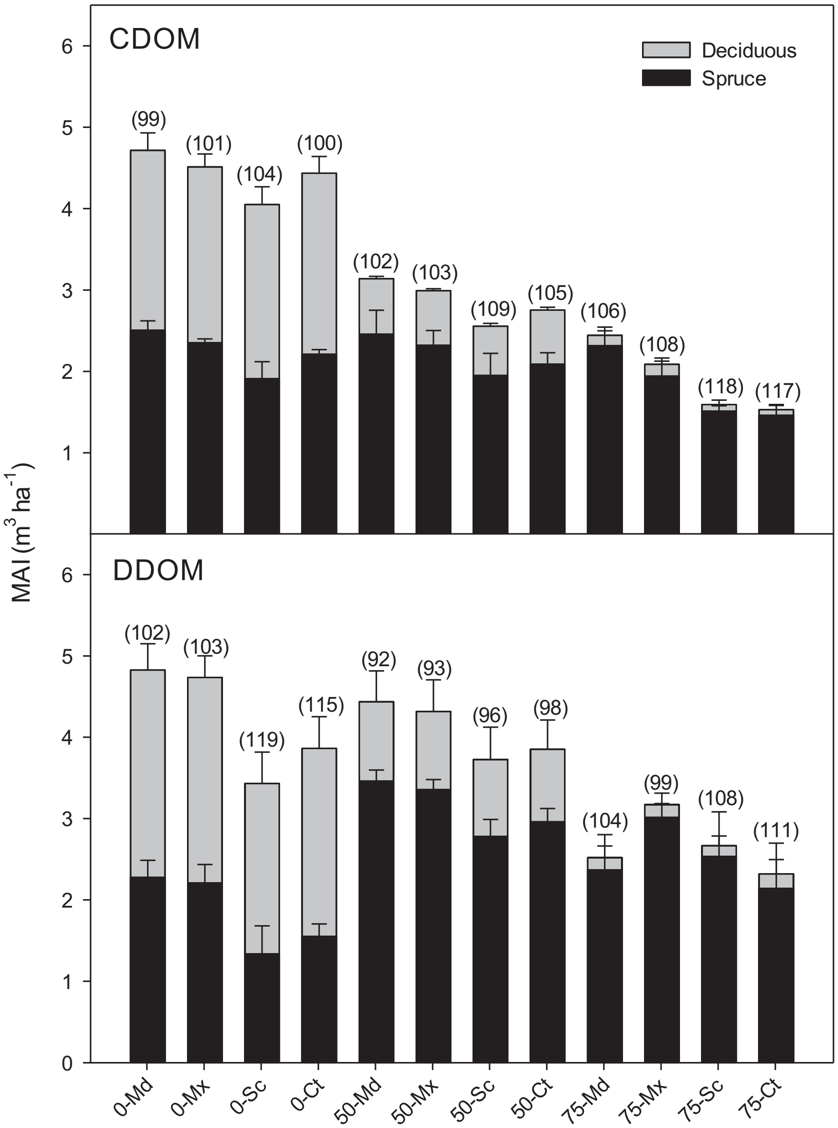
	Md	Mx	Sc	Ct
Md		0.491	0.068	**0.013**
Mx	0.271		**0.019**	**0.004**
Sc	**0.023**	0.167		0.378
Ct	0.299	0.945	0.149	

	Md	Mx	Sc	Ct
Md		0.345	**0.042**	**0.015**
Mx	0.111		**0.007**	**0.003**
Sc	**0.003**	0.081		0.576
Ct	**0.046**	0.633	0.185	

unforeseen benefits such as early colonization of roots by mycorrhizal fungi in mounds (Menkis et al. 2010) that sustain growth into the future. A sustained differential in height growth of spruce with mechanical site preparation can also be discerned in the data interval of 10–15 years for Sutton et al. (2001) and 15–19 years for Boateng et al. (2009). Continued benefits of mixing and mounding treatments between years 11 and 15 supports Hawkins et al.'s (2006) statement that appropriate site preparation is financially beneficial for timber production, although it appears that using 50% retention in deciduous-dominated stands had an even stronger effect on growth than the site preparation (Figs. 2 and 3; Appendix Table A1).

In this experiment, using the top heights of spruce trees at year 15 allowed for the estimate of site index (SI) (Appendix Table A1). Across the range of treatments, the estimated SI varied from 14.3 to 23.5 m (base age 50) (GYPSY 2009 DLL Interface). This is an enormous range in estimated SI in an experimental situation in which we assumed that the actual differences in site quality generated by the retention and site preparation treatments were only moderate. The estimated SI of spruce is likely strongly influenced by the amount of deciduous tree regeneration in this experiment (Table 1), but other factors likely also contribute (see above). In the deciduous-dominated stands with 0% overstory retention, the regenerating spruce had a heavy cover of juvenile aspen and balsam poplar. Such juvenile stands have high leaf area index (Lieffers et al. 2002), and it is likely that such a deciduous canopy would have a sustained suppression on height growth. This deciduous cover can suppress height growth of spruce over much of the life of the stand (Krebs 2016). In terms of effects of the residual overstory of mature trees, the effects on growth are already implicit in the top height of the spruce and are included in the GYPSY projection by reduction in SI. We expect, however, that the effects of these mature trees will decline with time as any release and crown enlargement of mature residual trees would be more than countered by their continued mortality as they age (Solarik et al. 2012). Despite our reservations about the accuracy of long-term model projections, the best overall MAI (4.7 m³·ha⁻¹) was projected to be from the 0% retention in the CDOM stands (Fig. 4)

Fig. 4. Modelled mean annual increment (MAI, m³·ha⁻¹, ±SE) of white spruce (black) and deciduous (aspen and balsam poplar trees; grey) within conifer-dominated stands (CDOM; top) and deciduous dominated (DDOM; bottom) by retention intensity (0%, 50%, and 75%) and site preparation (Md, mound; Mx, mix; Sc, scalp; Ct, control) combinations. Average stand age is indicated in parentheses.



where the regenerated poplars yielded about the same amount as spruce. The highest SIs of ~23 were achieved at 50% retention in the DDOM stands with mound and mix treatment (Appendix Table A1), and spruce MAI was projected to be ~3.4 m³·ha⁻¹ and culmination of MAI was early (~92 years). The estimated overall MAI in these stands was still good (~4.4 m³·ha⁻¹), indicating a relative shift in proportion of yield to the spruce with only the moderate addition of regenerated aspen and balsam poplar. The SIs and projected MAIs in these stands are in the range expected for plantations with vegetation management on better sites of Alberta (K. Stadt, personal communication). Even in the CDOM stands, the 50% retention also had projections of spruce growth that were about equal to that of the 0% retention, likely a reflection of the much lower regeneration density of poplars (Fig. 4).

Management recommendations

The EMEND study has indicated that increasing levels of biodiversity of the mature forest can be sustained after logging in proportion to the level of retention of the mature forest overstory for bryophytes (Bartels et al. 2018), spiders (Pinzon et al. 2018), and vascular plants (Macdonald and Fenniak 2007). Also, the influence of mature conifers in the overstory has a lasting influence on sustaining the biodiversity of redeveloping stands. Most timber managers, however, quietly view variable retention of mature trees as a loss of fibre and the residual trees as an impediment to growth of the regenerating trees. This study suggests that in the deciduous-dominated stands, leaving 50% of mature overstory trees produced conditions that produce greater yield of planted spruce compared with the 0% retention. A 50% canopy of mature deciduous trees was by far the best starting point for spruce growth in our study, where no vegetation control was applied. Coupling this canopy treatment with the mix or mound treatment produced superior results; however, we would direct managers to the mix treatment as it does not produce persistent holes on the site, with their visual and topographic impacts.

Relatively pure aspen and balsam poplar stands occur naturally in western Canada and could be the starting point for thinning the deciduous canopy and then planting spruce; in mixed composition stands, such residual deciduous canopy could be developed if mature spruce were removed leaving the deciduous trees as the shelter. The partial retention of deciduous overstory is also effective in reducing the sucker regeneration of the poplars on these sites (Gradowski et al. 2010). Once the planted spruce are well-established, overstory aspen might be left to slowly decline and be gradually replaced by the planted spruce and the juvenile deciduous trees in the understory; in essence, this would ensure a well-stocked spruce component in the natural succession. Alternatively, the mature aspen and balsam poplar might be removed after year 15 to firstly capture the economic value of mature deciduous trees and secondly reduce the breakage to the spruce caused by the fall down of the mature deciduous trees. Knowledge gained through the understory protection studies of natural mixedwood stands (MacIsaac and Krygier 2009) could guide the timing and design for removing of the mature trees.

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Appendix A

Table A1. Mean survival and growth characteristics at year 15 for planted white spruce (year 11–15 for height increment) in the EMEND experiment.

Retention (%)	Site preparation	Height (m)	Height increment (cm·year^{-1})	Top height (m)	Tree volume (L)	Stand volume (m^3·ha^{-1})	Survival (%)	Site index	Spruce MAI* (m^3·ha^{-1})	Total MAI* (m^3·ha^{-1})
Stand composition: CDOM										
0	Mound	3.3	37	4.8	1.7	2.4	88	20.6	2.51	4.72
	Mix	3.1	42	4.5	1.3	1.7	85	19.6	1.96	4.51
	Scalp	2.0	18	4.0	0.5	0.5	65	18.3	1.91	4.05
	Control	2.8	34	4.6	1.6	1.6	69	19.9	2.21	4.44
50	Mound	2.7	27	4.2	1.1	1.4	75	18.9	2.46	3.14
	Mix	2.3	24	4.1	0.8	0.9	69	18.4	2.32	2.99
	Scalp	1.9	20	3.4	0.4	0.5	66	16.7	1.95	2.56
	Control	2.1	22	3.8	0.7	0.7	60	17.8	2.09	2.76
75	Mound	2.3	26	3.7	0.7	0.8	72	17.5	2.32	2.44
	Mix	1.9	20	3.5	0.4	0.4	60	16.7	1.94	2.09
	Scalp	1.5	16	2.7	0.2	0.2	55	14.3	1.51	1.59
	Control	1.5	15	2.7	0.2	0.2	50	14.3	1.46	1.53
Stand composition: DDOM										
0	Mound	2.9	31	4.5	0.9	1.3	87	19.4	2.28	4.83
	Mix	2.6	26	4.4	0.7	0.9	84	19.2	2.21	4.73
	Scalp	1.7	17	2.7	0.2	0.2	72	14.2	1.34	3.43
	Control	1.9	20	3.1	0.2	0.3	78	15.6	1.55	3.86
50	Mound	4.2	52	6.2	3.6	5.1	88	23.5	3.46	4.44
	Mix	4.2	51	5.9	4.0	5.9	91	22.8	3.35	4.32
	Scalp	3.4	43	5.1	2.0	2.3	73	21.2	2.78	3.73
	Control	3.1	37	5.0	1.5	2.2	91	20.7	2.96	3.85
75	Mound	2.3	27	4.0	0.9	1.2	68	18.1	2.73	2.52
	Mix	3.0	35	4.6	1.7	2.4	91	19.9	3.02	3.17
	Scalp	2.5	29	3.9	1.1	1.5	85	17.8	2.53	2.67
	Control	2.0	23	3.4	0.4	0.6	74	16.4	2.14	2.32

Note: Treatments were stand composition, retention of mature canopy, and site preparation.

*Stands were projected to rotation using the performance age scenario tool of the GYPSY model (Alberta Environment and Sustainable Resource Development 2014). This is based on growing the stand to culmination of mean annual increment (MAI) of conifer stems; utilization of 15 cm bottom diameter, 10 cm top and 30 stump height; regular distribution of spruce stems and clumped distribution of deciduous stems.

Appendix Figures A1–A2 appear on following pages.

Fig. A1. Survival of planted white spruce in coniferous-dominated (CDOM) compartments (block) by retention intensity (top) and site preparation (right; Md, mound; Mx, mix; Sc, scalp; Ct, control) for year of measurement. Compartment number relates to the EMEND cutblock/control identification number. [Colour version available online.]

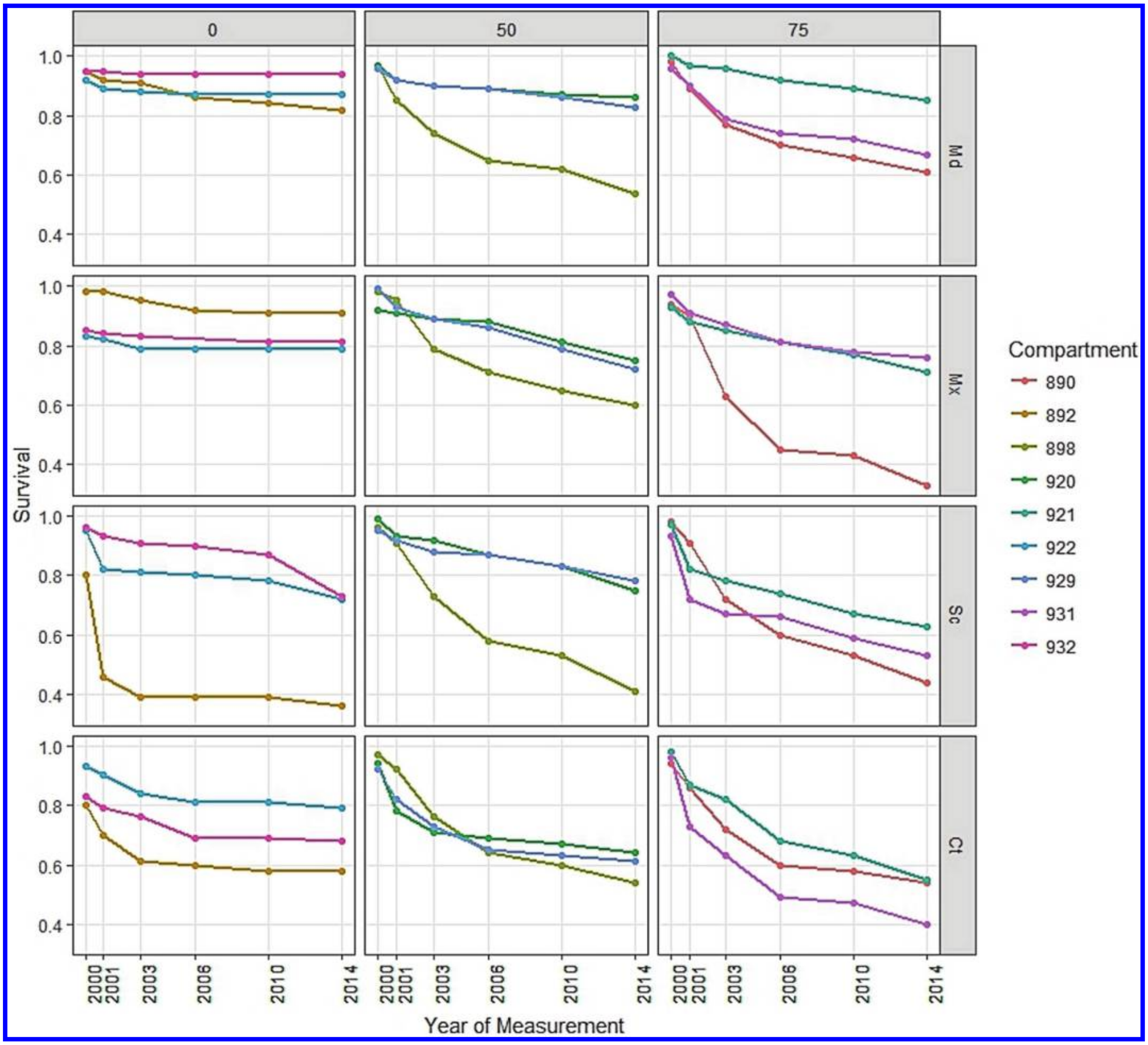

Fig. A2. Survival of planted white spruce in deciduous-dominated (DDOM) compartments (block) by retention intensity (top) and site preparation (right; Md, mound; Mx, mix; Sc, scalp; Ct, control) for year of measurement. Compartment number relates to the EMEND cutblock/control identification number. [Colour version available online.]