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**Creating boreal mixedwoods by planting spruce under aspen: successful
establishment in uncertain future climates**

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Abstract

Planting white spruce under established aspen stands has substantial potential for regenerating mixedwood ecosystems in the western Canadian boreal forest. The presence of an aspen overstory serves to ameliorate frost and winter injury problems and suppresses understory vegetation that may compete with white spruce. Under future climatic regimes with more frequent and severe drought episodes, underplanting may be a cost-effective strategy for lowering the risk of mortality in mixedwood regeneration. We examine the growth of white spruce during the first 18 years after being planted beneath a 39 year old stand of trembling aspen. Treatments included thinning from over 6000 stems ha^{-1} to 3000, 2000 and 1000 stems ha^{-1} , and fertilization. Initial stimulation of understory vegetation by fertilization had no measureable effect on spruce heights or diameters at year 18. Aspen thinning treatments did not have a significant effect on spruce height growth rates after spruce crowns had emerged above the understory shrub layer due to rapid aspen basal area increases post-thinning. Small, but significant increases for spruce height and diameter were present in the 1000 and 2000 stem ha^{-1} aspen thinnings. A much wider range of aspen stand conditions may be suitable for planting spruce to create mixedwood ecosystems than has been previously considered.

Keywords: white spruce, aspen, boreal mixedwood, underplanting, thinning

Introduction

The underplanting of mature (40 – 60 year old) trembling aspen (*Populus tremuloides* Michx.) stands with white spruce (*Picea glauca* (Moench) Voss) has been recommended as a feasible mixedwood management silviculture practice that would result in stands similar in structure to many natural mixedwood stands (DeLong 2000, Lieffers and Grover 2004). Experimental underplantings of aspen stands with white spruce were first established in the western Canadian boreal forest in the 1960's (Duffy 1963), and there was a resurgence of interest in the topic in the 1990's (Lieffers and Grover 2004). Reports of good survival and early growth of underplanted spruce in various settings (Stewart et al. 2000; Comeau et al. 2004, 2009) support the application of this technique in boreal mixedwoods.

Moisture deficits or temperature induced drought stress have defined the more recent boundaries between white spruce forest ecosystems and grasslands (Chhin and Wang 2008). Northern expansion of grassland climates and declines in boreal forest ecosystems have been predicted under several climate change scenarios in western North America (Mbogga et al. 2010, Rehfeldt et al. 2012). Western Canadian boreal forests may be particularly vulnerable to the combined effects of multi-year droughts (Wang et al. 2014), drought induced mortality of susceptible tree species (Hogg 2001, Hogg and Bernier 2005), increased fire frequency (Haughian et al. 2012, de Groot et al. 2013), and human caused disturbances (Nlungu-Kweta et al. 2014). Increasing fire frequency could change the dynamics of conifer recruitment under aspen stands (Nlungu-Kweta et al. 2014). With projected changes in climate, it is likely that dramatic and unexpected changes may occur in boreal ecosystems (Price et al. 2013). Some modelling studies have suggested that the current aspen parkland ecosystems might be replaced

by grasslands, and that upland mixedwood forests might be replaced by aspen dominated types (Hogg and Bernier 2005, Schneider et al. 2009).

Boreal forests in north-eastern British Columbia have historic (1961-1990) annual climatic moisture deficits ranging from 172 mm in Dawson Creek to 122 mm in Fort Nelson, which are projected to increase by 38 mm in Dawson Creek, and 29 mm in Fort Nelson by the 2050's (Wang et al. 2012, <http://climatemodels.forestry.ubc.ca/climatebc/downloads>). With a lesser degree of change in climate, modification of current stand level practices may be effective in maintaining current forests at the level of stands and landscapes. The projected increases of mean annual temperature in north-eastern BC (<http://www.pacificclimate.org/news-and-events/news/2013/regional-climate-summaries>) of over 3.2 °C would reach the threshold of conditions where 'novel silviculture', or a wider array of silviculture practices and sources of knowledge, needs to be considered to regenerate desired future forests (Park et al. 2014). Changing climates may favour strategies of establishing regeneration under an existing forest cover (Park et al. 2014), adding new dimensions to the traditional silvicultural view of how overstory trees modify the environment of seedlings and saplings (Pommerening and Murphy 2004), in particular the balance between water conservation, evapotranspiration and consumption by the mature forest.

In boreal ecosystems conifer regeneration generally occurs long after the initial disturbance and often continues throughout the life of the stand (Bergeron et al. 2014). Underplanting of conifers is a management option to maintain this feature in the boreal forests which develop under future climates, particularly if spruce seed sources are decreased on the landscape. When spruce seedlings are planted under 40 to 60 year old aspen canopies, they are less vulnerable to stochastic factors such as weather and the combinations of seed source,

seedbed, and microclimate required for successful white spruce natural regeneration summarized by Gartner et al. (2011).

Compared to a clearcut, the growing environment under a mature aspen canopy has reduced risk for growing season frost (Groot and Carlson 1996, Pritchard and Comeau 2004), and white pine weevil (*Pissodes strobi* Peck) incidence (Taylor et al. 1996). Moisture conditions for underplanted spruce are also expected to be superior due to the greater relative humidity and lower temperature (Marsden et al. 1996) and improved rooting zone soil moisture conditions created by redistribution of soil water by the aspen root system (Brown et al. 2014).

This study builds on the previous work of Comeau et al. (2004, 2009) describing the effects of fertilization and thinning treatments carried out in aspen stands on the initial growth of white spruce planted beneath them. Fertilization stimulated understory vegetation and did not benefit the planted spruce (Comeau et al. 2004). Thinning to 2000 and 1000 stems ha⁻¹ did not increase the light reaching seedlings during the growing season when spruce crowns were primarily below the 1.5 m tall shrub layer (Comeau et al. 2009). However, there were small, statistically significant increases in spruce height and diameter for the 1000 and 2000 stems ha⁻¹ thinnings compared to the control and 3000 stems ha⁻¹ thinning (Comeau et al. 2004, 2009). The significant differences in spruce growth between aspen treatments are likely due to differences in seasonal light transmission; that is, when deciduous trees and understory plants are not fully leafed out (Constabel and Lieffers 1996, Chen et al. 1997, Prevost and Pothier 2003), the conifers are photosynthetically active (Man and Lieffers 1997). In previous studies, photosynthetically active radiation levels declined rapidly between May 15 and June 8 as deciduous trees and shrubs leafed out (Comeau et al. 2009) and increased rapidly after August 30 with leaf senescence measured at 1.5 m above ground level. At the end of September light levels

in the 2000 st ha⁻¹ treatment were 40% of the open sky values, while control and 3000 st ha⁻¹ treatments had only 30% of open sky values (Comeau et al. 2009).

Continued examination of long term experiments allows for the testing of new hypotheses, for example, the environment under aspen stands would be more favourable than a conventional clearcut for survival and growth of planted spruce under changing future climates. We also need to consider the validity of early experimental results as the influence of different ecosystem components, such as the shrub layer, varies with continued height growth of spruce.

This paper presents 18 year results from two studies conducted to examine the growth of spruce following underplanting. The first study (Sierra Road, near Fort Nelson, British Columbia) involved underplanting spruce in plots that were previously established for a factorial experiment designed to examine the effects of thinning and fertilization on a 39 year old trembling aspen stand. We also present results from analysis of data from a second study established in 1993 by DeLong (2000) near Dawson Creek, British Columbia, where spruce were underplanted in two untended stands that were approximately 45 years old. Data from both studies are used to examine height and diameter growth of underplanted spruce, and to determine if survival, height and diameter growth during the first 18 years is similar in untended aspen stands at the two locations.

Hypotheses being investigated are:

- i) Thinning aspen improves conditions for growth of planted white spruce
- ii) Fertilizing aspen impedes establishment of white spruce
- iii) Underplanted spruce growth rates increase when the spruce canopy layer becomes taller than the 1.5 m shrub layer.

Materials and Methods

Sierra Road study

The Sierra Road experiment was established in the fall of 1991 in a 39 year-old aspen stand located 85 km east of Fort Nelson, B.C. (58° 45' N, 121° 37' W). The site was classified as a Trembling aspen – Green alder – Highbush cranberry site series (BWBSmk/101\$6B.1, DeLong et al. 2011) with a mesic soil moisture regime and medium nutrient regime on loam texture soils with gently undulating topography. The original intent was to examine the effects of spacing and fertilization on aspen growth. The experiment involved 4 levels of spacing: 1) untreated (basal area 35.2 m²·ha⁻¹, between 6000 and 8000 stems·ha⁻¹); 2) 3000 stems·ha⁻¹ (basal area 27.7 m²·ha⁻¹, 1.83 m square spacing); 3) 2000 stems·ha⁻¹ (basal area 19.9 m²·ha⁻¹, 2.24 m square spacing); and 4) 1000 stems·ha⁻¹ (basal area 12.5 m²·ha⁻¹, 3.16 m square spacing). Spacing treatments were completed during fall of 1991 using chainsaws, with slash left untreated on the ground. The four levels of fertilization used in this study were: 1) untreated; 2) 100 kg·ha⁻¹ of N applied as ammonium nitrate; 3) 200 kg·ha⁻¹ of N applied as ammonium nitrate; and, 4) a complete fertilizer mix comprising 200 kg·ha⁻¹ of N (ammonium nitrate) plus 100 kg·ha⁻¹ phosphorus, 100 kg·ha⁻¹ potassium, 25 kg·ha⁻¹ magnesium, 50 kg·ha⁻¹ sulphur, and 1.5 kg·ha⁻¹ boron. Fertilizer was applied in the selected plots by hand during June of 1994. A randomized block design was used, with three separate blocks each containing sixteen 40 m by 40 m plots. The original plan was to apply each of the 16 thinning-fertilizer combinations to one plot per block; however, errors during treatment application resulted in some treatments being repeated more than once in certain blocks and some treatments not occurring in certain blocks.

In 1996, each plot was planted in early July with container (2+0 415B Styroblock) grown white spruce seedlings at a density of 1300 stems·ha⁻¹ (2.8 m square spacing). Seedlings were

planted in a regular pattern with up to 0.5 m variation allowed in spacing if required to avoid debris piles or living aspen stems. The central 20 m by 20 m area in each plot was chosen as the assessment area and 20 spruce seedlings within the plot were tagged for repeated assessment. Height and root collar diameter were measured in 1999, 2002, and 2007. In 2007 spruce measurements were limited to two fertilizer treatments (control and nitrogen plus micronutrients). Height and diameter at 1.3 m (dbh) were measured for all treatments in 2014. Damage resulting from hare browsing or other factors was noted at the time of measurement. Between 2007 and 2014 three plots located in two blocks at Sierra Road were lost as the result of road construction or oil and gas exploration activities.

All the live aspen taller than 1.5 m in 2003 and 2014 were measured for dbh within the central 20 m x 20 m (400m²) permanent sample plot.

Dawson Creek Study

Results from underplanting of 1-year old container grown (1+0 415B Styroblock) spruce seedlings in two aspen stands, located near Dawson Creek, B.C. (55°35'N, 120°50'W) were examined to evaluate overall trends in eighteen year height growth. This is one component of a much larger study described by DeLong (2000). The two additional sites used for this component of the study were 45 and 42 years old, having basal areas of 23.8 m²·ha⁻¹ and 32.2 m²·ha⁻¹ and densities of 3100 and 2400 stems·ha⁻¹ respectively when spruce seedlings were planted. These two sites had south to southwest aspects and submesic to subhygric soil moisture regimes, classified as Trembling aspen – Prickly rose – Creamy peavine site series (BWBSmw 101\$6B.1, DeLong et al. 2011). In each stand, seedlings were planted in 1993, with planting locations for each tree selected to be as far from adjacent aspen stems as possible, while trying to

achieve an overall planting density of 1120 stems·ha⁻¹. Shrub and herbaceous vegetation were removed by clipping within a 1 m radius surrounding each planted seedling immediately prior to planting. Height, root collar diameter and dbh (when 1.3 m height was achieved) were measured regularly between 1993 and 2015 (year 18 post planting). At year 15, circular permanent sample plots were established within the original rectangular plots, which reduced the number of trees being measured. Survival is reported on all trees monitored from planting to year 15 at the Dawson Creek site. Damage resulting from hare browsing or other factors was noted at the time of measurement.

Data analysis

Data analysis was completed using SAS (SAS Institute Inc., Cary, North Carolina). An ANOVA of the growth performance of planted spruce was carried out by fitting the following mixed-effects model:

$$(1) \quad y_{ijklm} = \beta_i + \mu + \alpha \times h_{ijklm} + S_j + F_k + SF_{jk} + \delta_{l(ijk)} + \varepsilon_{m(ijkl)}$$

where i, j, k, l , and m denote respectively block, spacing level, fertilizer level, plot, and tree; y_{ijklm} is the 2014 (18 years post planting) growth variable of interest (height, DBH, etc.) and h_{ijklm} is the corresponding height in 1997 (as measured in 1999); μ is the overall (fixed) mean; and $\alpha \times h_{ijklm}$ is the fixed effect of planting height, which was included to adjust for initial differences unrelated to treatment; S_j , F_k , and SF_{jk} are respectively the fixed main and interactive effects of spacing and fertilizer; and β_i , $\delta_{l(ijk)}$, and $\varepsilon_{m(ijkl)}$ are respectively the random effects of block, plot (block $\times$ spacing $\times$ fertilizer interaction), and tree. All random effects were assumed to be independent and normally distributed, with mean 0 and respective variances σ^2_β , σ^2_δ , and σ^2 . Model parameters were estimated by the restricted maximum likelihood method (REML method, PROC MIXED).

The statistical significance of the main and interactive effects of spacing and fertilizer were tested by pseudo-F tests with denominator degrees of freedom approximated by the Satterthwaite method. Adjusted least-squares means (assuming a common planting height of 27 cm) were calculated for the main and interactive effects of spacing and fertilizer. Mean differences, estimated standard errors, and unadjusted p-values based on the corresponding t-tests (Bonferroni-adjusted p-value = $6 \times$ unadjusted p-value) were calculated for all pairs of spacing levels. Fertilizer differences were found to be small and not statistically significant, and are not reported. Differences between the mean growth of spruce underplanted in control plots (no spacing or fertilization) at the Sierra Road site (Fort Nelson) and the corresponding growth at the Dawson Creek site were tested by applying a t-test (with degrees of freedom approximated by the Satterthwaite method) to the respective least-squares (year 18) means.

Results

Survival of white spruce at Sierra Road 18 years after planting was between 95 and 99% (Table 1) and 95 to 97% at year 15 in Dawson Creek. Incidence of damaging agents was very low in at both sites (data not shown).

Results of the ANOVA of fertilization and aspen spacing effects on spruce growth (using height at planting as a covariate) are summarised in Table 2. Aspen spacing had a significant effect on spruce height, diameter at 1.3 m, and height/diameter ratio (Table 2a). Spruce height at age 18 decreased with increasing aspen density (Figure 1). It was lowest for the control and the

Figure 1. Mean spruce height ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

treatments, with no significant difference between the two treatments, and greatest for the 1000 st ha⁻¹ and 2000 st ha⁻¹ treatments, again with no significant difference between those two treatments. Spruce diameter increased with thinning (Figure 2) with significantly larger diameters for the 1000 st ha⁻¹ and 2000 st ha⁻¹ treatments compared to the control and 3000 st ha⁻¹ treatments (resulting, respectively, in estimated gains of 64 ± 26 (mean $\pm$ standard error) mm and 45 ± 24 mm relative to the control, and 75 ± 27 mm and 56 ± 26 mm relative to the 3000 st ha⁻¹ treatment). The spruce height/DBH was significantly lower in the 1000 st ha⁻¹ and 2000 st ha⁻¹ treatments (-36 ± 12 and -25 ± 12 , respectively; Figure 3), compared to the 3000 st ha⁻¹ treatment, but there was no significant difference when compared with the control.

Spacing had only a marginally significant effect ($p = 0.11$) on mean spruce height increment between 2002 and 2014 (Table 2b, Figure 4); the largest differences were between the 1000 st ha⁻¹ and 3000 st ha⁻¹ treatments (3 ± 2 cm/year, $p = 0.04$) and between the 1000 st ha⁻¹

239 Figure 2. Mean spruce breast height (1.3 m) diameter ($\pm$ standard error) in 2014 for the aspen
 240 thinning treatments at Sierra Road.

241
 242 Figure 3. Spruce height/dbh ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra
 243 Road.

244
 245 treatment and the control (3 ± 1 cm/year, $p = 0.06$). The aspen spacing treatment had no
 246 significant effect (Table 2b) on mean spruce height increment between 2007 and 2014. There
 247 was a significant difference in root collar diameter growth for the spacing treatments between
 248 2002 and 2007 (Table 2b), the largest differences were between the 1000 st ha^{-1} and 3000 st ha^{-1}

treatments (5 ± 2 mm/year, $p=0.03$). There were no significant difference ($p=0.45$) between the control and 3000 st ha⁻¹ treatments or the 1000 and 2000 st ha⁻¹ treatments ($p=0.88$) for root collar diameter growth between 2002 and 2007. Root collar diameter measures were not done in 2014, and only 48 spruce were measured for DBH in 2007. As a result, differences between aspen thinning treatments for spruce root collar diameter or DBH increments from 2007-2014 could not be tested.

Figure 4. Mean spruce height increment 2002 – 2014 ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Mean spruce heights at age 18 for the control aspen treatment at the Sierra Road and Dawson Creek sites, 2.29 ± 0.21 m and 2.22 ± 0.08 m, respectively, were not significantly different ($p = 0.78$). Likewise, the estimated mean spruce diameters, for the control aspen treatment, 1.82 ± 0.28 cm and 1.69 ± 0.11 cm, did not differ significantly ($p = 0.66$) between the two sites. Height to dbh was 149 at Sierra Road and 145 at Dawson Creek.

During the 1993 to 2014 measurement period, aspen stand mean density declined at the Sierra Road site (Table 3) and basal area increased for all aspen spacing treatments. Between

1992 and 2003 the 3000 st ha⁻¹ treatment had increased basal area to 36.3 m² ha⁻¹, which was very similar to the control at 38.5 m² ha⁻¹ (Table 3). By 2014 the 3000 st ha⁻¹ treatment had a greater basal area than the control. The 2000 st ha⁻¹ treatment had the greatest basal area growth between 2003-2014, and 2014 basal area for this treatment was only 8.5% less than the control (Table 3).

Discussion

At the Sierra Road site, white spruce had good survival and acceptable early growth rates. There was no detectable difference in spruce survival between the different aspen densities at Sierra Road, and no apparent difference in spruce survival between Fort Nelson and Dawson Creek. These rates compare favorably with the 20 year survival rates from Alberta underplanting done in the 1960's, which ranged from 28 to 83% (unpublished data 1983, Forestry Canada Project A.83 – as cited by DeLong 2000) and five year survival of trees planted on scarified strips under aspen in Manitoba which averaged 73% (Dyck 1994). The greatest occurrence of hare damage was observed in year 5 at Sierra Road (Comeau et al. 2004) and at a similar age at the Dawson Creek sites. The occurrence of other damaging agents was minor at both Sierra Road and Dawson Creek in the first 18 years after planting, consistent with the reduced incidence of damaging agents such as white pine weevil (Taylor et al. 1996) in boreal mixedwoods.

Fertilization of the aspen stand did not have significant positive or negative consequences for white spruce growth eighteen years after planting. Initially, fertilization stimulated growth of understory vegetation and increased the Leaf Area Index (LAI) of the understory vegetation layers (Comeau et al. 2004).

The differences in mean height between treatments were statistically significant but relatively small during the measurement period, since the change in light levels created by the aspen thinning treatments were limited to the beginning and end of the growing season (Comeau et al 2009). At the Sierra Road site the differences were 10 cm at year 5 (Comeau et al. 2004), approximately 30 cm in year 10 (Comeau et al. 2009), and approximately 45 cm year 18, representing 20% greater height in the 1000 st ha⁻¹ treatment compared to the control. The 1000 and 2000 st ha⁻¹ treatments had greater diameters and lower height/diameter ratios than the control and 3000 st ha⁻¹ treatments. These results reflect the fact that diameter growth of conifers is more sensitive to competition than height growth (Lanner 1985). *Viburnum* and *Rosa*, which dominated this study site, do not form the extremely light limiting shrub layers found in other aspen ecosystems, e.g. those comprising *Corylus* and *Acer* in central Manitoba and eastern Canadian boreal forests (Waldron 1959, Trottier 1981, Kembell et al. 2005). There may be additional interactions between spruce seedlings and shrubs below ground which this study design was unable to examine (Montgomery et al. 2010).

It was anticipated that there would be a clear acceleration of spruce growth with better light availability in the more open aspen spacings, which should have enabled growth through the understory shrub layer into an even better light environment. There was no evidence that spruce in the less dense aspen environments had a significantly more rapid growth rate as they grew above the understory shrub layer. There were no significant differences in spruce height growth rates between the four aspen treatments in the more recent 2007 – 2014 measurement interval. The relationship between the different aspen thinning treatments for root collar diameter growth 2002 – 2007 was similar to the relationship for spruce DBH in 2014, where it was lowest for the control and the 3000 st ha⁻¹ treatments, with no significant difference between

the two treatments, and greatest for the 1000 st ha⁻¹ and 2000 st ha⁻¹ treatments, again with no significant difference between those two treatments.

Differences in aspen basal area between the treatments were much smaller in 2014 than when the experiment was established in 1992 (Table 3), as the retained aspen responded rapidly to the available growing space on this productive site. As the planted spruce were emerging through the shrub canopy, ten years after the aspen spacing took place, the initial differences in basal area and aspen canopy light environments had decreased. The benefits to the spruce portion of the mixedwood stand from the aspen thinning treatments were small but statistically significant. With a commercial thinning of the aspen, there would be improved growing conditions for both species. In the absence of economically viable aspen thinning treatments, these results indicate that spruce could be successfully planted under a relatively wide range of aspen basal area conditions, with appropriately lower expectations for initial spruce growth rates.

The growing environment in a clearcut has greater and more variable air temperatures throughout the growing season, and greater soil temperatures, than under an aspen canopy (Carlson and Groot 1997). At the Sierra Road site, there were dramatic differences in growing degree days (GDD) between the aspen stands (GDD 699 – 754) and an adjacent open area (GDD 1067) (Comeau et al. 2009). Differences between the different aspen densities in their associated air temperatures and GDD were relatively small. Based on the Sierra Road site, a range of aspen densities greater than 1000 st ha⁻¹ at age 40 or a minimum basal area of 12 m² ha⁻¹ could provide an ameliorated environment for the establishment of spruce under the more variable and stressful climates predicted for the future.

Underplanted white spruce have lower rates of height and diameter growth than spruce grown in clearcuts. The total heights of underplanted spruce at the Sierra Road site ranged from

2.7 to 2.3 m compared to 3.3 m tall white spruce with a ht/dbh of 117 in a fifteen year old clearcut near Fort Nelson which were mixed with aspen (unpublished data from remeasurement of Kabzems et al. 2011). In the same experiment, the white spruce in a vegetation control treatment (glyphosate) averaged 4.3 m in height with a ht/dbh of 85 (unpublished data from remeasurement of Kabzems et al. 2011).

The goal of underplanting is to set the stage for a harvest of the mature aspen canopy in the future, while retaining sufficient spruce to create an additional harvest opportunity. The underplanted spruce at the Sierra Road site is predicted to reach a sufficient height (4 m, Johnson 1986) within 30 years of planting, to stay above post harvest aspen regeneration. A height to diameter ratio less than 100 would reduce windthrow risk (Navratil 1996) after aspen harvest in the application of an understory protection management approach (Grover et al. 2014). However, the design of leave strips to provide adequate wind protection is far more critical to retaining spruce post harvest (MacIsaac and Krygier 2009).

Underplanting is a technique which is consistent with recommended forest management options for adapting to climate change. Regeneration of white spruce in a less stressful environment will increase the chance of subsequent regeneration success in managed forests (Johnston et al. 2009). The identification of novel silviculture applications will enhance adaptive capacity (Johnston et al. 2009). The establishment of mixed species and uneven-aged stands enhances ecosystem resiliency (O'Hara and Ramage 2013). Aspen canopies facilitate building of snow pack and greater water yield (LaMalfa and Ryle 2008) which conserves snow and soil moisture in the drier environments of the western Canadian boreal forest (Wang et al. 2014). Given the current future climate projections, these positive hydrologic features of aspen dominated stands become more valued for the successful establishment of spruce.

Our results provide encouraging evidence for operational implementation of planting spruce under aspen. In this regard, we recommend further research on a number of topics to support successful adoption of this novel management practice. There needs to be careful examination of implications for future timber supply through growth and yield modelling. The valuable knowledge of protecting spruce understory during aspen harvest (MacIsaac and Krygier 2009) needs to be incorporated into landscape level planning as well as day-to-day harvesting operations. The economic implications of this novel mixedwood practice need to be evaluated both spatially, in the context of timber supply analysis, and temporally, as projections over mid-term and long-term timeframes.

Conclusions

Planting spruce under aspen could be a viable approach for a wider range of aspen and understory light conditions than have been initially suggested in the literature. There was a statistically significant growth benefit of approximately 25% in height and 40% in diameter, conferred by planting spruce into aspen stands where basal area was reduced by thinning. In addition, spruce in lower basal area aspen stands had lower height/dbh which would make the spruce less susceptible to windthrow after an aspen harvest. Moreover, a lower aspen stem density would contribute to reduced damage to retained spruce when the aspen overstory is removed during understory protection harvesting.

The moderated environment under aspen is likely to become increasingly advantageous if more frequent and sustained drought episodes are a critical feature of future climates.

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518 Table 1. Summary of spruce survival to 2014, by aspen spacing treatment at the Sierra Road
519 site and year 15 survival at the two Dawson Creek sites.

Aspen spacing treatment	Survival (%)
Control	95
3000 stems ha ⁻¹	96
2000 stems ha ⁻¹	98
1000 stems ha ⁻¹	99
Dawson Creek	95 - 97

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523 Table 2a. Analysis of Variance of planted white spruce diameter, height, and height/dbh in 2014.

Effect	Diameter @ 1.3 m			Height			Height/dbh		
	df	F Value	Prob $\geq F$	df	F Value	Prob $\geq F$	df	F Value	Prob $\geq F$
Height 1997	1	42.04	<.01	1	65.35	<.01	1	4.24	0.06
Spacing (S)	3	3.72	0.02	3	3.02	0.05	3	3.09	0.04
Fertilizer (F)	3	0.02	1.00	3	0.03	0.99	3	0.85	0.48
S x F	9	0.67	0.73	9	0.92	0.52	9	0.54	0.84

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525 Table 2b. Analysis of Variance of planted white spruce height increment 2002-2014, height
526 increment 2007-2014, and root collar diameter growth 2002-2007.

Effect	Height increment 2002-2014			Height increment 2007-2014 (2007 sub-sample)			Root collar diameter growth 2002-2007 (2007 sub-sample)		
	df	F Value	Prob $\geq F$	df	F Value	Prob $\geq F$	df	F Value	Prob $\geq F$
Height 1997	1	34.54	<.01	1	10.37	<.01	1	13.90	<.01
Spacing (S)	3	2.18	0.11	3	0.73	0.55	3	3.00	0.07
Fertilizer (F)	3	0.01	1.0	1	0.93	0.35	1	0.40	0.53
S x F	9	1.11	0.39	3	0.28	0.84	3	0.69	0.57

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Table 3. Summary of aspen stand mean density and basal area in 1992, 2003 and 2014, by treatment at the Sierra Road site.

Aspen spacing treatment	1992		2003		2014	
	Stems ha ⁻¹	Basal area (m ² ha ⁻¹)	Stems ha ⁻¹	Basal area (m ² ha ⁻¹)	Stems ha ⁻¹	Basal area (m ² ha ⁻¹)
Control	5271	35.2	3492	38.5	1952	38.9
3000 stems ha ⁻¹	3026	27.7	2704	36.3	1839	39.8
2000 stems ha ⁻¹	1942	19.9	1840	28.9	1523	35.6
1000 stems ha ⁻¹	1011	12.5	960	23.1	881	27.3

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Figure 1. Mean spruce height ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Figure 2. Mean spruce breast height (1.3 m) diameter ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Figure 3. Spruce height/dbh ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Figure 4. Mean spruce height increment 2002 – 2014 ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Figure 1. Mean spruce height ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Figure 2. Mean spruce breast height (1.3 m) diameter ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Figure 3. Spruce height/dbh ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

Figure 4. Mean spruce height increment 2002 – 2014 ($\pm$ standard error) in 2014 for the aspen thinning treatments at Sierra Road.

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