

FINAL contract report

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Potential impacts of including broadleaf trees in managed boreal and sub-boreal forest stands in British  
Columbia: A literature review

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## **1 Introduction**

### **1.1 Objective and scope**

The objective of this literature review is to provide a comprehensive summary of the potential impacts of including broadleaf trees in managed boreal and sub-boreal stands in British Columbia. Comparisons are made between mixedwoods and “pure” stands. The terms of reference for the project included:

- Consideration of all forest values, not just productivity/ growth and yield.
- An emphasis on white-spruce-trembling aspen and lodgepole pine-trembling aspen mixtures. Literature pertaining to lodgepole pine-aspen mixtures was found to be limited so the majority of the review deals with the white spruce-aspen combination.
- Inclusion of information from other species combinations that occur in conifer-broadleaf mixtures in British Columbia and northern Alberta such as paper birch, balsam poplar, jack pine and black spruce where information for spruce-aspen and lodgepole pine-aspen forests is limited.
- A focus on information from the Boreal White and Black Spruce (BWBS) and Sub-Boreal Spruce (SBS) biogeoclimatic zones in British Columbia, but information from other similar areas was to be included where local data is lacking or limited.
- An emphasis on published and peer-reviewed literature.

The review brings together results from studies that have investigated the influence of including broadleaf trees (especially aspen) in forest stands on the following values: achievement of free-growing; economics; wood quality; timber productivity/ growth and yield; carbon storage; resources needed for tree growth (light, soil moisture soil temperature, and soil nutrients and soil properties); forest health (insects, diseases, animal damage, and frost); biodiversity including soil biota, ectomycorrhizal fungi ,coarse woody debris, birds, mammals, and understorey vegetation; hydrology; fire hazard; cultural values; and visual values.

For the purposes of this review “mixedwoods stands” are defined as forest stands on boreal or sub-boreal mixedwood sites in which two or more species occur together with no one species comprising more than 80% of the total basal area. An exception to this was made for literature which defined mixed stands as having at least 70 or 75% of the stand in a single species, rather than 80%. A mixedwood landscape is defined as an aggregation of tree communities on boreal or sub-boreal sites in which no single tree species comprises 80% or more of the aggregated total basal area, within a defined physiographic boundary (from University of Northern British Columbia 2002). Stands that occur across the landscape may be mixed or single-species.

### **1.2 Past reviews**

A number of literature reviews and meta-analyses have already been completed for British Columbia and elsewhere that address how inclusion of broadleaf trees in forest stands affects various forest values. These publications are listed below. Most focus on boreal/northern forests.

1. Astrup, A. 2005a. Review of the relationship between light availability and growth of understorey pine. B.C. Min. For. Range, Res. Br., Victoria, B.C.
2. Astrup, R. 2005b. Review of the relationship between light availability and growth of understorey spruce. B.C. Min. For. Range, Res. Br., Victoria, B.C.
3. Cavard, X., S.E. Macdonald, Y. Bergeron, and H.Y.H. Chen. 2011. Importance of mixedwoods for biodiversity conservation: evidence for understorey plants, songbirds, soil fauna, and ectomycorrhizae in northern forests. *Environ. Rev.* 19:142–161.
4. Davis, I. 1998. Non-crop vegetation, detrimental or not? Redefining free-growing. B.C. Min. For., For. Pract. Br., Victoria, B.C.
5. Hart, S.A. and H.Y.H. Chen. 2006. Understorey vegetation dynamics of North American boreal forests. *Critical Rev. Plant Sci.* 25:381–397.
6. Jarvis, J.M., G.A. Steneker, R.M. Waldron, and J.C. Lees. 1966. Review of silvicultural research. White spruce (*Picea glauca*) and trembling aspen (*Populus tremuloides*) cover types, mixedwood forest section, boreal forest region, Alberta–Saskatchewan–Manitoba. *Aspen Bibliography*, Pap. 5882.
7. Johnson, H.J. 1986. The release of white spruce from trembling aspen overstories: a review of available information and silvicultural guidelines. *Dep. Nat. Resourc., For. Br. Man.*
8. Macdonald, E., N. Lecomte, Y. Bergeron, S. Brais, H. Chen, P. Comeau, P. Drapeau, V. Lieffers, S. Quideau, J. Spence, and T. Work. 2010. Ecological implications of changing the composition of boreal mixedwood forests: a state of knowledge report. *Sustainable Manag. For. Netw.*, Edmonton, Alta.
9. Rothe, A. and D. Binkley. 2001. Nutritional interactions in mixed species forests: a synthesis. *Can. J. For. Res.* 31:1855–1870.
10. Schofield, S., N. Gooding, and M. Peterson. 2003. Options for managing spruce and Douglas-fir in combination with aspen (deciduous) and measuring success: a literature review. *Lignum Limited. FIA Project #1017026.*
11. Man, R. and V.J. Lieffers. 1999. Are mixtures of aspen and white spruce more productive than single species stands? *For. Chron.* 75(3):505–513.
12. Zhang, Y., H.Y.H. Chen, and P.B. Reich. 2012. Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. *J. Ecol.* 100:742–749.

### 1.3 List of abbreviations and Latin-common names.

Table 1 lists abbreviations and Table 2 lists Latin-common names used in this review.

### 1.4 The boreal forest

**Location and extent:** Boreal forests account for about one-third of the forested area in the world, encircling the upper part of the northern hemisphere. They are found in Canada, Alaska, Sweden, Norway, Finland, Russia, and other jurisdictions. They are the most widespread forest type in Canada (Rowe 1972); they occur from the Yukon across all of the provinces to Newfoundland. In British Columbia, the boreal forest occurs in the north and comprises the Boreal White and Black Spruce

(BWBS) biogeoclimatic zone (Meidinger and Pojar 1991). It covers about 15% of the province but makes up less than 1% of the worldwide boreal forest.

***Climate:*** The BWBS zone has a northern continental climate with long, very cold winters, deeply frozen ground for a large part of the year and short growing seasons (Meidinger and Pojar 1991).

***Tree species:*** Forests in the BWBS zone are commonly mixed stands of conifers and broadleaf trees ("mixedwoods") and the white spruce-trembling aspen species combination is the most common. It dominates the landscape in the better-drained plateau, foothill, and cordilleran sections of the zone (Meidinger and Pojar 1991). In addition to white spruce and aspen, black spruce, tamarack, subalpine fir, balsam poplar, and paper birch also occur. Relatively open pine-lichen forests occur on the driest sites, which are usually rapidly drained outwash deposits. Mixed pine and black spruce stands are common on level or gentle north-facing sites on compacted morainal or lacustrine soils. Dense black spruce-moss communities occur on imperfectly drained sites.

***Stand development and dynamics:*** Forest stand dynamics in the BWBS zone are largely driven by wildfires, which have a short-return interval (less than 100 years on average). The fires are generally not hot enough to destroy the organic soil horizons and upper roots, and aspen typically suckers and sprouts vigorously following fires, as well as after logging. Densities of up to 200,000 stems per hectare (SPH) can be reached within two years of disturbance (Peterson and Peterson 1996). Self-thinning to lower densities is rapid.

If a seed source is available or planting is carried out, white spruce becomes established with the aspen immediately after disturbance. In other situations recruitment of white spruce may occur over several decades (Lieffers et al. 1996a). White spruce is shade-tolerant, therefore it can survive and grow under an aspen canopy. Because aspen usually grows more rapidly in height than spruce, these mixed stands tend to be two-storied and aspen-dominated for the first 40-60 years after disturbance (Chen and Popadiouk 2002). White spruce can persist in only 10% full sunlight (Lieffers and Stadt 1994) and favourable growth occurs with only 30% full sunlight (Comeau et al. 1998). Typically after about 70-80 years the spruce is able to reach the height of the aspen canopy and by 100-120 years become the dominant species in the stand (Ball and Walker 1997). The natural BWBS landscape includes white spruce-trembling aspen mixedwoods that represent many successional stages and proportions of the two species.

Stands in the Fort Nelson area may develop differently than in other boreal regions in British Columbia. Kabzems and Garcia (2004) examined spruce-aspen stand development on five productive sites in the BWBSmw2 subzone near Fort Nelson. The stands were 84-139 years-old with total merchantable stand volumes of at least 300 m<sup>3</sup>/ha. Stem analysis was done to look at patterns of height and radial growth over time. Two general patterns of species establishment were identified: (1) age of trembling aspen and spruce overlapped (codominant stands), and (2) the ages did not overlap (stratified stands). The stratified stands were associated with a 29-58 year lag in white spruce recruitment and aspen was 18-21 m taller than the spruce. Height and diameter growth of spruce was slower than in the codominant stands and it was estimated that it could take 166-200 years after establishment for spruce to catch up

to the aspen. In the codominant stands, the dominant white spruce sustained periods of rapid height and diameter growth, without going through the period of suppression followed by release associated with aspen mortality, as commonly occurs in other boreal mixedwood stands. Some spruce were in the upper canopy 40-60 years after stand initiation. Rates of mortality, initial density, and distribution of the trees cannot be told from this type of study but it was estimated that it would still take 150 years for spruce to be the dominant species in both codominant and stratified stands. Height and diameter growth of aspen was similar in the two stand types, even though the spruce component of the two types varied. The vigour and longevity of aspen in the Fort Nelson area appear to prolong the period of aspen dominance well beyond that observed in other boreal mixedwoods.

**Management:** The management strategy used for harvesting and regenerating a mixed white spruce-trembling aspen stand influences the resulting proportion of broadleaf trees and conifers and the relative size of the two species. Historically, white spruce had a much higher value than aspen so the “default” silviculture regime in the BWBS zone in British Columbia has been to promote spruce. This typically is achieved by clearcutting, followed by site preparation, applying herbicides to kill aspen suckers, and planting white spruce. Using one dominant strategy such as this across the landscape, including keeping the softwood and hardwood landbases separate, creates a forest landscape that is different and less complex than that found naturally. Ongoing management of this sort will result in the loss of structural complexity (green trees, snags and downed woody debris) in young forests, loss of older successional stages, and the separation of aspen and conifers (Roy et al. 1995). This in turn will affect not only the timber supply but the whole range of ecosystem values including biodiversity and soils and the ecological processes that exist in the forests.

Deliberate management for mixedwoods in the BWBS zone has been discussed for many years (e.g. Lieffers, MacMillan et al. 1996) but practiced less commonly, and in 2003 Hawkins and Maundrell stated that it was in its infancy in British Columbia. Lieffers, MacMillan et al. (1996), University of Northern British Columbia (2002), and Comeau et al. (2005) outline a number of possible ways to manage white spruce-trembling aspen stands in British Columbia and Alberta either as mixtures or pure stands. Approaches identified by Comeau et al. (2005) include:

#### Successional management of two-storied mixtures

- Two-storied mixedwood with natural spruce regeneration (“doing nothing”)
- Two-storied mixedwood where spruce is planted or seeded within 1-3 years of clearcutting
- Two-storied mixedwood where spruce is underplanted when aspen are 30-60 years old
- Strip clearcutting
- Row thinning (alternating strips where aspen is clearcut, thinned and left intact)

#### Single-story management of intimate mixtures

- Manipulation of aspen densities
- Tending individual spruce

“Unmixing” the mix into discrete groupings of aspen and spruce

- Splitting the cutblock
- Large circles, strips, or clusters

## 1.5 The sub-boreal forest

This section focuses on the lodgepole pine-trembling aspen species mixture although other species are common in sub-boreal forests as well.

**Location and extent:** Sub-boreal forests occur farther south than the BWBS zone and occupy the vast rolling plateau that dominates central interior British Columbia. The biogeoclimatic classification of sub-boreal forests is the Sub-Boreal Spruce (SBS) zone.

**Climate:** The SBS zone has a continental climate with extremes of temperature (British Columbia Ministry of Forests 1998). Summers are short, warm, and moist, and winters can be severe. The SBS has some boreal characteristics but the climate is slightly less continental with less seasonal variation in temperature, shorter winters, a longer growing season, and generally more precipitation (Meidinger and Pojar 1991).

**Tree species:** SBS forests are broadly transitional between boreal forests to the north, true montane Douglas-fir forests to the south, drier colder pine-spruce forests to the southwest, and subalpine fir forests at higher elevations (Meidinger and Pojar 1991). White spruce and subalpine fir are the dominant climax tree species and lodgepole pine is common in mature forests in the drier parts of the zone. Seral stands are extensive and both lodgepole pine and trembling aspen are common pioneer species which often occur together as mixtures. Paper birch is another pioneer tree species, typically found on rich, moist sites. Douglas-fir occurs on dry, warm, rich sites, and less commonly black spruce also occurs.

**Stand development and dynamics:** In the SBS zone in central interior British Columbia, lodgepole pine typically regenerates naturally after fire and mixtures of lodgepole pine and trembling aspen may develop. Mixtures of spruce and aspen are not as common as in the BWBS zone. Aspen has rapid early growth rates and so is often taller than lodgepole pine for at least the first 40 years of stand development. On some sites pine may grow at an equal rates to or faster than the aspen (Newsome et al. 2004a; Comeau et al. 2006).

**Management:** Lodgepole pine and trembling aspen are both shade-intolerant which limits the range of silviculture systems that can be used for mixed stands of these species. Traditionally clearcutting and natural regeneration or planting has been employed, with or without site preparation. Brushing of aspen is often needed to meet free-growing requirements.

## 2 Potential impacts and influences of including broadleaf trees in managed boreal and sub-boreal forests

The choice of management strategy (including silviculture system, logging method, regeneration method, site preparation, brushing, and thinning) affects the proportion of broadleaf trees in a stand. There are many implications of either including or excluding broadleaf trees from managed stands and these form the topics covered by this review.

## 2.1 Achievement of free-growing

Following logging in British Columbia, stands must be declared “free-growing” within a given time period (15 years in the SBS and BWBS zones) (British Columbia Ministry of Forests 2000; 2002), which requires doing a free-growing survey in which a specified number of 50 m<sup>2</sup> (radius = 3.99 m) plots are evaluated, depending on the block size. Within each plot, trees are assessed to see if the minimum required number of free-growing trees are present. A free-growing crop tree must (British Columbia Ministry of Forests 2011):

1. Be well-spaced (usually a minimum of 2.0 m from another well-spaced conifer crop tree)
2. Be a preferred or acceptable species
3. Meet damage criteria
4. Meet minimum height standards
5. Meet the ¾ brush free quadrant criteria

Once it is established whether the first 4 criteria are met, one goes on to determine if criteria 5 above is met for the conifer crop trees in question. To make this determination, a cylinder of 1 m in radius is envisioned around the crop tree. If there is herb or shrub vegetation taller than the crop tree in more than one quadrant of the cylinder, the crop tree is not free-growing. If this vegetation is not present and there are no broadleaf trees (trembling aspen, paper birch, black cottonwood, balsam poplar) in the cylinder that are taller than the allowable conifer: brush ratio (150% for the SBS and BWBS zones), the crop tree is considered free-growing. If more than one quadrant contains a broadleaf tree that is taller than the allowable conifer: brush ratio the tree is not-free-growing. If one quadrant contains a broadleaf tree taller than the allowable conifer: brush ratio, the tree is “potentially free-growing.” The next step is to calculate the median height of the potentially free-growing trees, then the number of broadleaf trees in the plot that are taller than the median height of the potentially free-growing trees are counted. The crop trees are deemed free-growing if the broadleaf tree count is below or equal to a maximum number. For lodgepole pine, the maximum allowable broadleaf count is five in the SBSdw1 variant except two on subxeric and drier sites, and two on all other SBS or BWBS site series. This represents 1000 and 400 SPH, respectively. For white spruce in the BWBSmw1 01, 03, 05, 06, or 07 site series the maximum allowable number is two aspen, black cottonwood or balsam poplar trees, or five paper birch trees. For all other units in the BWBS zone and the SBS the maximum number is five.

There are mixedwood stocking guidelines for deciduous-coniferous stands in the BWBS zone (British Columbia Ministry of Forests 2001). Individual white spruce trees are not considered to be impeded by competition from overstorey deciduous *crop* trees if there is a minimum distance of 2.0 m between the spruce crop tree and the deciduous crop tree, and if the spruce trees have a height: basal diameter ratio of 70 or less. In this case, competing vegetation within 1 m of the crop tree only refers to grasses, herbs,

shrubs and non-commercial tree species. Thus, a healthy, well-spaced spruce in the understory of a boreal mixedwood stand is considered to be free-growing if it meets the following criteria specified in the silviculture prescription:

1. The minimum height
2. The height of the tree relative to competing vegetation (grasses, herbs, shrubs and non-commercial tree species) within a 1 m radius of the trunk of the crop tree
3. Inter-tree distance of 2.0 m between white spruce crop trees and deciduous crop trees
4. A height to basal diameter ratio of 70 or less

A healthy, well-spaced aspen or balsam poplar in the boreal mixedwoods is considered free-growing if it meets the following criteria:

1. The minimum height
2. The height of the tree relative to competing vegetation (grasses, herbs, shrubs and non-commercial tree species) within a 1 m radius of the trunk of the crop tree
3. Inter-tree distance of 2.0 m between white spruce crop trees and 1.4 m between deciduous crop trees

The crop tree: brush height ratio (150% in the SBS and BWBS) is the only competition index used to assess whether a crop tree is free-growing with respect to “non-crop” vegetation. Concerns about restrictive crop tree: brush ratios have been around for a long time (e.g. Davis 1998).

In British Columbia and Alberta, the government requirement of achieving free-growing status often drives the choice of silviculture treatments that are applied to blocks. The regeneration standards for British Columbia and Alberta have been controversial because they are resulting in stands that are dissimilar in composition and structure to those found naturally (Lieffers et al. 2008), especially in areas such as the BWBS where mixedwoods are a dominant forest type. Management for mixed stands has been limited by these strict standards. Because only a limited broadleaf component is permitted, site preparation, planting, and then herbicide application have been the common silviculture scenario. This produces a structurally simple forest (one canopy layer) that is dominated by white spruce or other conifer species.

The free-growing criteria assume that any non-crop species found within the 1-m radius cylinder will always have a negative influence on the crop tree (Davis 1998). However, as other sections of the report at hand show, the presence of non-crop vegetation such as trembling aspen is not always detrimental. For example, aspen can have a positive impact on nutrient cycling, improving soil physical and chemical properties, biodiversity, habitat and shelter for mammals and birds, root rot and insect attack incidence, and the incidence frost damage to young white spruce seedlings.

Some research data collected in British Columbia compares achievement of free-growing on brushed versus untreated mixed conifer-aspen stands. In the SBSdw3 subzone, a 10-year old two-storied spruce-aspen stand had no FG trees (according to 1995 standards) compared to 950 FG SPH in the glyphosate-treated plot, which was a single-layer stand dominated by conifers (Biring et al. 1999). In the BWBSmw

subzone near Dawson Creek, an untreated spruce plantation with a dense balsam poplar component had less than 70 FG SPH compared to an area where the poplar was killed with herbicides (>700 FG SPH) (Harper et al. 1997). Other data that suggests that brushed but not untreated mixed stands tend to meet free-growing requirements are from lodgepole-pine aspen and Douglas-fir-paper birch PROBE (PProtocol for Operational Brushing Evaluations) installations in the MS and IDF zones in the southern interior of British Columbia (Simard et al. 2001).

The data of Simard et al. (2001) and others indicates that although overtopping restrictions are not met when more than a minor number of broadleaf trees are retained, trees may be growing satisfactorily in the presence of broadleaves. Newsome's work with lodgepole pine-aspen interactions in the central interior since the early 1990's (see Section 2.4.4.2) and Lieffer et al.'s (2007) work in Alberta, show that free-to-grow status has been a poor index of future conifer performance. Newsome et al. (2012) found that lower conifer: brush ratios of broadleaves than are permitted under the current free-growing guidelines will not substantially hinder lodgepole pine growth and survival. Her data is now being incorporated into revised free-growing standards for the SBPSxc subzone in the Cariboo, with work in progress for other biogeoclimatic units including the SBS zone.

## 2.2 Economics

**White spruce-trembling aspen stands:** Readers are referred to Comeau et al. (2005) for a summary of costs associated with various mixedwood management regimes for white spruce-aspen stands. The quoted costs are based on results of an informal survey conducted in northeastern British Columbia and Alberta in 2004. The least expensive treatment is "doing nothing" but they note that this may result in lower conifer volumes than more expensive treatments. Other successional management treatments of two-storied mixtures also have low short-term costs because brushing and thinning are not required. "Unmixing" mixtures into discrete patches of spruce and aspen may require brushing, sometimes with two or three entries, which increases the total short-term cost, which is considered moderate. Based on Comeau et al.'s figures single-storied management of intimate mixtures is the most expensive option, with total short-term costs moderately high. It requires brushing (on some sites) as well as treatments to control aspen densities. Multiple entries may be required for aspen treatments.

Approximate costs of the various management phases are:

- Protection of the understorey during harvest - \$4/m<sup>3</sup>
- Planting immediately after disturbance - \$700-\$1000/ha
- Underplanting - \$700-\$1000/ha for planting; \$76/ha for seeding
- Mechanical site preparation - \$400-900/ha
- Scarification for underplanting to create regeneration spots - \$500/ha
- Brushing – aerial chemical \$250-\$300/ha; broadcast ground chemical \$350-\$700/ha; broadcast manual cutting \$400-\$1200/ha; spot chemical \$1/tree; spot manual cutting \$0.75/tree

The costs identified by Comeau (2005) are for the short term. Long-term economic analyses of stand establishment treatments provide critical guidance for silviculture prescriptions. They can also be used to evaluate the economic consequences of forest policy and regulation (i.e. requirements for free-

growing and green-up). Long-term cost effectiveness studies have rarely been done for British Columbia or elsewhere in Canada but one British Columbia and two Ontario studies were found.

In British Columbia, Hawkins et al. (2006) looked at silviculture performance, costs, projected timber yields and financial returns associated with various site preparation treatments compared to “raw planting” (no site preparation). The study took place in the SBSvk subzone 80 km southeast of Prince George on a moderately productive site. Spruce seedlings were planted the year following site preparation and survival, height, diameter, and condition were assessed periodically for 15 years. In general, site preparation increased seedling survival and accelerated height and diameter growth which led to earlier and lower cost compliance with reforestation standards. A direct result of the differences in seedling survival and growth was that raw planting resulted in timber yields of only 33-60% of the yield on site prepared areas, and a lower financial return when calculated over conventional rotation lengths. The chemical site preparation treatment resulted in the greatest Land Expectation Value (LEV; discounted value of a future stream of net revenues produced by an infinite stream of identical rotations) even though timber yields were lower than that of some more expensive treatments. Thus it was the most cost-effective method of stand establishment. Raw planting had the lowest LEV: \$1850/ha at one site, or less than half that of other treatments. The overall conclusion of the study was that investing in site preparation can substantially increase future timber yield, stumpage revenues and financial returns, but investments in these treatments might only be done if tenure conditions give the benefits of such treatments to the forest company making the investment.

Dampier et al. (2006) carried out a study at the Fallingsnow Ecosystem Project in northwestern Ontario to determine the cost-effectiveness of various vegetation management treatments in sub-boreal white spruce plantations. Their objective was to determine the relationship between release treatment costs and juvenile spruce stem volume ( $\$/\text{m}^3$ ) 10 years after the treatments. Clearcut blocks were planted with white spruce at 2 to 2.5 m spacing then 4-7 years later the following treatments were applied: cutting 18 cm above the ground with person-operated brush saws, mechanical cutting 33 cm above ground level with a Silvana selective cutting head attached to a boom and mounted on a tractor, aerial glyphosate application, aerial triclopyr application, and an untreated control. Cost estimates were arrived at by applying 1993 time-study data to estimated 2003 market costs. The untreated control (doing nothing) had no vegetation treatment cost and a cost-effectiveness value of  $\$0/\text{m}^3$  so it was excluded from the analysis. The triclopyr treatment resulted in the greatest white spruce volume after 10 years, followed by the Silvana Selective, the glyphosate treatment, the brush saw, and the untreated control. The two herbicide treatments were three times more cost-effective than the two cutting treatments (least dollars invested to gross volume produced ( $\$/\text{m}^3$ )). The main reason they were more cost effective was a very low application cost per hectare and relatively high volume growth response. There was no significant difference between the 2 cutting treatments or between the two herbicide treatments, but the triclopyr treatment tended to be the best, producing 1.5 times the gross total spruce volume of the glyphosate treatment even though the glyphosate treatment was much more effective at killing aspen. The greater volume increase for the triclopyr treatment was attributed to survival of some aspen which encouraged the spruce to allocate biomass from branches to the stem.

The researchers also suggested that aspen litter on the triclopyr area may have benefitted spruce growth productivity by enriching the soil, enhancing nutrient cycling, and raising the pH of the soil.

Homagain et al. (2011) carried out a stand-level benefit-cost analysis of alternative vegetation management treatments in Ontario. The treatments that were assessed were: aerial glyphosate spray, continuous removal with glyphosate, EZ-ject glyphosate injection, mist blower application of glyphosate, reel and hose application of glyphosate, aerial triclopyr spray, basal bark triclopyr, brush saw, brush saw cutting with glyphosate, continuous removal by brush saws, and a control. Ten and 16-year post-treatment crop tree measurement data were used in the analysis. Planted white spruce, black spruce, and jack pine were the crop tree species. Gross total and merchantable value were projected to 70 years using the Forest Vegetation Simulator (FVS<sup>Ontario</sup>). BUCK-2 software was used to optimize the quantities of sawlogs, pulpwood and hog fuel.

Aerial glyphosate spray had the lowest per unit treatment cost (\$211 per hectare) followed by aerial spray of triclopyr. The highest costs were associated with continuous removal treatments (multiple entries), with the most expensive priced at \$1750 per hectare. Average total cost including site preparation, planting, brushing, harvesting, transportation and overhead ranged from \$5870 per hectare (control) to \$6663 per hectare (cutting). The highest projected gross total volume of crop tree species was for aerial herbicide (257 m<sup>3</sup>/ha) and continuous removal treatments, followed by mechanical cutting. The control was projected to produce the least crop species gross total volume (172 m<sup>3</sup>/ha). Trends were similar for gross merchantable volume. The control produced the highest non-crop gross merchantable volume followed by the cutting and herbicide group. The highest value of fibre produced, including crop and non-crop species, was attained by the aerial herbicide treatments (\$25,492 per hectare). The control produced \$17,745 per hectare which at some sites was not the lowest.

The aerial herbicide treatments were not only the most cost effective treatment, produced the greatest gross total volume and gross merchantable volume, and had the highest average value of fibre produced but they also had the highest Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR). At a 2% discount rate the aerial herbicide treatments produced more than double (for crop species) and more than triple (for crop and non-crop trees) the NPV of any other treatment group. The IRR for crop species was 4.32%, 2.90%, 2.82% and 2.50% for aerial herbicide, manual brush cutting, ground-applied herbicide, and brush cutting plus herbicide treatments, respectively. When all species were included the IRR for the aerial herbicide treatments was 4.49%. The overall result was that all of the vegetation management treatments are economically viable.

Comeau et al. (2005) list the following economic benefits of managing stands as mixedwoods rather than pure conifer stands:

- they provide high-quality fibre
- markets for aspen are expanding
- a greater diversity of products is possible

- white spruce is expensive and difficult to establish in pure stands following disturbance
- spruce stems may be higher quality if grown in mixtures versus open-grown
- overall yield may be greater

**Lodgepole pine-trembling aspen stands:** No published information on costs of brushing lodgepole pine-aspen stands was found. However, retaining all regenerating broadleaf trees in juvenile lodgepole pine stands is expected to initially be less expensive than brushing to remove them, since there is no treatment cost. The cost of selective versus broadcast brushing treatments may be intermediate between total retention and broadcast removal treatments, or more expensive depending on the complexity of the treatment.

### 2.3 Wood quality

The presence of aspen in spruce stands has reduced weevil damage levels (Taylor et al. 1996) thus lowering the incidence of forks and crooks and reducing problems with wood quality. On the other hand, seedlings grown under heavy aspen competition may be crooked or forked which is expected to reduce wood quality (Cayford 1957).

Wood quality of open-grown trees may be lower than trees growing in denser stands due to less taper and more branches. Including aspen in stands can improve wood quality by enhancing natural pruning and decreasing the amount of taper. Numerous studies cited elsewhere in this review show that height:diameter ratio is usually lower (more taper) in open grown spruce and lodgepole pine trees than those growing with aspen. Newsome (1995) noted that the number and diameter of pine branches may be reduced by leaving a small amount of aspen in the plots, which could increase lumber value. Based on a comprehensive literature review, Astrup (2005a) found that lodgepole pine live crown ratio and number of branches per whorl decreases with decreasing light availability.

Ballard and Long (1988) state that log quality characteristics that can be influenced by stand density and the rate of live crown recession include branch size, stem taper, wood density and the proportion of sapwood and juvenile wood and examined the influence of stand density on log quality of lodgepole pine stems. They examined 80 year-old stands of predominantly pine, which had developed at varying densities. Trees in plots with low stand density had branches that remained alive longer and were larger than those on trees where stand density was high. There was a strong relationship between the average diameter of the 5 largest branches per tree and stand density ( $R^2 = 0.90$ ). Large branches result in large knots which reduce product value more than small branches. Average first log taper was regressed against stand density and quadratic mean diameter and the relationship was quite strong ( $R^2 = 0.66-0.67$ ). Excessive taper reduces the amount of recoverable lumber and is unacceptable for some products such as power poles. The relationship between proportion of sapwood basal area and stand density was not as strong ( $R^2 = 0.44$ ). Lumber cut from sapwood is often less resistant to insect and fungal attack and may be less valuable than lumber from heartwood. Average wood density was not significantly related to stand density. Low wood density reduces lumber strength.

## 2.4 Growth and yield

### 2.4.1 Overview of productivity of mixed versus single species stands

Several reviews questioning the productivity of tree species mixtures compared to monocultures have been done (e.g. Kelty 1992; Kelty 2006; Knoke et al. 2008; Pretzsch 2009), still an ever-evolving debate has been ongoing regarding which type of stand is more productive. In the early 1990's, Kelty stated that there is enough data to indicate that productivity of forest mixtures generally exceeds the expected production if yield were simply the average of monoculture yields of the component species. Good "ecological combining ability" (significant differences in growth characteristics that will reduce competition or foster facilitation) generally results in increased productivity of mixtures. In particular, the species interactions must increase the efficiency of use of a resource that is limiting productivity.

Zhang et al. (2012) performed a meta-analysis of 54 studies to determine diversity-productivity relationships in forest ecosystems. Their results showed a global average of 24% higher productivity in mixed forests than in monocultures. Productivity benefits increased with increasing species evenness and richness, but plateaued when richness reached six species. Contrasting life-history traits, especially high variation in shade tolerance, were associated with higher productivity of mixtures compared to monocultures. Stand age was also an important factor, with age effects greatest at 65-70 years, which the authors note may represent a canopy transition stage in boreal and temperate forests. Stand origin (planted or natural) had a negligible effect on diversity-productivity relationships. The relationships were also not related to biomes.

Other authors (Legare et al. 2004, cited by Knoke et al. 2008; Pretzsch 2005;) have also shown that yield of mixed stands compared to monocultures depends strongly on the degree of differentiation in their ecological niche, and also on site quality, silviculture treatment, and the proportion of the different species. As well, reducing stand density has been found to decrease the yield of mixed stands much less than for monocultures (Pretzsch 2005). Pretzsch (2009) reported that growth in mixed stands can be increased by almost 30% over that of pure stands by combining early and late successional species, early and late establishing and developing species, or shade intolerant and shade-tolerant tree species. Where species niches are similar, negative effects from species interactions may lead to a 20% reduction in productivity in temperate and boreal forests (Pretzsch 2009).

Macdonald et al. (2010) briefly summarized research on productivity of mixed versus monoculture stands based on studies where mixedwoods included trembling aspen in combination with white spruce, black spruce or jack pine. All of the studies were from outside of British Columbia. An overall conclusion from their review was that "low to moderate" densities of broadleaves in conifer-dominated stands can sometimes result in more total volume at rotation age. Mixed stands are most likely to exhibit increased productivity compared to their pure counterparts when they are comprised of a mixture of shade-tolerant and intolerant species, when they are vertically structured, when the mix includes fast-growing species, when the mixture includes N-fixing species. The first three criteria are met for white spruce-aspen mixtures but probably only the third criterion holds true for pine-aspen stands.

## **2.4.2 Methods of comparing growth and yield of mixedwood and conifer stands**

Growth and yield differences among stands with varying broadleaf components can be measured as height and diameter growth, merchantable or total volume, total biomass, above-ground biomass, and stocking and survival. The proportion of broadleaf trees relative to conifers may be described by density (SPH), basal area ( $\text{m}^2/\text{ha}$ ), or volume ( $\text{m}^3/\text{ha}$ ).

Yield comparisons can be made through:

1. Growth and yield tables
2. Projections from models
3. Studies in older natural stands, in which growth and yield of established spruce and aspen are compared among stands with varying proportions of aspen
4. Planting trials in which aspen and spruce are established together in intimate mixtures at varying densities and proportions
5. Underplanting trials in which spruce established under an intact aspen canopy is compared with open-grown spruce
6. Underplanting trials in which spruce established under partial canopies/shelterwoods is compared with open-grown spruce and spruce under an untreated canopy
7. Release trials, in which all or part of the overtopping aspen canopy is removed, and growth is compared with spruce in the untreated stand

In this review, information comparing growth and yield of white spruce-trembling aspen mixtures and pure white spruce in boreal (and occasionally sub-boreal) forests is organized under the 7 headings listed above. Because light is a primary determinant of white spruce performance (see Green 2004), an overview of available information on the influence of light on white spruce performance is presented. This is followed by information on the relationship between light and aspen measures, and a list of threshold light and aspen levels that will give varying degrees of white spruce performance.

Growth and yield information relating to lodgepole pine-trembling aspen mixtures begins with a description of a study comparing the growth and yield of mature natural mixed pine-aspen stands and mixed pine-birch stands to mature pure pine stands. Next is a summary of trials conducted in sub-boreal British Columbia including the series of experiments in juvenile (< 25 year-old) lodgepole pine-trembling aspen stands conducted by Teresa Newsome beginning in the 1990's. This is followed by results from other trials done in mixed pine-aspen stands in British Columbia, Alberta, and Ontario. Following this is an overview of available data relating to light-lodgepole pine performance interactions, some successful competition indices that have been developed for lodgepole pine-aspen, and threshold levels of light and aspen needed for desired survival and growth of lodgepole pine.

## **2.4.3 White spruce-trembling aspen**

### **2.4.3.1 Growth and yield tables**

Growth and yield tables do not provide conclusive evidence that mixed stands are more productive than pure stands. Mixedwood stands in Alberta have been reported to out-produce pure stands of either broadleaf trees or white spruce (Anonymous 1985, cited by Qin 1998), but other data from Alberta and Saskatchewan indicate that total yields are about the same for pure white spruce and mixedwood stands at a 70-year rotation (Johnson 1986). The reason for these differences is not clear because very limited information was included in these references. Johnson (1986) reported that gross total volume of well-stocked mixedwoods is not changed significantly by treatments, but yield shifts towards the dominant species. However, the type of treatments referred to in the report is not clear. Volume of spruce alone has been documented to be less in natural well-stocked mixedwood stands than in pure white spruce stands at age 90. Rotation age of spruce in pure stands is 30–40 years less than in mixed stands due to aspen competition in the latter. The information in this section was obtained from unpublished reports (Johnson 1986; Qin 1988), and has not been verified.

#### **2.4.3.2 Model projections**

Modelling facilitates comparison of white spruce-trembling aspen mixedwoods with “pure” white spruce stands without carrying out traditional long-term research trials. These trials are valuable but cannot provide yield information quickly enough for timely decisions to be made regarding management decisions for the array of mixedwood stands, so efforts are being made to increase modelling capabilities. The most widely used source of managed stand yield information in BC is the Tree and Stand Simulator (TASS) (Harper and Polsson 2007). Yield tables are generated by TASS and made available using the software TIPSYS (Table Interpolation Program for Stand Yields). Together these two systems predict managed stand yields for most conifer species in BC as well as red alder and trembling aspen, and they are being applied to BC’s boreal forests. However, they currently do not allow for yield projections for mixed stands of conifers and broadleaves.

The Mixedwood Growth Model (MGM) from Alberta is currently the only model suited to making projections of mean annual increments and volumes at rotation for mixedwood compared to pure white spruce and pure aspen stands in the BWBS zone in British Columbia Bokalo et al. (2013) compared stand-level predictions from the model with data from remeasured permanent sample plots (volume, basal area, diameter at breast height (DBH), average and top height, and density). Four datasets were used for the validation: the Alberta Sustainable Resource Development Stand Dynamics juvenile PSPs, the Western Boreal Growth and Yield Association juvenile PSPs, Alberta Sustainable Resource Development mature stand PSPs, and Saskatchewan Ministry of Environment PSP data. The model effectively simulated juvenile and mature stages of stand development for pure and mixed aspen and white spruce stands in Alberta. The model was slightly biased for top height. Average height, average DBH, and densities of mature broadleaves and conifers were predicted well, except for the Saskatchewan dataset where it underestimated broadleaf density and volume. The dataset as a whole overestimated increment growth in older stands, especially pure stands, probably because of age-related pathology and weather-related stand damage.

Several publications include projections from MGM (Biring and Hays-Byl 2000; Pitt, Mihajlovich

and Proudfoot 2004; Comeau et al. 2005; Kabzems et al. 2007), described below. Mean annual increments and volumes at rotation are compared for mixedwoods and pure white spruce and pure aspen stands.

Kabzems et al. (2007) used MGM version 2002A to predict growth of BWBS stands up to age 80 using (1) 10,000 SPH of aspen, (2) 1200 SPH of spruce, and (3) 1200 SPH of spruce in combination with each of 1000, 2000, 5000 and 10000 stems per hectare of aspen. Mixed stands with the highest aspen densities were projected to produce slightly less total volume than pure spruce stands, but mixtures with moderate aspen levels (1000 SPH aspen) were predicted to produce 21% more total volume than pure spruce stands. As aspen stocking decreased, spruce volume production was predicted to increase, but at a slow rate. A relatively small amount of aspen (below 1000 SPH) was predicted to have a large effect on spruce production but yield appeared to be relatively insensitive to a wide range of aspen densities above 1000 SPH. The threshold for aspen density to affect white spruce growth was suggested to be below 1000 SPH of aspen. The model indicates that retaining 1000-10,000 SPH of aspen could increase total volume production but spruce merchantable volume would be only about half that of the pure spruce regime. The model predicts convergence of mixedwood stand types with time due to self-thinning of the aspen although stands starting with more aspen will continue to have more aspen and less spruce. In mixed stands, spruce growth is predicted to vary less than that of aspen but projected to increase with decreasing aspen density.

Pitt et al. (2004a) used the MGM model for boreal mixed spruce-aspen stands in Alberta. Stands treated various ways (no treatment, herbicide, pre-commercial thinning, commercial thinning) to create varying proportions of aspen and white spruce developed the same total volume at rotation but average piece size, stem density and proportion of the volume that was broadleaf varied. The model predicted that the untreated stand will stay broadleaf-dominated over a 100 year period. Total aspen volumes are projected to peak at age 60-70 years at 350 m<sup>3</sup>/ha at which time conifer volume will be about 100 m<sup>3</sup>/ha. After 70 years, conifer volume will increase only slightly and broadleaf volume will go down considerably. Conifer volume is estimated to make up only 22% of the stand basal area (54 m<sup>2</sup>/ha) and density (790 SPH). Both broadleaf and conifer trees are estimated to average 41 cm in DBH at 70 years, suggesting that untreated stands may offer reasonable solid wood opportunities if broadleaf trees are desirable. Treated stands (one herbicide release treatment) are projected to stay conifer-dominated with about 20% of the stand basal area and density from broadleaf stems. Although the conifer component will likely increase in volume beyond 100 yrs, total volume is estimated to equal the projected high for the untreated stand by about age 80. At this time an average of 360 m<sup>3</sup>/ha conifer volume and 90 m<sup>3</sup>/ha of broadleaf volume will be available (total stand volume 450 m<sup>3</sup>/ha). Thus it would take at least 10 years longer for the treated stand to attain the same total volume as untreated stands, although a much higher conifer volume is obtained by removing broadleaf trees. Average piece size in the conifer-dominated stands is projected to be smaller than for the mixed stands (23 cm for both conifers and broadleaf trees) which would potentially support pulp and small log markets. In the treated stands, broadleaf volume is projected to slowly increase for 100 years in the treated stands without declining. Model simulations in which all or nearly all of the broadleaf trees were removed produced virtually the same total volume as treatments that retained broadleaf stems, but conifer release

amounted to trading broadleaf volume for conifer volume. Other scenarios, such as having two herbicide treatments, or including precommercial or commercial thinnings were projected to produce similar total volumes over an 80 year rotation as the untreated or pure conifer approaches, but the percentage of volume that was conifer, density of conifers and broadleaf trees, and average piece size was projected to differ among regimes. In short, including broadleaf trees in the managed stands was not predicted to improve total volume that could be obtained, but maximum volume was reached sooner and piece size of conifers and broadleaf trees was much larger. Volume over age graphs are provided in the paper for eight different management scenarios. They show the projected coniferous and broadleaf volume, density and diameter of conifers and broadleaf trees at different ages on the way to rotation.

Comeau et al. (2005) used MGM version 2005A for estimating mean annual increment (MAI) for six management scenarios in mixed white spruce-trembling aspen stands in Alberta. The highest total MAI and the second highest spruce and aspen MAIs were projected for underplanting at age 40, harvesting the aspen at age 60 with understorey protection, and harvesting the remaining trees at age 120 (spruce age 80). The lowest total MAI, where aspen MAI was low and spruce MAI was moderate, was projected for the scenario of splitting the block into discrete aspen and spruce patches and harvesting at age 90. Planting spruce into a dense aspen stand resulted in low spruce yields, moderate aspen yields, and low total yield at age 90. Planting spruce, then thinning aspen at age five to 1000 SPH resulted in fairly high total yield but spruce yield was only half that of a pure spruce stand. The pure spruce stand had the highest spruce yield at age 90 and one of the higher total yields (surpassed only by underplanting). The pure aspen stand with a rotation age of 60 years had the highest aspen yield and a total yield similar to management for pure spruce and the scenario of planting spruce then thinning the aspen at age five.

Biring and Hays-Byl (2000) used the MGM model for white spruce-trembling aspen stands in the SBSdw3 subzone at Tsilcoh River, British Columbia. Note that the model has not been calibrated or validated for use in this zone and so it may be inappropriate. The authors used it anyways because of lack of a quantitative model for growth and yield projections for mixedwoods in the SBS. Spruce volume at rotation was projected by MGM simulations to be 235% greater where aspen was removed with glyphosate than in the mixed control stand, with rotation age projected to be reduced from 100 to 70 years. However, broadleaf volume was reduced by 92% in the treated area, resulting in a lower projected total volume than in the control at rotation age. Total volume at rotation age was projected to be 539 m<sup>3</sup>/ha in the mixed control stand compared to 408 m<sup>3</sup>/ha in the predominantly conifer stand at 90 years. If both the treated and mixed stands were harvested using a two-pass system (harvesting all but 15% of the aspen at age 50) the conifer rotation age would be reduced, more conifer volume would be attained and there would be less aspen and less total volume in the treated plot compared to the mixed stand.

#### **2.4.3.3 Comparison of natural stand types**

Four studies were found in which growth and yield of aspen and spruce was determined from measurements in natural older stands.

MacPherson (2000) investigated whether growth of aspen was affected by white spruce understories in the boreal mixedwood forest of Alberta. He looked at 29 sites, and assessed aspen growth in areas where there was no spruce understory versus areas where spruce was present in the understory. The stands had even-aged aspen canopies with >75% canopy closure and uniform stem density (average 1460 SPH of aspen) with no large canopy gaps. The age of the aspen in the stands ranged from 48-105, while the age of the understory spruce was 4-64. Overall, plots with white spruce and aspen growing together had greater total productivity than pure aspen plots. The mixedwood plots had 23% greater basal areas, 10% more total biomass and 13% more periodic annual increment (PAI) than pure aspen plots. The mixtures had lower aspen productivity than the pure aspen plots but the reduction in aspen productivity was only weakly correlated with the amount of spruce. PAI was 25% greater for aspen in the pure plots than the mixed plots. Twenty-five of the 29 surveyed stands had greater aspen PAI in the pure plots than the mixed plots compared with only four stands with greater aspen PAI in the mixed plots. Twenty stands had greater total biomass in the mixed than the pure plots; nine stands had greater total biomass in the pure plots. MacPherson notes that because the surveyed stands included young stands with little spruce it is possible that the reported increases in productivity (13% greater PAI and 10% more biomass) are an underestimate of the yield increase that could be realized under mixedwood management.

In an older investigation in Saskatchewan, Kabzems and Senyk (1967) compared the mean annual production of well-stocked white spruce, aspen, aspen-spruce, and spruce-aspen stands on average sites. The data was based on 6,956 random relascope sample plot measurements in natural forests. The mean annual wood production increment was highest in the mixed aspen-spruce ( $1.33 \text{ m}^3/\text{ha}$ ; 80 year rotation) and spruce-aspen stands ( $1.27 \text{ m}^3/\text{ha}$  at 85 years), lower in the aspen type ( $1.13 \text{ m}^3/\text{ha}$  at 65 years) and lowest in the spruce stands ( $1.05 \text{ m}^3/\text{ha}$  at 90 years)

Cayford (1957) examined five mixed stands of aspen and white spruce in Saskatchewan to determine the effect of the aspen overstorey on white spruce growth. Natural stands where spruce had penetrated the aspen canopy were looked at, and only the spruce that had reached the canopy level were measured. A comparison was made of the growth of "free" spruce (growing in small openings) and suppressed spruce (growing with aspen). Each spruce tree was assigned to one of three age classes (55-60, 70-75 or 95-100 years) which were decided upon once the data was collected and sorted. Stem analysis indicated that in each of the three age classes, total volume per tree was about twice as much for free spruce compared with suppressed spruce. Suppressed trees usually had poor form; many stems had sweep, crooks and forked tops, which lower wood quality. The effect of aspen on the spruce began when the spruce were very young. White spruce suppressed by aspen took significantly longer to reach breast height (8.7 years) than the free trees (7.1 years), and longer to eventually overtop the aspen. Height growth of aspen exceeded that of free spruce for the first three decades and exceeded that of suppressed spruce for up to 40 years. Maximum height growth of both free and suppressed spruce occurred at 10-20 years of age. At age 50-60, height growth of suppressed spruce tended to approach or occasionally surpass that free spruce. The results show that for up to 100 years of age, spruce

growing with aspen has slower diameter, height and volume growth than spruce growing in small openings.

In west-central Alberta, Lieffers, Stadt and Navratil (1996) looked at nine mature aspen-white spruce mixedwood stands which had an understorey of white spruce and healthy overstories dominated by aspen. Time since disturbance (aspen age) was 45-88 yrs. At each site, 50 understorey spruce were cut for stem analysis. Most sites had a wide range of spruce ages. Recruitment occurred over 15-20 yrs for some sites, or many decades for other sites. Annual height increment for spruce increased as the trees grew in height (<10 cm/year when less than 30 cm tall and 30 cm/year or more when taller than 230 cm). The authors concluded that spruce height growth was not reduced “excessively” by being under aspen (they compared their growth data to that reported from clearcut sites in other studies). The understorey spruce were considered to be on a growth curve that will produce trees at least 25 m tall at age 100.

#### **2.4.3.4 Planting trials in which spruce and aspen are established at the same time**

Table 3 lists spruce responses (height, diameter, stem volume, HDR, survival) to treatments where aspen density was manipulated in planting trials. Table 4 lists aspen responses to these treatments. Results from the individual trials are in Appendix 1.

Kabzems et al. (2007) and Kabzems, Harper and Fielder (2011) compared growth and yield of boreal “pure” white spruce managed stands with that of white spruce-trembling aspen mixtures of the same age and Biring and Hays-Byl (2000) made this comparison in the SBS zone. Harper et al. (1997) compared growth and yield of boreal pure spruce stands with white spruce-balsam poplar mixtures. An additional 9 trials from boreal spruce-aspen mixedwood forests in other Canadian provinces are included in the table.

The trials were all located on medium or rich sites where trembling aspen and white spruce had been important species in the pre-harvest stand. In all of these trials, the two species were established at about the same time: spruce was planted and aspen was allowed to sucker naturally. No studies of natural spruce regeneration growing with manipulated levels of young aspen were found. In each trial, plots were established where aspen was completely removed, partially removed, or not treated at all (controls). Measurement periods ranged from 3 to 41 years after trial establishment, but for most studies the data was collected after a maximum of 10 growing seasons. Some of these studies include projections of yield to rotation using the MGM model, described earlier in Section 2.4.3.2.

**Survival and condition:** Survival of planted white spruce was almost always good (greater than about 85%) under all levels of aspen competition, even where suckering was prolific (e.g. Biring and Hays-Byl 2000; Man et al. 2008; Pitt et al. 2010; Kabzems, Harper and Fielder 2011). Survival was also as good in a dense balsam poplar stand as where the broadleaves were killed by herbicide (Harper et al. 1997). However, in one Ontario study where aspen presence was partially to completely reduced by manual cutting, mechanical cutting, glyphosate application, and triclopyr application, survival was 12% lower in

the untreated mixed stand (Pitt and Bell 2005). On a site in Quebec where 5 levels of birch competition were created (leaf area index of 0, 25, 50, 75 and 100%), the survival rate was 5% higher at low levels of broadleaf cover compared with complete cover (Jobidon 2000).

Information on the vigour and condition of seedlings is limited. On one BWBSmw site, seedlings suffered extensive hare damage where aspen was dense but not where aspen was removed (Coopersmith et al. 2000). The proportion of seedlings damaged by hares was 63% in the 10,000 SPH aspen plot and 39% in the 5000 SPH plot compared to 3% where there was no aspen. The hare damage at this site intensified the negative effects of aspen on spruce height growth at this site. Similarly, in the same subzone, hares clipped 50% of spruce seedling leaders in an untreated spruce-balsam poplar stand compared to 0-13% in herbicided areas (Harper et al. 1997). In Quebec, hare damage was also significantly associated with treatment, with the highest incidence (about 7%) where birch cover was complete (Jobidon 2000). On an SBSdw3 site, spruce seedling vigour was better where aspen was killed by herbicide versus on the matching untreated control area (Biring and Hays-Byl 2000). In another case, 2-m radius spot treatment to the aspen reduced exposure of seedlings to frost (Man et al. 2008).

**Height:** Three to 15 years after treatment, average spruce height in untreated mixed spruce-aspen stands areas was either less (e.g., Biring and Hays-Byl 2000; Pitt et al. 2010; Kabzems, Harper and Fielder 2011; Bokalo et al. 2012) or not significantly different (e.g., Pitt, Mihajlovich and Proudfoot 2004; Man et al. 2008) from open areas where aspen abundance was greatly reduced. Spruce height growth was never reduced by complete or partial removal of aspen. Spruce height growth tended to be insensitive to partial removal treatments (e.g., Man et al. 2008; Kabzems, Harper and Fielder 2011) but Pitt et al. (2010) found that spot treatments increased height growth as much as complete removal.

**Diameter:** Diameter growth of spruce seedlings tended to respond positively to removal of aspen (DeLong 2007; Kabzems et al. 2007; Pitt et al. 2010; Kabzems, Harper and Fielder 2011; Bokalo et al. 2012) or balsam poplar (Harper et al. 1997) or birch (Jobidon 2000). Three years after treatment on an Alberta site, diameter increment was three times that of the control (Man et al. 2008). Spruce diameter growth was insensitive to partial aspen removal in 2 studies in the BWBS zone (Kabzems et al. 2007; Kabzems, Harper and Fielder 2011). Twenty years after treatments in Alberta and Saskatchewan, average root collar diameter decreased with increasing aspen density but was not significantly different among 0 and 200 SPH aspen treatments or between 200 and 500 SPH treatments (Bokalo et al. 2012). There were no cases in which spruce diameter growth was reduced by partial or complete removal of the aspen and no studies were found in which the greatest diameter growth was in the mixed stand.

**Volume:** Five to 10 years after treatment, volume of spruce where aspen was completely removed tended to be double that on untreated controls (e.g., Kabzems et al. 2007; Pitt et al. 2010; Bell, Dacosta, et al. 2011; Kabzems, Harper and Fielder 2011). Partial retention of aspen sometimes resulted in volumes similar to the control (e.g., Kabzems et al. 2007; Kabzems, Harper and Fielder 2011) and sometimes similar to the open areas (e.g., Pitt et al. 2010). Removing aspen tended to shift the volume of the stand towards spruce but not necessarily increase total volume. There were no cases in which spruce volume was reduced by partial or complete removal of the aspen and no studies were found in

which the greatest spruce volume was in the mixed stand. However, total stand volume was sometimes higher in the mixedwood than the treated areas, due to high aspen volume (e.g., Pitt and Bell 2005).

In the BWBS zone, white spruce volume was doubled by removing all aspen compared to spot treatments, retention of 1000, 2000, 5000 or 10,000 SPH of aspen or no treatment (Kabzems et al. 2007; 2011a). Although 7 or more years had passed since most of the treatments, only 2 years had passed since thinning to 1000 and 2000 which is likely insufficient time for growth responses to be realized on those plots. Spruce volume on the control was not significantly different from other treatments, but the general trend was for it to be less. Five years after treatments in Alberta and Ontario, complete vegetation removal, woody removal only and removal in 2-m radii around seedlings resulted in similar seedling volumes (Pitt et al. 2010). Volumes on these plots were double that of the control.

Seven years after various aspen treatments on sites in Ontario, the untreated control which was 80% broadleaf, had the highest total stem volume and the highest aspen volume but the lowest spruce volume (Pitt and Bell 2005). Broadcast herbicide treatments resulted in the lowest total volume but a spruce volume that was about twice that of the control. In another Ontario study, at age 20, ten years after aspen was treated, gross total volume of spruce where aspen was completely removed with glyphosate was 202% greater than on the untreated control (Bell et al. 2011). Where triclopyr was aerially applied gross total volume of spruce was 127% greater than on the control. The manual and mechanical cutting treatments had no significant effect on spruce gross total volume at stand age 20 but gross total aspen volume was significantly reduced by 47-100% by the treatments. Total stand gross volume at age 20 was significantly less (29-66% less) for all treatments compared to the control except aerial spray triclopyr.

Fu et al. (2007) found that 15 years after treatment, control of aspen with glyphosate increased spruce volume by several times over the control but decreased aspen volume. The net result was no effect on total volume.

Five years after leaf area index (LAI) levels of 0%, 25%, 50%, 75% and 100% were created with birch, spruce volume dropped the most from the zero aspen level to the 25% level, and continued to significantly decline (but at lesser rate) as LAI increased (Jobidon 2000).

**Biomass:** In a 41-year Ontario study, herbicide use greatly reduced broadleaf biomass but did not significantly increase stand level biomass of planted white spruce compared to spruce biomass in the untreated spruce-aspen mixture (Fleming and Smith 2011). The lack of response in spruce biomass production was a result of lower survival in the herbicided plots which was suggested to be due to increased physiological stress (e.g., frost damage, sunscald, and winter desiccation). In Quebec, complete removal of birch increased above-ground biomass by ten times over the untreated control (Jobidon 2000). The greatest drop in biomass was from the open condition to the 25% LAI condition. This is the same pattern as that for height, diameter, and volume.

**Height: diameter ratio:** HDR of spruce was consistently significantly lower in open areas than where all aspen was left untreated, and the differences were large (Table 3) (e.g., Harper et al. 1997; Biring and Hays-Byl 2000; Kabzems et al. 2007; Man et al. 2008; Kabzems, Harper and Fielder 2011; Bokalo et al. 2012). Average HDR for open-grown seedlings varied from 33 to 50, and HDR of control seedlings from 61 to 79. HDR was not always higher where a portion of the aspen was retained compared to the open areas. For example, Kabzems, Harper and Fielder (2011) found that seven years after treatment, HDR was lowest on chemically treated areas, but there was no significant difference between the control and spot-treated areas. The HDR's on the 1000 and 2000 SPH aspen plots were also similar to the control but this was based on a two year measurement period only. On the other hand, Man et al. (2008) found that three years after planting, HDR in spot treated areas was intermediate between the control and complete removal treatment. Bokalo et al. (2012) found that 20 years after treatment, HDR increased with increasing aspen density but did not differ significantly between areas with 200 and 500 SPH of aspen or between the 4000 SPH plot and the control. Coopersmith and Hall (1999) found that HDR was lowest in the open area, significantly lower in the 5000 SPH plot and lower still in the 10,000 SPH plot. In Jobidon's (2000) study with birch and white spruce, HDR five years after treatment increased with each increasing LAI level except levels 50 and 75 which did not significantly differ from each other.

**Stand structure:** Elimination of much of the aspen from a white spruce-aspen mixedwood shifts the stand structure from a two-storied stand to a single-storied, conifer dominated, less complex stand (Biring and Hays-Byl 2000). Removal of aspen in spots around seedlings retains a broadleaf component and a more complex stand yet may have the same benefits to spruce growth as complete aspen removal (Pitt et al. 2010). Triclopyr treatment, in which only the tops of aspen were killed, has resulted in larger spruce than manual or mechanical cutting, or glyphosate treatment with missed strips, but the stand will still develop into a mixed stand (Pitt and Bell 2005).

In addition to data from boreal or sub-boreal trials in white spruce-trembling aspen mixedwoods, many other studies have shown that spruce growth responds positively to vegetation removal. Of interest is a study in Ontario by Sutton (1995) that provides long-term results, although the vegetation species being controlled was not specified. Sutton found that 30 years after vegetation control, white spruce stem volume was 53-96% greater than where there was no treatment.

#### **2.4.3.5 Underplanting trials in which spruce is established under an intact developed aspen canopy**

##### **Overview**

Man (2003) conducted a meta-analysis of underplanting growth and yield data from studies conducted in boreal mixedwoods (trembling aspen-white spruce) from northern British Columbia to Manitoba between 1950 and 2000. Most of the data was from spruce plantations less than 10 years old. Highlights of this meta-analysis are:

**Height growth:** Mean percentage underplanting/control ratio for white spruce is 0.94, close to 1, indicating no substantial overall difference between height growth of spruce trees planted under a forest canopy compared to in the open. Of the 92 subdata sets for height growth, less than 8% show a

strong negative effect (R/C ratio  $<0.59$ ), 28% have a negative effect (R/C ratio  $0.60 - 0.89$ ), 43% have zero effect (R/C ratio  $0.90 - 1.09$ ) and 21% have a positive effect (R/C ratio  $> 1.10$ ).

**Diameter growth:** Mean percentage underplanting/control ratio for white spruce is 0.76, suggesting that average spruce trees planted in the understory are about 24% smaller than those planted in the open. Of the 60 data sets subsampled, about 28% show no difference in diameter between underplanted and open grown seedlings and most of the rest show a negative effect (50% of data sets) or strong negative effect (18% of data sets). Only 3% show a positive treatment effect.

**Survival:** The mean underplanting/control ratio for white spruce is 1.07, meaning there is almost no treatment effect. Of the total cases where comparisons were made, 38% showed no effect of underplanting on survival, 28% showed a positive effect, 28% showed a negative effect and 6% a strong negative effect.

**Response relationships:** The relationship between either height, diameter, or survival response and years after planting was weak, and separating responses into the overhead canopy types of mature aspen, mature mixedwood and young aspen canopies also did not reveal strong trends. Man noted that the inability to develop robust predictive models reflects the fact that most of the data is from young spruce plantations (less than 10 years-old), for which potential performance is related to a wide range of factors other than overstorey type, such as stock problems, soil type, site preparation, temperature and precipitation at the time of planting, vegetation competition, and hare population levels. Man suggests that the both positive and negative responses of height and diameter growth to underplanting may be related to the relative degree to which the overstorey is beneficial in dampening environmental extremes. For example, underplanting may be highly beneficial in frost-prone areas, thus providing a positive growth response, and less of a benefit on site where frost is less common.

### British Columbia studies

Four British Columbia boreal and sub-boreal studies were found in which growth and yield responses of white spruce underplanted beneath established aspen canopies were compared to growth and yield responses in open (clearcut) areas (Kabzems and Lousier 1992; DeLong 2000; Hawkins 2005; Comeau et al. 2009a) (Table 5). Seedling survival was generally good two to ten years after underplanting, but was lower than in the clearcut on one British Columbia site (as well as the Ontario site). Both height and diameter growth were generally less under the canopy than in clearcuts. Incidence of frost was less under the canopy but hare damage was greater. One site had more rodent damage in the open than under the canopy.

DeLong (2000) compared responses of white spruce seedlings planted in three recently-logged clearcuts to responses of seedlings planted under three 40-80 year old-aspen canopies. The sites were located in the BWBS subzone 80 km southwest of Dawson Creek, British Columbia. The clearcuts were mechanically site prepared, and in the aspen canopy plots site preparation consisted of either removing the shrub/herb layer in a 1 m radius around each seedling location with a brush saw, or brushing plus screefing a 50 x 50 cm patch centred on the seedling location. Seven years after planting, spruce survival was 94% under aspen and 88% in the clearcut. Frost damage occurred in the clearcuts (up to 14% of

seedlings damaged) but not under the aspen. Hare damage occurred under the intact aspen canopy at one site (total of 68% of seedlings damaged over three years) and on one clearcut (13% of trees damaged). Height growth of spruce under aspen was fairly steady over the seven growing seasons, whereas in the clearcut it started slowly then increased exponentially in the last four years. Spruce seedlings in clearcuts were significantly taller (average height 106 cm) than under aspen (78 cm) after seven years. By the fifth growing season, root collar diameter was significantly greater for seedlings in the clearcuts than at the aspen sites (values were not provided). HDR after 5 years was higher at the aspen sites than at 2 clearcuts but similar to the other clearcut (values were not provided). No growth differences were apparent between seedlings planted in screefed and non-screefed spots under aspen, indicating that under a canopy site preparation was not needed to get the seedlings established. By year seven, the number of interwhorl buds and foliar needle mass were generally higher for seedlings in the clearcuts than under the aspen. Foliar nutrient concentrations were generally slightly higher or the same for seedlings planted under aspen compared to in clearcuts except levels of Zn and Mn which were higher for the open-grown spruce. At the growth rates occurring at this site, most of the underplanted and open-grown trees were expected to reach the minimum height required for free-growing (1.0 m) by year 15, as specified in the 1995 establishment to free-growing regulations.

Kabzems and Lousier (1992) compared responses of white spruce seedlings planted in the open with those underplanted in a 120-year-old aspen stand in the BWBS zone near Fort Nelson, British Columbia. Spruce was harvested from a 120-year-old aspen-white spruce mixture with 175-450 SPH aspen and 100-650 SPH residual white spruce (most < 3 m tall) and it was replanted with white spruce the following year. Open areas that were chosen for comparison had 0-75 SPH residual aspen, 0-75 SPH residual spruce, and some natural spruce regeneration. Two years after planting, white spruce seedlings under the residual aspen canopy were significantly shorter (62 cm) than those in the adjacent clearcuts (75 cm) but vigorous seedlings with average leader increments of about 23 cm were present on both sites. Although total seedling height differed between the two stand types, no significant differences were found in leader height (12.4 cm under residual aspen versus 15.5 cm in the open) or root collar diameter (1.0 cm under residual aspen versus 1.1 cm in the open). Average crown diameter and the number of buds on the leaders were very similar between the two stand types. Within-site variation was high for all the spruce variables. Compared with seedlings under the residual aspen, those in the open had lower foliar  $\text{SO}_4\text{-S}$  levels and greater foliar copper, Zn and aluminum levels. Foliar N was the same for seedlings grown in the two conditions. Foliar N and S levels were below recommended adequate levels for all sites. The open area had more potential frost events than under the residual aspen (air temp  $<0^\circ\text{C}$  at 100 cm) but no frost damage occurred at either site.

Comeau et al. (2009a) compared responses of fertilized and unfertilized white spruce seedlings planted under a 39 year-old aspen canopy with those in areas where the aspen was thinned to 1000, 2000, and 3000 SPH, or left untreated. Sites were located in the BWBS zone near Dawson Creek and at Sierra Road in northern British Columbia. High survival rates and reasonable growth rates of white spruce were found under all densities of aspen, even where overstorey basal area reached  $51\text{ m}^2/\text{ha}$ . Thinning the overstorey aspen to 1000 or 2000 SPH improved diameter and height growth of the planted seedlings. Fertilization prior to planting had no effect on spruce seedling or aspen size or growth rates after 10

years. At the end of the study, spruce height, root collar diameter, 3-year height increment and 5-year diameter increment were larger in the 1000 SPH and 2000 SPH treatments than the control; values for the 3000 SPH plot were intermediate between the control and the 1000 and 2000 SPH treatments. Spruce height increment averaged 14 cm/yr in the 1000 SPH plot, compared with 15 cm/yr in the 2000 SPH plot, and 11 cm/yr in the control and 3000 SPH plot. Hare damage was present in areas adjacent to protective cover.

Hawkins (2005) compared responses of white spruce seedlings planted under an old-growth aspen canopy with responses in a clearcut and young stands where the aspen was left untreated (control)(>5000 aspen SPH) and thinned by girdling and snapping to 600, 1200, 1500 and 5000 SPH. The study area was a productive site in the BWBS zone located at Rice Property, British Columbia. Four-year survival of the white spruce seedlings was about 80-90% in the underplanted thinned plots and control, and most seedlings were healthy. Survival was lowest (about 70%) for seedlings underplanted in the old growth stand. About 20% of the seedlings in the clearcut were sick or chlorotic and expected to die. The least amount of seedling damage, which was mainly due to rodent browsing, was in the old growth stand and young aspen stand thinned to 2500 SPH. Four years after planting, height and diameter growth of spruce seedlings did not differ significantly among treatments but those in the clearcut were clearly larger in height and diameter than those growing in young thinned aspen or underplanted in the old growth stand. By year five the best spruce growth was where there were 1200 SPH of overstorey aspen. This density of broadleaf trees was thought to have maintained an appropriate light and temperature regime, while minimizing competitive effects of understorey shrubs and herbs. However, year five was the first year differences in spruce growth among treatments were found, and longer term observations are needed. TWIGS, SORTIE and MGM models all predicted complete mortality of spruce in the young aspen stand thinning treatments so no growth and yield projections could be done. Aspen diameter growth increased as thinning intensity increased.

### **Alberta studies**

In a controlled lab experiment, Landhausser and Lieffers (2001) transplanted one year-old seedlings in pots to the understorey of a mixed aspen-balsam poplar stand and an adjacent open site. Height increments of understorey-grown white spruce were 3 times greater than those of open-grown seedlings. Diameter increments were not measured. Shoot mass did not vary with growth environment but total root mass was lower in understorey-grown seedlings than open-grown seedlings.

### **Ontario studies**

In northeastern Ontario, MacDonald and Thompson (2003) looked at fifth-year effects of three harvesting intensities (uncut, clearcut, and 50% partial cut with and without removal of residuals three years later), Two site preparation treatments (none and scalping) and three types of chemical brushing (none, single, or multiple treatments) on survival and growth of planted white spruce. The intact stand that was underplanted was a 70-year year old aspen and paper birch stand. Survival of spruce seedlings under the intact aspen-birch canopy was significantly less (46%) than in the partial cut areas (85%) and

clearcut (90%). Survival in the clearcut was significantly better than for the other treatments. Low survival under the intact canopy was explained by the very low light levels that were measured. Animal damage was infrequently observed in all treatments (<0.1%) but abiotic damage (breakage, wounding or uprooting) was greater in harvested areas (6-7%) than under the intact canopy (3%). Survival was not improved by weeding. Spruce height five years after treatments was significantly greater in the clearcut (71 cm) than the 2 partial cutting treatments (46 cm) which in turn was significantly greater than under the canopy (24 cm). Seedling height in brushed plots was significantly greater than in unbrushed plots, and multiple brushing treatments increased seedling height more than single treatments. Mean leader diameter of spruce in the clearcut (4.5 mm) was significantly greater than in the partial cutting treatments (3.1 mm), which in turn was significantly greater than under the intact canopy (1.1 mm). Mean diameter in brushed plots versus unbrushed plots followed the same trend as height. Site preparation had no effect on conifer seedling performance or broadleaf regeneration. Fifth-year mean broadleaf height in the clearcut (132 cm) was significantly greater than in the partial cut treatments (71 cm) which in turn was significantly greater than under the intact canopy (27 cm). Mean broadleaf height in unbrushed plots was double that of brushed plots. Multiple brushing treatments decreased broadleaf height and density more than single treatments. For all brushing intensities, broadleaf density was highest in the partial cut treatment in which residuals were removed 3 years later, due to dense suckering. Density in this partial cut treatment was 2.5 times greater than in the uncut area.

#### **2.4.3.6 Planting trials in which spruce is planted under partial canopies/ shelterwoods**

This section describes the performance of white spruce seedlings planted into shelterwood cut areas. Four studies done in boreal forests were found: one from each of British Columbia, Alberta, Saskatchewan and Ontario (Table 6).

##### **British Columbia studies**

Kabzems (2001) looked at the performance of white spruce seedlings planted into two sizes of circular openings (shelterwood gaps), 40 m diameter and 113 m in diameter, representing 1.25 and 3-4 times the height of adjacent aspen. Seedlings in the openings created by shelterwood cutting were monitored for three years. The sites were in the BWBSmw2 subzone and located at Hoffard Creek and Fort Nelson River in northern British Columbia. The original stand at Hoffard Creek was 90-years-old and the forest at the Fort Nelson River site was about 150-years-old. No significant differences were found in survival, height, height increment, or basal diameter of the spruce seedlings in the two opening sizes three years after planting. Average height was 44 cm and average leader length 12 cm. After three years, aspen density in the larger openings averaged 31,200 SPH compared with 24,200 SPH in the small openings, but the height of aspen was about the same in the two opening sizes (125 cm) and so was its basal diameter (about 1.2 cm). There were almost no natural spruce trees in the openings after 3 growing seasons.

##### **Alberta studies**

White spruce seedlings were planted under aspen-dominated (>70% broadleaf basal area) (d-dom) and white spruce-dominated (>70% conifer basal area) (c-dom) overstories following partial removal of the canopies (50% and 75% retention), and complete removal of the canopy (clearcut) in a study that was part of the Ecosystem Management Emulating Natural Disturbance (EMEND) experiment in northern Alberta (Gradowski et al. 2008). Eighteen stands were treated altogether. For each stand composition type, three stands were treated by each of the three retention levels. In the 75% retention treatment, every third 20-m wide strip was harvested. In the 50% retention treatment, the strips were harvested as in the 75% retention, and the remaining 25% removal was accomplished by harvesting every third tree by reaching 7.5 m on each side of the machine corridors. Four spot site preparation treatments were done within each stand and seedlings were planted a few weeks later. Seven years after planting, survival was higher in the aspen-dominated stands (84%) than the spruce-dominated stands (73%). Root collar diameter growth was highest in the clearcut followed by the 50% then 75% retention plots. In the d-dom plots the largest diameter was in the stand with 50% retention. Height of the seedlings was 93 cm in the d-dom plots compared with 76 cm in the c-dom plots seven years after planting. Tree and stand volume of the planted seedlings were higher in the d-dom plots than the c-dom ones in year seven. In a similar trend as for diameter, tree and stand volume increased with decreasing retention level in the c-dom plots but in the d-dom volumes were highest in the 50% retention plots. Eight years after harvest the d-dom plots averaged 19,000 SPH of broadleaf saplings compared to 6300 SPH in the c-dom plots. Clearcuts of the d-dom plots had 33,000 broadleaf SPH compared to 11,900 broadleaf SPH in clearcuts in the c-dom. The density of sprouts in the 75% retention was similar in the c-dom and d-dom plots. Site preparation treatment had no effect on sprouting density. The study demonstrated that aspen-dominated stands support spruce seedlings better than conifer-dominated stands, which the authors relate to the greater interception of radiation by mature white spruce than aspen and greater light transmission in the d-dom stands in the leaf-off period. Also, the c-dom understory was dominated by mosses (versus shrubs under the d-dom) which insulates the soil from solar radiation and warm air. In the d-dom stands, greater performance of spruce in the 50% retention plots versus the clearcuts or 75% retention plots was thought to be due to denser aspen regeneration in the clearcuts and protection from frost under the canopy.

In Alberta, Man and Lieffers (1999b) found that shelterwood cuts create regeneration conditions for white spruce that are a good compromise between conditions in clearcuts and unmanaged boreal mixedwoods. Compared with clearcuts or unmanaged mixedwoods, seedlings in shelterwoods exhibited earlier bud break, reduced terminal bud and seedling mortality, increased capacity for photosynthesis, and slightly improved growth. Relative to the clearcuts, the shelterwoods had higher humidity, cooler maximum and warmer minimum temperatures and reduced occurrence and severity of night frosts which all benefit the establishment of white spruce. The treatments that were compared were clearcuts, high and low density shelterwood, and an uncut 120-year-old spruce-aspen mixed stand (control). Basal area in the control was 18 m<sup>2</sup>/ha of aspen and 13 m<sup>2</sup>/ha of spruce. In the high density shelterwood, residual basal areas were 17 m<sup>2</sup>/ha of aspen and 4 m<sup>2</sup>/ha of spruce and in the low density shelterwood, the basal area of spruce was also 4 m<sup>2</sup>/ha but aspen basal area was only 9 m<sup>2</sup>/ha. Shelterwood cutting increased light transmission from 20% in the control to 46% in the high retention and 73% in the low retention area. Frequency of frost increased, minimum air temperature decreased, and maximum air

temperature increased with reduction of the canopy. The number of nights with frost was 27 in the control, 28 in the high density shelterwood and 49 in the clearcut. Relative humidity decreased as canopy density decreased. Soil temperature was not affected by canopy reduction treatments.

Voicu and Comeau (2006) found that negative effects of shading by aspen on white spruce growth were restricted to a narrow band adjacent to an aspen patch that was 0.3 times the height of the aspen. This was determined at sites near Grande Prairie and Peace River, Alberta.

### **Saskatchewan studies**

In west-central Saskatchewan, seedlings were planted in and beside 80 x 340 m rectangular gaps, separated by 100 m wide buffers of uncut white spruce-aspen forest (Milakovsky et al. 2011). Two vegetation management treatments were applied (brush saw cutting of all aspen to ground level, and mixing of vegetation and ground rootstocks), along with a no-treatment control. Growth and survival of the spruce seedlings were measured for four years. Survival was initially significantly higher in gaps than under the canopy and was best at the southern edge of gaps, but by year four survival was about 75% for all treatments including the control. Height growth of planted spruce was initially best in gaps at south edges until year four when best growth was at gap centres, although growth differences were modest (7.3 cm/year in the centre of gaps versus about 6 cm/year at the edges). Spruce height growth was greatest where the more severe vegetation management treatment (mixing) was done. Ungulate exclusion improved height growth. No diameter or HDR ratio data was available.

### **Ontario studies**

In northern Ontario, overstorey manipulation treatments and vegetation control were applied at three locations to examine shelter and competition effects on planted white spruce (Groot 1999). Overstories were aspen-conifer mixedwoods and nearly pure aspen. Treatments included clearcutting, uniform shelterwood (40% canopy removal), strip shelterwood (widths from 0.5 to 1.0 H, where H = height of dominant trees), patch shelterwood (openings with a diameter of about 1 H), narrow strips (width 0.25 H) and intact overstorey (control). Vegetation control treatments were herbicide and no herbicide. Seedlings were planted into the various treatment plots and measurements taken two years later. Survival was generally high but was only 52% for seedlings planted under an intact overstorey with no herbicide control. Second-year white spruce height and diameter growth was generally poorest for treatments that maintained intact or nearly intact overstories (0.5H strips) and in these treatments vegetation control had little effect on seedling performance. The greatest diameter growth of spruce tended to be in clearcuts with vegetation control and the greatest height growth tended to be in shelterwoods with vegetation control. Vegetation control in clearcuts always increased seedling diameter but not height. In the shelterwood plots vegetation control often increased both height and diameter growth and this combination was the best treatment for establishing white spruce. Light levels below the intact canopies were only 23% of above canopy values, well below the level needed for optimal growth of white spruce. Inadequate soil moisture and nutrient levels may have also reduced performance.

### 2.4.3.7 Release cuttings where an aspen overstorey is removed from established white spruce

This treatment differs from the one in the previous section in that here regeneration is already established before the canopy is removed, compared to planting of seedlings into areas with partially removed canopies.

#### Overview

Man's (2003) meta-analysis summarizes the trends in survival, height, diameter, and volume responses of white spruce to release treatments in boreal aspen-spruce mixedwood stands. Data used in the analysis was collected between 1950 and 2000 in British Columbia, Alberta, Saskatchewan and Manitoba.

The mean percentage release/control ratio for height growth is 1.61, for diameter growth is 1.73, for volume growth is 1.32 and for survival is 1.04. This means that released trees have on average 61% greater height growth, 73% greater diameter growth, 32% greater volume growth and have a 4% greater survival rate compared with unreleased control trees. For the three growth variables, strong positive responses dominate. Of the 76 datasets for height growth, 12% show a negative treatment effect (R/C ratio <0.89), 16% show no effect (R/C ratio 0.90-1.09), 32% show a positive treatment effect (R/C ratio 1.10–1.49) and 49% have a strong positive treatment effect (R/C ratio  $\geq 1.50$ ). Diameter growth had a stronger positive effect than height growth, with <2% of data sets showing a negative effect, 6% with zero effect, 41% with a positive effect and 51% with a strong positive effect. For volume growth, 3% of the datasets show a negative effect, 3% show zero effect, 24% show a positive effect and 70% a strong positive effect. However, for survival, most of the subdata sets are in the zero (47%) or negative (32%) category. Only 11% fall in each of the positive and very positive effects.

Growth responses of released white spruce are related to initial tree height, years since release, and residual basal area. Height response pattern is largely determined by initial tree height and increases slightly with number of years after release. The height growth response is greatest when understorey spruce are 9-11 m tall, and there is little response for trees less than 3 m tall. The diameter growth response is also greatest at an initial tree height of 9-11 m but positive diameter responses occurred over the range of initial tree height covered by the data in the analysis. The greatest volume growth response again occurs at an initial tree height of 9-11 m, and there is little response for trees less than 3 m tall. The data covers a range of residual basal area of 1-17 m<sup>2</sup>/ha, and within this range, there was a positive response to release in all three forms of growth measurements (height, diameter, volume). Height response increases with increasing residual basal area, with a maximum response at 13-15 m<sup>2</sup>/ha. Diameter and volume response generally decrease with increasing basal area at release. Man discusses possible explanations for the trends that were seen.

The following is a summary of results from Canadian trials in boreal mixedwoods in which white spruce were released from established aspen canopies. None of them took place in British Columbia.

### Alberta, Saskatchewan, and Manitoba studies

One of the longer term release trials was carried out in Alberta (Yang 1991). Spruce growth and yield responses were followed for 35 years following release from aspen competition at an average age of about 50 years. All aspen within a circular area two times the crown diameter surrounding the selected spruce trees were removed (minimum radius 3 m). Aspen was left untreated for control spruce trees. Diameter at breast height and height were measured periodically and after 35 years and used to calculate tree volumes with Honer's (1967) volume equation (see Honer 1966, cited by Yang 1991). Release effects on diameter, height, and volume were measured on individual trees, not at the stand level. Release treatments increased spruce volume growth over 35 years by 82% compared with spruce growing in mixture with aspen. Average DBH at 35 years ranged from 11 to 34 cm (average 21 cm) for released and 7 to 23 cm (average 15 cm) for control trees, an improvement in DBH growth of 41% over the 35-year period. Thirty-five years after release, average spruce height was 8.0 to 15.5 m (average 11.9 m) for released trees and 5.7 to 11.6 m (average 8.6 m) for unreleased trees, an average increase of 38%. Yang calculated that when spruce are released in 46-65 year old aspen-spruce stands, spruce volume yield can be increased by  $144 \text{ m}^3/\text{ha}$  on medium or better sites in 35 years, provided stands are moderately stocked with 350 SPH of spruce.

Yang (1989) published long-term (30-50 year) results from release cutting in aspen-spruce mixed stands for 8 sites in Manitoba. Seven of the sites were measured for 30 yrs and one for 50 years (Duck Mountain, discussed in the next paragraph). At the seven sites, average age of aspen ranged from 25-30 to 55-60 years-old and average spruce age ranged from 10-25 to 35-50 years. Mortality of small spruce was higher in the controls than released areas. Complete release of white spruce from aspen competition increased DBH increment over 30 years by 15-177% compared to the controls. The greatest improvements occurred when the released spruce were 15-40 years old and response was greatest in small trees (2-6 m height). Complete release resulted in 30-year spruce height increments that were 28-60% greater than when there was no treatment. Complete release improved spruce total basal area by 18-244% over the control in 30 years. The periodic annual increment of spruce total volume averaged  $4.83 \text{ m}^3/\text{ha}/\text{yr}$  after release and  $2.50 \text{ m}^3/\text{ha}/\text{yr}$  for the control, a 93% increase. Release from aspen markedly improved spruce merchantable volume in all areas but the density of spruce residuals following release dictated stand yield. Merchantable volume increment over 30 yrs was 29-239% higher in complete release treatments than controls, except much higher at one site (Riding Mountain). Total volume increment over 30 years was 24-304% higher in complete release treatments than controls. In partial release treatments (uniform 50% removal), total volume and merchantable volume increments over 30 yrs were similar or less than for the controls. These are some highlights from the results; much more detail is available in the paper.

The Duck Mountain study in Manitoba (Yang 1989; Steneker 1963) provides results of partially releasing white spruce from aspen in a 50-year-old mixedwood. A light release treatment (44% of total basal area of the stand removed) and a heavy release treatment (60% of the basal area of the stand removed) were applied. Trees that were "competing with" or overtopping white spruce were removed. A mixedwood area was left untreated as a control. Twenty-one years after treatment, total volume of

white spruce from the light and heavy release treatments was about twice that of the control. Merchantable volume of white spruce for the light and heavy release treatments were about double and triple that of the control, respectively. The control produced the greatest total volume (all species combined) and the heavy release treatment produced the least. DBH increment over 50 years was 28% greater than in the untreated control in the light release treatment and 50% greater than the control in the heavy release treatment. Total volume increment over 30 yrs was 260% higher for the heavy release treatment ( $164 \text{ m}^3/\text{ha}$ ) than the control ( $46 \text{ m}^3/\text{ha}$ ). The total volume increment of trees in the light release treatment was  $83 \text{ m}^3/\text{ha}$ . Merchantable volume increment gains were  $52 \text{ m}^3/\text{ha}$  for the control,  $90 \text{ m}^3/\text{ha}$  for the light release and  $174 \text{ m}^3/\text{ha}$  for the heavy release. In the control roughly 2/3 of the total volume increment was in aspen (the rest white spruce and pine), in the heavy release about 1/4 of the volume increment was in aspen, and in the light release about 1/3 was in aspen.

Jarvis et al. (1966) bring together results from many old release studies, in addition to those described by Yang (1989). They were carried out in Alberta, Saskatchewan and Manitoba in the 1960's and earlier. They concluded that any overstorey of trembling aspen hinders development of the spruce beneath it and all ages and sizes of spruce respond to overstorey manipulation. The amount of response was directly related to the intensity of the release cutting and 30-40 year old trees had the greatest potential to increase their growth rate for a given degree of release (Blyth 1952; Jarvis and Steneker 1962; Steneker and Jarvis 1963; Steneker 1963 and Lees 1966, all cited by Jarvis et al. 1966). Large increases in spruce volume are reported following reductions in canopy density (as at Duck Mountain). Readers are referred to Jarvis et al. (1966) for summaries of each individual study. Steneker (1963) cites comments from some of the old studies: Kagis (1952) said that as a result of competition and suppression from aspen, losses of white spruce volume are "enormous." Cayford (1957) concludes that spruce volume production may be 50% lower in mixedwoods compared with open grown spruce stands. Kabzems (1952) said that height growth of white spruce in mixedwood stands is always less than in pure spruce stands, partly due to mechanical damage to spruce leaders from the overtopping broadleaf canopy.

### Quebec studies

In a five year study In Quebec, Prevost and Pothier (2003) tested five partial cutting intensities in a mixed aspen-conifer stand to investigate natural conifer regeneration. The treatments were removal of 35, 50 and 65% of basal area, a clearcut with careful logging around advance regeneration, and an uncut control. Initial basal areas varied from  $3.3$  to  $20.3 \text{ m}^2/\text{ha}$  of aspen,  $0.2$  to  $13.7 \text{ m}^2/\text{ha}$  of white birch, and  $1.1$  to  $10.6 \text{ m}^2/\text{ha}$  of spruce and fir (total stand basal area  $15.7$  to  $30.4 \text{ m}^2/\text{ha}$ ). Initially understorey aspen was sparse, but after cutting it suckered vigorously, with suckering increasing as overstorey removal increased ( $4,700$   $17,600$ ,  $32,300$  and  $50,600$  SPH in the 35, 50, 65 and 100% cuts one year after treatment). Density of aspen suckers dropped after the first year. Spruce seedlings established well where scarification was done but not without it. Five years after harvesting and scarification, density of natural spruce regeneration was higher in the 65% cut ( $32,500$  SPH) than the 50% cut ( $15,100$  SPH), 35% cut ( $9,800$  SPH) and 0% cut ( $8,000$  SPH). After five years, most conifer seedlings were much smaller (30 cm tall) than the aspen suckers. The percentage of light transmitted to the understorey was 20%, 20%, 30%, 48% and 90% of full sun for the control, 35% cut, 50% cut, 65% cut, and 100% cuts, respectively,

during the first summer. In the first year, summer soil temperature on the 35% cut was similar to in the control, while other treatments resulted in temperature increases from 2.4–3.2 °C in the 100% cut and 1.5–2.5 °C in the 50% and 65% cut). After 5 years, mean summer soil temperatures were still 1.0–1.4 °C higher in the 50%, 60% and 100% treatments than the control. The same magnitude of increases occurred for the summer maximum temperature, with no differences between the higher cutting densities. Mean winter temperature was not affected by the treatments.

#### **2.4.3.8 Light and white spruce performance – an overview**

Light is crucial for photosynthesis and is one of the most important factors influencing understorey plant or tree growth (numerous references cited by Voicu and Comeau 2006). Much research has been done that indicates that competition between conifers and broadleaf trees in mixedwood stands (at least stratified stands) primarily reflects light limitations resulting from overstorey broadleaf trees (see Green 2004 for list of references). Because light is generally considered to be the resource most limiting to white spruce growth in boreal and sub-boreal forests, knowledge of the relationship between light and growth and survival of understorey white spruce is of paramount interest.

In a comprehensive literature review, Astrup (2005b) summarized the available knowledge on light-growth relationships for spruce. He identified 35 Canadian and one U.S. (Minnesota) study where measurements of both light availability and spruce growth had been taken. Twenty of the studies investigated white spruce, and the remainder black spruce, Engelmann spruce, Engelmann spruce-white spruce hybrids or interior spruce–Sitka spruce hybrids. The majority of studies were not from the BWBS or SBS zones in British Columbia, nevertheless the results are of interest for white spruce-trembling aspen stands in this province.

Astrup's key findings in regard to light/growth relationships for spruce are: Maximum height and diameter growth occurs in full sun. The majority of the literature indicates that under aspen-dominated canopies, spruce height increment follows an asymptotic pattern. Height increment rapidly increases between 0 and 50% light, and the gain between 50 and 100% light is small (generally less than 20%). High variability was found both in the height increment observed at a given light level and the general shape of the light-growth response curve. Under conifer-dominated canopies, height increment and diameter increment of spruce increases in an approximately linear, or slightly exponential or asymptotic relationship. Under aspen-dominated canopies, spruce diameter increment increases to a maximum at 100% light, but the gain between 75 and 100% light is likely small. In general, height: diameter ratio is greater for understorey spruce than open-grown spruce. There is very little literature relating light availability to measures of spruce growth other than height and diameter (e.g. above-ground biomass, leaf area, and crown allometry). Above-ground biomass production is well correlated with diameter growth, so light-growth relationships are similar for the two, with above-ground biomass production increasing linearly with available light until 100% light.

Spruce growth rates at full light are generally controlled by climatic and site conditions, but the shape of the light-growth response is considered to be greatly affected by the type of overstorey canopy, with

broadleaf canopies impacting spruce growth less than conifer canopies. Astrup attributes this to differences in the composition and quality of understorey light, the leaf-off period in aspen stands, and difference in soil temperature and nutrient availability. He found that a large proportion of the variation in growth rate for a given light level was attributed to tree size. Within the range of tree heights in the reviewed papers (0-11 m), growth rate generally increased with tree size, but at very low light levels size did not increase growth rate. Increased growth of large trees compared to small ones was generally attributed to differences in photosynthesis. Variability of growth rate was also caused by differences in climatic conditions (geographic areas) and site conditions.

Light levels required for what may be considered acceptable, good, and optimal growth for spruce can be estimated from Astrup's (2005b) graphs and tables, taking into account the stand age, site, and geographic area of the studies.

#### **2.4.3.9 Relationship between light levels and aspen measures**

Relating light levels to stand attributes at a given age such as basal area is useful for operational decision-making when planning how much aspen to retain in a mixedwood.

- Light levels are variable for a given basal area (Comeau 2001).
- Light availability can be predicted from broadleaf basal area, broadleaf quadratic mean diameter and height of the tallest broadleaf tree. Broadleaf density alone is not a good predictor of light availability in young stands because it does not include a measure of individual or collective broadleaf size (MacClarnon and Heineman 2003)
- In boreal forests in northeastern B.C and sub-boreal forests in central interior British Columbia, understorey light levels and aspen basal area are strongly related (Comeau et al 2006; Comeau 2001).
- Aspen relative density (ARD) was found to be a slightly better predictor of light levels than aspen basal area for the SBS zone but a poorer predictor for the BWBS zone.  $ARD = BA/QMD^{0.04}$  where  $BA$  = aspen basal area per hectare, and  $QMD$  = quadratic mean diameter of aspen.  $QMD = (\sum DBH_{ai}^2/n)^{0.5}$  where  $DBH$  is diameter at breast height of an individual aspen tree and  $n$  is the number of aspen trees in the plot ( $r=3.99$  m) (Comeau et al. 2006).

#### **2.4.3.10 Threshold light and aspen levels for spruce performance**

Threshold levels of light and/or aspen required for various levels of spruce performance have been identified in the literature and are listed below. These relationships should not be widely extrapolated to regions beyond the location of the study and represent results for certain stands at certain ages.

- Light levels of 8% of full sunlight are required for survival of white spruce in western boreal forests (Lieffers and Stadt 1994). Minimum light levels for survival may increase with spruce size because larger trees must support more respiring tissue (Givnish 1988 and Messier 1999; cited by Comeau 2001).

- Kobe and Coates (1997) report that survival is very poor at light levels that are less than 15%. One study showed that for early establishment and survival, natural white spruce under conifer canopies required 30% of full sunlight (Klinka et al. 1992, cited by Comeau 2001).
- Light levels under maturing aspen canopies are best for spruce establishment when they are between 25 and 40% (Comeau et al. 2009a, summarizing literature).
- Maximum photosynthesis in white spruce shoots occurs at 40-60% of full light levels (Man and Lieffers 1997).
- Percent light required to attain 40%, 60% and 80% of maximum diameter growth of spruce is 28%, 46% and 66%, respectively (Wright et al 1998).
- In boreal forests, an overstorey aspen basal area of 8 m<sup>2</sup>/ha or greater results in light levels that are less than 60% of full sun (based on stands aged 12-40 years). At this point spruce diameter growth is estimated to be reduced to 70% of maximum and height growth is estimated to be reduced to 80% of maximum. To achieve an aspen basal area that is less than 8 m<sup>2</sup>/ha, aspen density has to be less than 2000 SPH when aspen diameter is 7.0 cm and less than 5000 SPH when diameter is 4.4 cm (Wright et al. 1998; Comeau 2001).
- When overstorey basal area reaches 10 m<sup>2</sup>/ha in 40 year-old or younger BWBSmw1 01 stands, understorey light levels of about 50% are predicted and spruce diameter growth is estimated to be reduced to 62% of maximum (Wright et al. 1998; Comeau 2001).
- An overstorey basal area of 14 m<sup>2</sup>/ha or greater results in light levels that are less than 40%, and spruce diameter growth will be only 51% of maximum (Wright et al. 1998; Comeau 2001). To achieve this, aspen density has to be less than 2000 SPH when aspen diameter is 9.3 cm and less than 5000 SPH when aspen diameter is 5.9 cm. This applies to 40-year-old or younger stands on BWBSmw1 01 sites.
- Height growth of understorey white spruce should be maximized when light levels are above 40% or when aspen basal area is below 14 m<sup>2</sup>/ha (from literature summarized by Comeau 2001).
- Spruce mortality is predicted to be very low up to 20 m<sup>2</sup>/ha of aspen basal area, but predicted to increase rapidly as basal area exceeds this threshold (Wright et al. 1998).
- Low densities (up to 1000 SPH) of aspen were found to have no effect on growth of 15-year old planted white spruce in Alberta (Griffiths 2008, cited by Macdonald et al. 2010).
- On medium to rich sites in the BWBS zone, spruce production appears to be fairly insensitive to a wide range of aspen densities above 1000 SPH, but a relatively small amount of aspen (less than 1000 SPH) is expected to have a large effect on spruce production. The threshold for aspen density to affect white spruce growth is suggested to be below 1000 SPH of aspen. The Mixedwood Growth Model indicated that retaining 1000-10,000 SPH of aspen could increase total volume production but spruce merchantable volume would be only about half that of the pure spruce regime (Kabzems et al. 2007).
- Above an aspen density threshold of 2500 SPH optimum growth of white spruce may not be achieved based on data from the SBSmk1 subzone, 60 km northwest of Prince George (DeLong 2007).
- No consistent broadly applicable relationship between white spruce growth and broadleaf (including aspen) competition measures were found for good productivity sites in Alberta.

Broadleaf competition explained 30-50% of the variation in white spruce growth, indicating that other limiting factors were important. The competition level that produced substantial growth reduction varied among areas but in general diameter losses of 20-40% were associated with the competition level expressed by a Basal Diameter Ratio index value of 2.5. This means that growth losses occurred when broadleaf tree with a diameter 2.5 times larger than the spruce were present within 2.0 m (Navratil and MacIsaac 1996).

- Relationships between spruce growth and aspen competition are site specific in stands that are less than 20 years-old (Filipescu and Comeau 2007a).

Some studies have aimed to determine paper birch threshold levels for spruce growth. Density thresholds that have been identified for boreal and sub-boreal stands are:

- Spruce growth is promoted at birch densities of up to 2000-2500 SPH, based on studies in the SBS zone at Sinclair Mills and Cozems Vama Vama (Lange et al. 2004).
- Acceptable diameter growth of white spruce is achievable at birch densities up to 1200 SPH in the ICH zone (Danskin and Lange 2006).
- Competitive interactions between spruce and birch are different on north and south facing aspects in the SBS zone (Green and Hawkins 2005).

## **2.4.4 Lodgepole pine-trembling aspen**

### **2.4.4.1 Natural mature mixed and pure stands**

Longpré et al. (1994) compared growth and yield in 70-year-old even-aged stands of pure jack pine, jack pine mixed in equal amounts with trembling aspen, and jack pine mixed equally with paper birch. No significant differences were found among stand types for total basal area, total merchantable stem volume ( $\text{m}^3/\text{ha}$ ), and average height of jack pine but average DBH of jack pine and the volume per jack pine tree were significantly greater in pine-birch mixtures than in either pure jack pine stands or pine-aspen mixtures. This is in spite of the fact that although both mixed types had higher forest floor pH and greater concentrations of exchangeable Ca than pure pine stands, the aspen-pine mixtures had the most favorable forest floor properties of the three types. The authors suggest that these forest floor properties were not limiting to jack pine growth on the study sites but light competition should be considered. Stem analysis revealed that pine and aspen grew at about the same rate, and so occupied the same canopy space, while birch grew much slower than the pine and so occupied a separate layer in the stand, which could have reduced interspecific competition for light for the pine and thereby increased its diameter growth. The authors noted that the significantly greater diameter growth of jack pine in mixed stands with birch suggests that some birch (up to  $5 \text{ m}^2/\text{ha}$ ; approximately 15% of the stand volume) could be maintained in jack pine stands without reducing the merchantable volume of the pine.

### **2.4.4.2 Studies of juvenile lodgepole pine-trembling aspen interactions**

Four studies from B.C and one from Ontario were found in which lodgepole pine growth and survival were measured in plots with varying levels of aspen (Table 7). Three of the British Columbia studies were done in the SBS zone and one in the SBPS (Sub-Boreal Pine Spruce) zone. There have also been a few studies done in the southern interior of British Columbia.

### **British Columbia sub-boreal studies**

Newsome (1995) assessed aspen competition in naturally regenerated 9-15 year-old lodgepole pine stands in the SBSdw1 subzone. On each of three sites, fifty 1.8 m radius plots, each centred on a lodgepole pine subject tree, were established. Lodgepole pine was measured for height, diameter, crown radius, age and condition. Each aspen tree in the plots was assessed for height, diameter, distance from the aspen stem to the edge of the subject pine, distance from the outer crown edge to the stem of the subject pine, and percent aspen cover.

Various competition indices developed by other researchers were plotted against the pine variables and those variables that appeared to have a relationship in the initial graphs were investigated further using non-linear regression. The Lorimer, MacIsaac and Daniels competition indices provided the best correlation with pine growth on the three sites. The highest  $R^2$  values (0.55-0.61) were obtained when aspen that was 125% of the pine height were considered. This indicates that the smaller aspen were not significantly affecting pine growth, and do not need to be treated when brushing. The Navratil-MacIsaac index, which was the best index, recommended that all aspen trees with diameter greater than 0.75 times the pine diameter be removed for optimal pine growth.

Newsome (1995) also looked how pine growth was related to aspen density using an ANOVA and Tukey's Studentized Range Test. Only aspen equal or taller than the subject pine ("tall aspen") were included in the analysis. As a single variable, tall aspen density was correlated with pine growth better than percent aspen cover or distance from pine to the aspen. The analysis showed that pine diameter and diameter growth do not become significantly reduced compared to pine growing free of competition until aspen density exceeds 2000 SPH. This means that one or two aspen taller than the height of the pine can be left in a 1.8 m radius plot without seriously affecting pine growth. Pine leader growth and total height were not significantly reduced until aspen density exceeded 5000 SPH.

Newsome (1995) cautions that the results of the study may not apply when site conditions and stand age are different.

The Tyee Lake study, located northeast of Williams Lake, British Columbia, was also established by Newsome et al. (2004a). The site is located in the SBSdw2 variant but is transitional to the SBSdw1 variant so it is considered representative of the SBSdw subzone for the Southern Interior Forest Region. The site was clearcut logged in 1980 and heavily regenerated with aspen, then in 1993, all of the aspen was cut with chain saws, mechanical site preparation was done with a ripper, and lodgepole pine was planted in 1994. Four treatments were applied at the site: (1) unbrushed control (1) removal of all aspen >10 cm tall within a 50 cm radius of pine, (2) removal of all aspen > 10 cm tall within a 100 cm radius of pine, and (3) broadcast aspen removal. Treatments were applied annually for 9 years. Assessments were

made of growth, survival and vigour of the pine up until 2002, and neighbouring aspen within a 1.78 m radius of crop pine trees were measured for height, stem diameter and distance to the pine.

At age nine, there were no significant differences in pine survival, stem diameter or height between any of the treatments, even though vole damage to newly planted seedlings was greater in the control and 50 cm radius treatments than the treatments where more aspen was removed (probably due to greater cover for these mammals). Vegetation competition was not an important cause of mortality, but there was a clear trend of declining vigour with increasing aspen density, even after seedlings stabilized when vole repellent was applied. Although growth differences were not significant among treatments in any year, a trend of greater diameter in the broadcast treatment relative to the 50 cm and 100 cm radius and control appeared to be developing over time. Beginning in year four, HDR was significantly lower in the broadcast treatment (51 in 2002) than the control (63) or 50 cm radius treatment (62).

Aspen height, diameter, and density within the 1.78 m<sup>2</sup> subplots were similar across the 50 cm, 100 cm and control plots throughout the study. However, average density of tall aspen decreased from 23 to 4 stems per subplot between 1994 and 2002, and average density of “all” aspen decreased 44 to 19 stems per subplot. The decreases were due to self-thinning and rapid height growth of pine relative to small, low-vigour aspen. Tall aspen was growing slightly faster than the pine. Broadleaf tree cover within a 1.78 m radius around the crop pine increased from 10 to 29% in the control, from 10 to 19% in the 50 cm treatment and from 7 to 16% in the 100 cm treatment in the nine year measurement period.

The calculation of Spearman’s rank correlation coefficients showed that all lodgepole pine growth variables (stem diameter, stem diameter increment, height, height increment, and leader length) except HDR were negatively correlated with tall aspen density (based on density in the 1.78m radius subplots). Correlations were weaker for height than diameter. At age nine, tall aspen density explained 55% of the variation in pine stem diameter and 46% of the variation in pine height. Aspen basal area explained less of the variation in pine growth than tall aspen density ( $R^2 = 0.42$  for pine stem diameter and 0.27 for pine height). Correlations between pine growth variables and “all” aspen density were much weaker than the relationships with tall aspen density.

In addition to the calculation of Spearman’s rank correlation coefficients, non-linear regression models were fitted. At pine age nine, tall aspen density explained 41% and 34% of the variation in pine diameter and height, respectively. Aspen basal area predicted 18% of diameter variation and 9% of height variation.

Another study of lodgepole pine-aspen interactions is the McKinley Lake experiment, located 37 km southeast of Horsefly (Newsome et al. 2006a). It was established in 1999 to investigate the effects of reducing aspen density on stand-level aspen and lodgepole pine growth in the SBSdw1. The pine regeneration on the site is a combination of patchy regeneration that came in naturally after clearcutting in 1988, and pine that was fill-planted in 2000. Ninety-four percent of the broadleaf trees on the site were aspen. Aspen retention treatments of 0, 500-800, 1000-1500 and 2000-2800 SPH were applied in 1999 to the 11-year-old mixed lodgepole pine-aspen stand and an untreated control was left.

Aspen suckering was much more prolific in the 0 retention treatment (28,187 suckers/ha two years after treatment) than the 500-800 SPH (5,981 suckers/ha), 1000-1500 SPH (4084 suckers/ha) or 2000-2800 SPH (344 suckers/ha). Suckers were not assessed in the control in year two but in year four this plot contained 264 suckers/ha. By year four sucker density had declined to 18,063 suckers/ha in the 0 retention area and 4,039 in the 500-800 and 1000-1500 SPH retention treatments.

Four years after treatments were applied to adjust aspen densities, there were no significant differences in lodgepole pine height, DBH, quadratic mean diameter, basal area, or HDR among the five treatments but pine vigour tended to be better where  $\leq 800$  aspen SPH had been retained. The overall condition of conifer stems was poorer than that of broadleaf trees, which were generally healthy (0-16% of broadleaf trees had poor vigour in year four). The greatest proportion (37-48%) of poor and moribund pine seedlings occurred where at least 1000 aspen SPH had been retained, but above 1000 aspen SPH the proportion of unhealthy pine did not increase consistently as aspen density increased. The 0 retention treatment had 21% poor or moribund pine seedlings and the 500-800 SPH retention treatment had 28%.

Spearman's rank correlation coefficient was used to assess the degree of association between density and basal area (total and broadleaf) and height and diameter increments of the target lodgepole pine. Correlations were better for diameter than height. Aspen basal area (based on aspen growing within a 3.99 m radius of the target lodgepole pine) explained 44% of the 2000-2003 pine DBH increment and 37% of the 2000-2003 pine height increment.  $R^2$  values were essentially the same when 2000-2003 aspen basal area increment was used instead of basal area. Tall broadleaf density (based on a 1.78 m radius plot) explained 48% of the 2000-2003 pine DBH increment and 38% of the 2000-2003 pine height increment. Correlations based on density in larger neighbourhoods ( $r=3.99$  m) or based on total (rather than tall) broadleaf density were weaker. The most highly correlated aspen abundance variables were further explored using regression analysis, but relationships were relatively weak. 2003 aspen basal area, 2000-2003 aspen basal area increment and 2003 tall broadleaf basal area each predicted 24-26% of the variation in 2000-2003 lodgepole pine DBH increment. Pine height increment was predicted less successfully than pine diameter increment.

Newsome et al. (2008) and Newsome (2009) looked at competitive interactions between naturally regenerated lodgepole pine and trembling aspen in four unmanipulated stands in the SBSdw1 and IDFdk3 (two stands in each variant) in the Cariboo-Chilcotin. The results from only the SBS stand are summarized here. Assessments were made at three time periods (stand ages 12-13, 17-18 and 22-23 years) of the survival, vigour, height and ground-level diameter (GLD) of pine that were growing among 11 naturally occurring densities of aspen (0, 1000, 2000, 3000... $\geq 10,000$  SPH). The densities only include aspen as tall or taller than the target pine. Neighbouring tall aspen within a 1.78 m radius of each target pine were measured for GLD and height.

Survival of 20-24-year old lodgepole pine declined significantly with increasing tall aspen density, with the threshold for 80% survival of pine at 7000 tall aspen SPH. Over 80% of pine had fair to good vigour in the 0 and 1000 SPH tall aspen density classes, but condition declined steeply as density increased above 1000. Above a density of 2000 tall aspen SPH, 60-100% of pine had poor vigour or were dead. Lodgepole pine growth declined significantly as tall aspen density increased, and competition effects became much

more evident as the stands aged from 12 to 23 years. At age 12-13, differences in pine GLD between aspen density classes were marginally significant, but at age 17-18 and 22-23 they were strongly significant. At the youngest age, differences in pine height and HDR were non-significant among density classes, but by age 17-18 they were strongly significant. A threshold of 1000 tall aspen SPH was associated with 90% open-grown lodgepole pine diameter growth for 12-23 year old stands.

Tall aspen height differed significantly between tall aspen density classes at stand ages 15 to 24 years. The height difference between pine and aspen generally increased with tall aspen density. Pine was growing faster than the aspen only where tall aspen density was 1000 SPH. Actual tall aspen density in classes that were defined at age 12-13 remained relatively constant in the  $\leq 3000$  tall aspen density classes over the next 10 years, but decreased by 2–27% in higher tall density classes.

Regression analysis showed that tall aspen density was well-correlated with lodgepole pine size, explaining 63% of the variation in pine diameter and 69% of the variation in height. Models that used total (tall and short) aspen density, tall aspen basal area or aspen relative density to predict pine GLD and height at age 22-23 were almost all significant but they explained less of the variation in pine size than tall aspen density. Of the four competition Indices that were tested (BDR, Lorimer, Daniels, Simard), the BDR index was the most strongly correlated with pine size, explaining 78% of the variation in pine GLD and 73% of the variation in 22-23 year-old pine height.

Below a light level of 28%, mortality of lodgepole pine sharply increases (Wright et al. 2000). When Newsome (2008) applied ecosystem-specific models that predict understorey light from aspen basal area developed by Comeau et al. (2006), light availability was below 28% where tall aspen density exceeded 1000 SPH.

In another study, Newsome et al. (2010) investigated lodgepole pine responses to varying levels of aspen removal at two sites in central British Columbia, one in the IDFdk3 subzone (Meldrum) and one in the SBPSxc (Sub-Boreal Pine-Spruce very dry cold subzone) (Clusko). Results from the former site are not described here since it is dis-similar to the SBS but the SBPS results are summarized below, even though it too differs from the SBS. The SBPS zone was originally part of the SBS zone, occurring in the driest, coldest parts of the SBS in the south and southwest (Meidinger and Pojar 1991). Compared to the SBS, it is drier with similar mean daily temperature in winter but cooler mean daily temperature in summer. The number of growing degree days above 5° C is significantly less than in either the SBS or BWBS zones.

A range of aspen retention levels were created by manual cutting treatments at Clusko when the natural lodgepole pine stand was 11 years-old, and measurements of the aspen and pine were made at the time of treatment and two- and four-years afterwards. The treatments were broadcast removal of aspen (0 SPH), 1000 SPH, 2500 SPH, removal within a 1-m radius, and an untreated control (14,200 aspen SPH). Mean aspen density immediately after treatment was significantly higher the control and 1-m radius treatments than the others, and this trend continued for the four year measurement period. Sucker density increased with decreasing aspen retention. By the fourth year after treatment, an average of

144 suckers/ha in the broadcast treatment had grown taller than the pine, but they were significantly shorter than in the other treatments.

Four years after treatment, survival of the 15-year old lodgepole pine was at least 98% in all treatments including the control, and almost all seedlings had good or fair vigour, with minimal damage. Two years after the aspen was treated, pine ground level diameter was significantly larger in the broadcast removal treatment than the control, and it remained significant into year four. For the four-year post-treatment period, mean GLD growth in the broadcast removal treatment (2.2 cm) exceeded that of the 1000, 1-m radius, and untreated control treatments (average 1.5 cm) but not the 2500 treatment (1.8 cm). Mean HDR was significantly lower in the broadcast removal treatment than the control two years after treatment, and it was lower in the broadcast removal treatment than the 1-m treatment after four years. Pine height, leader length and crown width did not differ significantly among treatments in year two or four, indicating that pine was performing well with up to 2500 tall aspen SPH.

Non-linear regression analysis was conducted to examine the relationship between pine GLD or height and density of tall aspen at a stand age of 14-15 years. Tall aspen density in 1.0 m neighbourhoods explained only 6% of the variation in height and GLD of the 15-year-old pine. Using a plot size of 2.6 m, tall aspen density explained 22 and 25% of the variation in pine GLD and height, respectively. A second set of regression analysis was done to compare tall aspen density and three competition indices for their ability to predict pine GLD or height. The competition indices were: (1) the BDR index (diameter of tallest aspen/diameter of target lodgepole pine (Navratil and MacIsaac 1993), (b) the Lorimer Index ( $\sum \text{aspen diameter} / \text{target lodgepole pine diameter}$ ) (Lorimer 1983) and (c) the Hegyi Index ( $(\sum \text{aspen diameter} / \text{target lodgepole pine diameter}) / \text{pine-aspen stem to stem distance}$ ) (Daniels 1976). These three competition indices which all included a measure of pine size relative to the aspen were better predictors of lodgepole pine diameter and height than tall aspen density. The BDR Index explained 18-21% of the variation in pine size in 1.0 m neighbourhoods and 52-61% of the variation in 2.6 m neighbourhoods. The Lorimer and Hegyi Indices predicted 64-75% of the variation in pine size in 1.0 m neighbourhoods and 42-63% in 2.6 m neighbourhoods.

Newsome et al. (2012) identified critical height ratios for predicting competition between trembling aspen and lodgepole pine in six juvenile stands in south central British Columbia. Two stands were on zonal SBSdw1 sites, one was in the SBPSxc, and three were in the IDFd3. The SBS sites were located at Hayfield and Two Mile Lake. The study showed that for all sites, aspen less than 1.25 times as tall as lodgepole pine were not important competitors with lodgepole pine at a stand age of 14-19 years (17-18 years for the SBS sites). Logistic regression analysis showed that the risk of declining vigour increased rapidly with increasing presence of aspen. In this study, density of principal aspen competitors was a better predictor of lodgepole pine diameter growth than aspen basal area. The degree of aspen competition, the risk of lodgepole pine vigour declining and the size of competing aspen decreases as site productivity decreased. The SBSdw1 sites were the most productive.

Harper et al. (2009) investigated neighbourhood aspen competition and canopy light environment of 14-19 year-old lodgepole pine-aspen mixedwood stands. Data was collected at 3 sites in the SBS zone in central interior British Columbia (McKinley Lake, Tyee Lake, and Teardrop). At each site, a wide range of

aspen-pine mixedwood stand conditions had been previously created by a variety of management treatments (thinning, herbicide application, and manual brushing). Aspen density ranged from 0 to 24,800 SPH and conifer density varied from 200 to 5600 SPH. At each site, 33-36 sample pine trees were selected to represent the range of light regimes produced by the various aspen competition levels. At each sample pine, competition and stand measurements were made along with a series of light measurements from the base of the tree to the top of the live crown.

An evaluation of various competition indices to try to relate lodgepole pine growth to aspen competition suggested that DRD index (sum of the ratio of each of the three nearest neighbour's DBH to the subject pine divided by the distance to the select pine) and the amount of available light at the top of the crown were the two best overall predictors of pine stem volume growth ( $R^2$  between 0.27 and 0.60). Results varied by site. Total aspen density and largest competitor DBH/distance ratio were the poorest of the significant competition index models. Height growth response of pine was found to be linearly related to the observed range of available light.

A site specific exponential relationship of relative pine stem volume growth to DRD was found and minimum growth response competition thresholds were determined. A minimum tree growth response threshold was approximated for each of the three sites, based on 20% of the maximum observed DRD level. The DRD threshold level was determined to be 0.02, 0.022 and 0.028 for McKinley Lake, Teardrop and Tyee Lake, respectively. The DRD is easily used to calculate an average threshold distance (ATD).  $ATD = \text{neighbor/pine DBH ratio}/(\text{minimum response level}/3)$ . An ATD for maximum growth can also be determined (5-10% of maximum DRD). Using McKinley Lake as an example, if a pine has an average neighbor/pine DBH ratio of 1.0 (neighbours and pine are of similar DBH) then the ATD for minimum growth response is 150 cm and the ATD for maximum growth response is 303 cm. If neighbours have a DBH only one-third that of the pine then ATD for minimum growth response is only 41 cm and the ATD for maximum response is 91 cm.

In another study (Teardrop) the relative impact of aspen competition and soil factors on white spruce and lodgepole pine were studied (DeLong 2007). The study sites were in the SBSmk1 subzone, 60 km northwest of Prince George. Results for white spruce were described in Appendix 1. Plots were established in an untreated control and across a gradient of natural aspen competition levels that had resulted from hack and squirt aspen control treatments one year before harvesting. Year five aspen densities ranged from 2300-32,175 SPH although none of the plots had densities between 7100 and 18,800 SPH. Aspen density, interspecific neighbourhood competition, soil type, humus/displacement depth, moisture regime and aspect were all significant factors in the regression models for lodgepole pine size. The single variable explaining the most variation in lodgepole pine size was aspen competition with 24% of the variability in diameter after 10 growing seasons accounted for by the natural log of the Light Interception Index (LII) for aspen competition (AC). If all lodgepole pine were removed from the analysis where  $AC=0$  (i.e. no aspen competition), the  $R^2$  increased to 0.42. Thresholds were identified for helping define levels at which brushing may be helpful. For lodgepole pine diameter growth, a significant threshold at a LII value of about 700 (equivalent to 14% cover of aspen, with a mean height of 100 cm with less than 1% cover within 20 cm of the apex of the response tree) was identified. LII is

calculated as  $LII = \sum(C_i * H_i) / P_i$  where  $i$  = each competing species that has >5% cover and >50% crop tree height,  $C$  = percent ground cover,  $H$  = average height (cm) of competing species, and  $P$  = proximity (dm) of competing species to crop tree. Regression analysis indicated that above an aspen density threshold of 2500 SPH (measured after 5 growing seasons) optimum growth of lodgepole pine may not be achieved.

### **British Columbia southern interior studies**

A few lodgepole pine-aspen competition studies have been done in the IDF, MS, and ICH zones in the southern interior of British Columbia.

Heineman et al. (2009) studied the effects of manual cutting of aspen in 7-10 year-old lodgepole pine stands on three sites near Kamloops, Salmon Arm and Penticton in the IDF and MS zones. Ten years after treatment, pine survival was excellent (97-98%) in the treated area and control. A minimum of 80% of pine were of moderate or better vigour one to ten years after treatment in both the control and treated area. Five years after cutting, average pine ground level diameter was significantly larger in the treated area than the control, and this difference was still apparent in year 10 (11.9 cm versus 9.8 cm). There was no significant difference in average pine height or stem volume between the treated area and control one, three, five, or ten years after treatment. In year three but no other years, average leader length was significantly greater in the control than the treated area (41 versus 38 cm) and HDR was significantly greater in the control than the treated area (68 versus 57). The density of aspen at least as tall as the pine predicted 36% of the variation in pine diameter and total aspen density predicted 36% of the variation in pine height. Above an average density threshold of 1867 tall aspen SPH pine stem diameter declined. The threshold was highly variable among sites (400 SPH in the IDFdk1, 1800 SPH in the MSdm2 and 3400 SPH in the IDFdk2). In year ten there were an average of 487 free-growing SPH in the control and 889 free-growing SPH in the treated area, but the difference was not significant due to variability among the three sites. Manual cutting had no effect on cover of broadleaf trees or aspen in any of the assessment years but their heights were reduced by the treatment. Average density of broadleaf trees and aspen also did not differ significantly in the treated area and control ten years after cutting.

At an unreplicated site in the ICHmw3 subzone near Clearwater, aspen in a 3 year-old lodgepole pine plantation were cut then one year later the regrowth sprayed with glyphosate (Mather and Simard 1997a). Survival was lower in the control than the treated area (89% versus 97%). Armillaria was the cause of 6% mortality in the control and 3% in the treated area. Pine vigour was similar in the treated area and control (all trees good or moderate). Five years after treatment, there was no significant difference in lodgepole pine height between the treated area and control but average pine diameter was significantly greater in the treated area (7.0 cm) than the control (5.5 cm), although there may have a pre-treatment difference. Five years after treatment, the number of free-growing SPH was 343 in the control and 783 in the treatment. The treatment greatly reduced aspen presence. Five years after treatment, average aspen cover and height were 4% and 121 cm in the treated area compared to 26% and 468 cm in the control.

Prasad (2002) investigated the response of 7 year-old lodgepole pine to manual cutting, triclopyr application, and application of the bioherbicide *Chondrostereum purpureum* to aspen near Grand Forks, British Columbia. Five years after treatment, all aspen removal treatments resulted in significantly greater pine height, diameter, and branch growth compared to the untreated control but responses did not significantly differ among the three release treatments. Survival information was not provided.

### Alberta studies

The EMLP2 study is examining effects of aspen on lodgepole pine in lower and upper foothills ecological subregions in western Alberta (Comeau 2010). During 2006 and 2007, nine installations were established in each ecological subregion with three installations per subregion in each of three age classes (10-20, 20-30 and 30-40 years-old). Within each installation, six sample plots (radius = 9.77 m) were established across a gradient of naturally occurring aspen densities. At each plot, all trees taller than 1.3 m were measured for DBH, height growth over the past five years, height to base of crown, and crown radius, and their locations were mapped. In each sample plot, the 12 pine located closest to the plot centre with no signs of disease or physical defects were designated as “subject” pine. Destructive sampling (collection of stem discs) was done at three plots in three installations in each age class to determine diameter growth of the pine and aspen. The 12 subject pine trees and a sample of 12 aspen located closest to the plot centre were cut and diameter growth was determined from the discs. Non-linear multiple regression was used to look for relationships between lodgepole pine growth and measures of competition.

Different effects of aspen on lodgepole pine were found in the two ecoregions. In the upper foothills, aspen, spruce and other pine were not having significant effects on pine height increment but at the lower foothills, aspen and pine were significantly affecting pine height increment. In both ecoregions, the three species all appeared to be significantly affecting pine diameter growth, but competition effects were stronger in the lower foothills than the upper foothills.

Analysis of data collected at the 9.77 m radius plots indicates that TPH (stems/ha) is the best competition index for explaining variations in height growth in both subregions ( $R^2 = 0.36-0.37$ ).  $R^2$  values for the other competition indices (BAHA = Basal area/ha; HR\*BAHA = Height ratio (pine height/competitor top height); SDI = Stand Density Index; and HR\*SDI = height ratio x SDI) were almost as high ( $R^2 = 0.31-0.33$ ). SDI and BAHA were the best competition indices for predicting pine diameter growth ( $R^2 = 0.75-0.76$  for lower foothills and  $R^2 = 0.43-0.47$  for upper foothills), but with the exception of TPH the other competition indices (HR\*BAHA and HR\*SDI) worked almost as well. Adding crown length to the models improved their ability to explain variations in pine growth. Filipescu and Comeau (2007b) and others have also found that adding tree size measures improves the power of the models.

Data collected in this study suggests that 5 m<sup>2</sup>/ha of broadleaf tree basal area (lower foothills) and 9 m<sup>2</sup>/ha or 1700 aspen stems/ha (upper foothills) are thresholds for diameter growth of lodgepole pine. When these levels are exceeded, diameter growth of pine is reduced by about 30%. Thresholds for pine

height increment are about 15 and 20 m<sup>2</sup>/ha of aspen basal area for the lower and upper foothills, respectively. Above these levels height increment would be reduced to 80-85% of that of trees with no competition.

Navratil and MacIsaac (1993) set out to define a competition index for juvenile (age 5-16) mixed stands of lodgepole pine and aspen in west-central Alberta (Upper and Lower Boreal Cordilleran ecoregions). They collected data within twenty 1.8-m radius circular plots (10 m<sup>2</sup>) per cutblock, centred on the closest undamaged lodgepole pine tree to sampling grid points. In each sample plot, all aspen trees were measured for height, quadratic direction from crop pine (NE, SE, SW, NW), stem-to-stem distance, closest crown-edge-to-pine stem distance, and farthest crown edge-to-pine distance. The tallest and closest aspen to the crop pine were measured for root collar diameter and height increments. The crop pine trees were measured for root collar diameter, radial increments (using stem discs cut at ground level), height increments, and crown radius.

Four single competition variables and six competition indices were evaluated to try to relate lodgepole pine growth to aspen competition measures. Pine growth response variables used in the analysis were height, basal area, height increment, and basal area increment, and single competition variables were aspen density, percent aspen cover, total tree density and percent total tree cover. The Basal Diameter Ratio (BDR) competition index had the most significant correlation with the four pine growth response variables ( $R^2 = 0.57-0.83$ ). Lodgepole pine height growth was fairly insensitive to aspen competition, with relatively high competition levels required before height growth was reduced. Pine radial growth was sensitive to competition. Maximum radial growth occurred at the competition levels where BDR values were less than 0.75. As BDR values increased from 0.5 to 1.0, increased competition represented mean pine basal area growth losses of about 45 and 33% for pine age groups of 5-10 and 11-16 years, respectively. The following local stand tending guideline was developed based on the study results: Any aspen within 1.8 m of the crop pine stem (based on stem-to-stem distance) with a basal diameter greater than 75-100% of the crop pine's basal diameter should be removed regardless of aspen-pine distance.

Lorimer's competition index ranked a close second to the BDR index, with slightly lower  $R^2$  values (0.55-0.75), and it was followed by the competition indexes of Daniels ( $R^2 = 0.45-0.70$ ) and Braathe ( $R^2 = 0.47-0.64$ ). Simple competition variables such as aspen density or percent cover were poorly correlated with pine growth ( $R^2 = 0.24-0.31$  for aspen density and  $R^2 = 0.06-0.22$  for aspen cover). Distance from pine crop trees to the tallest and closest aspen were weakly related to pine growth and aspen position (quadrant) did not affect pine growth.

In contrast to Navratil and MacIsaac (1993), Navratil et al. (1990a) found that for site sampled in Alberta, aspen cover could be used to predict pine growth. Ten to 20% aspen cover had a positive effect on growth of 4-12-year old lodgepole pine growth. Higher levels had a negative effect on growth.

MacIsaac (1996) carried out an experiment on three blocks in the Lower Foothills subregion of Alberta that tested the application of the Basal Diameter Ratio (BDR) competition index (Navratil and MacIsaac

1993) and investigated growth response of 8-13 year old lodgepole pine to four levels of aspen removal. The treatments were no aspen removal (control), removal of all aspen within 1.8 m of the target lodgepole pine where the aspen basal area was larger than the pine, removal of all aspen within 1.8 m of the target lodgepole pine where the aspen basal area diameter was 75% of the pine diameter or greater, and removal of all aspen within 1.8 m of the target pine, regardless of aspen size. Two years after treatment, the control plots had significantly slower diameter growth than the other treatments (no significant difference between the removal treatments). There were no significant differences in pine height growth among treatments. There was no significant difference in survival among treatments although there was a trend toward higher mortality and mechanical and pest damage in plots where all the aspen was removed.

In a controlled lab experiment, Landhausser and Lieffers (2001) transplanted one year-old seedlings in pots to the understorey of a mixed aspen-balsam poplar stand and an adjacent open site. Height growth of lodgepole pine was unaffected by growth conditions. Diameter increment was not measured. Lodgepole pine growing under the broadleaves had less shoot, root and total biomass than open grown pine. Total leaf area per plant in open-grown pine was almost triple that of understorey-grown seedlings. Lodgepole pine appeared better adapted to high light conditions and did not adjust to low light conditions therefore it is unlikely to survive in typical understories except where disturbances create gaps.

### **Ontario studies**

Jack pine growth responses were assessed ten years after various release treatments at the Bending Lake and Espanola research sites in Ontario (Bell, Dacosta et al. 2011). The goal was to determine whether removal of aspen increases gross total conifer volume but decrease gross total stand volume in boreal forests. Volumes were projected to age 60. Aspen manipulation treatments at Bending Lake were: (1) complete removal with glyphosate (0 SPH aspen, 100 SPH other broadleaf); (2) aerial glyphosate (25 SPH aspen, 75 SPH other broadleaf); (3) brush saws (350 SPH aspen, 250 SPH other broadleaf); and untreated control (1825 SPH aspen, 1175 SPH other broadleaf). Treatments at Espanola were: (1) complete removal with glyphosate (0 SPH aspen, 500 SPH other broadleaf); (2) aerial spray glyphosate (90 SPH aspen, 250 SPH other broadleaf); (3) mist blower glyphosate (1375 SPH aspen, 792 SPH other broadleaf); (4) basal bark triclopyr (1458 SPH aspen, 2417 SPH other broadleaf); (5) brush saw (1833 SPH aspen; 333 SPH other broadleaf), and (6) untreated control (5958 SPH aspen, 1500 SPH other broadleaf). The numbers in parentheses are the densities of aspen and other broadleaf trees >130 cm tall in year ten. Density of jack pine >130 cm tall varied from 3275-5600 SPH at Bending Lake and 1417-2333 SPH at Espanola. Density of other conifer species was 25-150 SPH at Bending Lake and 0-333 SPH at Espanola. Net gross total volume of varying mixtures of jack pine and aspen were compared ten years after the aspen densities were manipulated (stand age 20 years). Gross total volume (all species combined) at age 20 tended to be higher in all treated areas than the control at both sites, but the difference was significant only for the aerial spray glyphosate treatment at Espanola (76% greater gross total volume than control). Gross total volume of trembling aspen was 69-100% less in the treated areas compared to the control. At age 20, jack pine gross total volume was 2.5 to 4 times higher in the treated

areas than the control, except for the basal bark triclopyr treatment at Espanola where the volume did not differ significantly from the control. The increases in pine volume were greatest where all the aspen was removed. At Bending Lake, jack pine represented 99% of the total gross volume for the continuous removal glyphosate, aerial spray glyphosate and brush saw treatments and 54% of the total gross volume for the untreated control plots. At Espanola, jack pine represented 99%, 96%, 95%, 94%, 66% and 43% of the total gross volume for the continuous removal glyphosate, brush saw, aerial spray glyphosate, mist blower glyphosate, basal bark triclopyr and untreated control plots respectively. Projections for the two sites to age 60 indicated that the conifer release treatments would increase jack pine net merchantable volume by 30-76% depending on treatment. Projections were based on yield curves (Penner 2008). The greatest increase was projected for the glyphosate and brush saw treatments at Espanola. At the same time, aspen net merchantable volume was projected to be reduced by 75-100% by the aspen treatments. The overall result was that at age 60, total (all conifer and all broadleaf trees) net merchantable volume in the treated stands was predicted to be within 5% of the net merchantable volume in the untreated control.

In northeastern Ontario, MacDonald and Thompson (2003) looked at fifth-year effects of three harvesting intensities (uncut, clearcut, and 50% partial cut with (PC100) and without (PC50) removal of residuals 3 years later), 2 site preparation treatments (none and scalping) and three types of chemical brushing (none, single, or multiple treatments) on survival and growth of planted jack pine (and white spruce, described in Section 2.4.3.5). The intact stand that was underplanted was a 70 year-old aspen and paper birch stand. Survival of pine seedlings was lower than that of white spruce. Survival was significantly lower in the uncut control (28%) than the PC100 (65%) which was significantly lower than the PC50 (81%). Spruce survival was lower in the clearcut than in the PC50 plots except in the single-weeded plots, where it was higher (83%). Damage due to mammals was minor in all treatment plots (1-4%) but abiotic damage levels (breakage, wounding or uprooting) were lower in the uncut forest (3%) than the harvested areas (6-8%). Mean height of jack pine declined from the clearcut (130 cm) to the partial cutting treatments (78 cm) to the uncut control (33 cm). Height did not differ between the 2 partial cutting treatments. Mean leader diameter in the clearcut (9.0 mm) was significantly greater than in the partial cutting treatments (5.4 mm) which in turn were significantly greater than in the control (1.3 mm). Mean leader diameter was significantly greater in the PC100 treatment (6.2 mm) than the PC50 treatment (4.5 mm). Pine mean diameter was greater in brushed plots (6.2 mm) than unbrushed plots (3.5 mm). The effects of the harvesting treatments on broadleaf trees was discussed with the spruce results.

Broadleaf density and height decreased with brushing frequency. Broadleaf density and height after harvesting generally increased with increasing harvest intensity for all brushing frequencies but decreased in the clearcut. Fifth-year broadleaf density was greater in the partial cut-2 entries treatment than any other treatment for all brushing frequencies. Mean broadleaf density in this treatment was 21,449 SPH compared to 8325 SPH in the clearcut.

Farmer et al. (1988) assessed competition between jack pine and aspen seedlings in a 12-week greenhouse study and a three-year field experiment in which plants were grown where nutrients and

moisture were not limiting and where no other plant species were present. In the greenhouse test, seedlings were grown at 10,000, 2844 and 729 plants/m<sup>2</sup> in ratios of 75:25, 50:50, 25:75 and in pure stands. In the field experiment, seeds were sown in April in the greenhouse then in June planted outside in the same mixture proportions as the greenhouse study, but at densities of 494, 205, 83 and 17 plants/m<sup>2</sup>.

**Greenhouse experiment:** Survival of pine was 99% for all densities and mixture proportions. Aspen survival was 100% for all mixtures at the lowest density, but its survival in pure stands was only 72% at the two highest densities and 80-90% in mixtures at these densities. In all mixtures, height increment of aspen was several times greater than that of pine at the lower densities but less than or similar to pine at the high density. Pine height varied little with density or mixture proportion. Aspen height was affected by density much more than pine height (it was taller at lower densities) but it was not affected by mixture proportion. Responses in plant weight were similar to those for height, but accentuated, and mixture proportion had a significant effect on aspen weight. Aspen seedlings were heaviest when grown at low densities in mixtures with 75% pine (0.93 g/plant) and lightest when grown at high density in any mixture proportion (0.02-0.05 g/plant). Pine seedlings were heaviest where grown at low densities without aspen (0.23 g/plant) and lightest when grown at high density in any mixture proportion (0.04-0.05 g/plant). Considering all mixtures and densities, total production was greatest in pure aspen stands at the middle density (628 g/m<sup>2</sup>) and decreased with increasing or decreasing density and increasing proportions of pine. Production of pure pine stands increased with density and was slightly higher than that of pure aspen at the highest density (364 versus 337 g/m<sup>2</sup>). Total production of mixtures was higher where there was only 25% pine (391-510 g/m<sup>2</sup>, depending on density) compared with 50% pine (266-459 g/m<sup>2</sup>) or 75% pine (321-335 g/m<sup>2</sup>). Mixtures did not generally increase total yield more than expected from an examination of pure stands, i.e., relative yield as per de Wit (1960) was not greater than one.

**Field test:** Pine survival gradually decreased as the proportion of aspen increased, even at lower densities. Its survival was reduced to 60-70% by the end of three years when it was grown in mixtures with 75% aspen. Aspen survival was high at all densities and in all mixtures except in pure stands at the highest density where it was only 62%. At all densities, height of pine after 3 years was significantly less when it was in mixture with aspen compared to in pure stands. Pine had the heaviest weight per plant in pure stands, where it was two-three times greater than in any of the mixtures. Pine plant weight did not differ greatly among 25, 50 and 75% aspen components, but it was up to ten times heavier in the lowest density compared to the highest density. Individual aspen benefitted from a decreasing proportion of aspen in mixtures and had their highest weight per plant in mixtures containing 75% pine. Total stand productivity (three-year dry weight production) was greater in mixtures than in pure aspen stands but not pure pine stands at lower densities. At the 83 plants/m<sup>2</sup> density, total three-year production was 1792, 2671, 1875, 1950 and 2903 g/m<sup>2</sup> for pure aspen, 75 aspen/25 pine, 50 aspen/50 pine, 25 aspen/75 pine and pure pine, respectively. At higher densities, mixtures were generally more productive than pure aspen or pure pine. Total 3-year production for the highest density was 6585, 8862, 7911, 5764 and 4233 g/m<sup>2</sup> for pure aspen, 75 aspen/25 pine, 50 aspen/50 pine, 25 aspen/75 pine

and pure pine, respectively. Relative yield was greater than one for all mixtures at the lowest density and for mixtures with at least 50% aspen at the higher densities.

#### **2.4.4.3 Light and lodgepole pine performance – an overview**

In a comprehensive review, Astrup (2005a) summarized the available literature regarding the relationship between light availability and growth of understory and suppressed pine trees. He identified 23 Canadian and American studies where growth of lodgepole pine or jack pine was related to light levels. Few studies were conducted in British Columbia. Information was summarized on the relationship between light availability and height or diameter increment, biomass and crown allometry. Key findings are:

- Under field conditions in conifer-dominated stands the relationships between light availability and height or diameter increment are approximately linear (slightly asymptotic or slightly exponential).
- Pine height and diameter increment increase with light availability throughout the full light gradient.
- There is insufficient literature to judge if light-pine growth relationships differ between aspen-dominated canopies and conifer-dominated canopies.
- Pine height and diameter increments at a given light level generally increase with tree size (for 0.1 to 7 m tall trees).
- Below 15% light availability height or lateral branch growth does not increase.
- In general, height: diameter ratio is larger for understory trees than open grown trees.
- Most available information indicates that biomass production of pine increases with light level throughout the full light spectrum.
- Limited studies indicate that crown morphology of lodgepole and jack pine is less responsive to changes in light availability than that of more shade tolerant species. Lodgepole pine live crown ratio and number of branches per whorl decreases with light availability, and specific leaf area decreases with increasing light availability.

#### **2.4.4.4 Some successful competition indexes for lodgepole pine**

Some of the most effective competition indices for predicting lodgepole pine growth are listed below. Many more have been tried. Results from them cannot be applied widely because the effects of aspen on lodgepole pine growth rates and light varies with climatic and site conditions and stand age (see for example, Comeau et al. 2006; Newsome et al. 2008; Harper et al. 2009).

- Since light is known to be very important for lodgepole pine growth, competition indices that link well with light levels should be effective at predicting pine growth. Light levels under aspen are best predicted with basal area, or measures that include both basal area and density (Comeau 2001)

- Density of aspen taller than a central lodgepole pine tree is an effective index for describing competitive effects (Newsome 1995; Newsome et al. 2008; Heineman et al. 2009). However, Lorimer's Index and Hegyis Index explain pine height and diameter better than tall aspen density (Newsome et al. 2008).
- For young stands, basal diameter ratio (the ratio of diameter of the tallest aspen to the diameter of the subject pine) was the best out of several competition indexes for stands in the SBS zone according to Newsome et al. (2003). Aspen density, basal area, Lorimer's index and Hegyis Index were also strongly correlated with pine size and growth rates.
- A variation of Hegyis Index which used diameter and distance of the nearest three aspen was the most effective index tested for the SBS zone by Harper et al. (2009).
- Navratil and MacIsaac (1993) also found that basal diameter ratio was the most successful competition index for young stand in Alberta, but several other indices were almost as strongly associated with lodgepole pine height and diameter growth (Lorimer's Index, Braathes Index and Hegyis Index).
- In Alberta the best index for explaining pine height variation was density, while basal area per hectare was most effective for predicting diameter increment (Comeau 2010).
- For maturing stands, basal area and Hegyis Index best described variation in lodgepole pine diameter growth. Basal diameter ratio worked poorly (Stadt et al. 2002; cited by Comeau 2010).
- Percent aspen cover and distance to the aspen were not correlated with lodgepole pine growth as well as density of aspen taller than the pine in the SBS zone (Newsome 1995).

#### **2.4.4.5 Threshold light and aspen levels for lodgepole pine performance**

The aspen thresholds listed in this section were identified at specific sites, for certain tree ages, and under other specific conditions and should not be extrapolated directly to other sites.

- Percent light required to attain 40%, 60% and 80% of maximum diameter growth of lodgepole pine was 62%, 68% and 90%, respectively (Wright et al 1998).
- Suppression of lodgepole pine occurred at light levels below 28% (Wright et al. 2000). Ecosystem-specific models that predict understorey light from aspen basal area indicated that light availability was below 28% where tall aspen density exceeded 1000 SPH (Comeau et al. 2006; Newsome 2008).
- Aspen that were shorter than 1.25 times the height of lodgepole pine did not significantly compete with 17-18 year-old lodgepole pine on zonal sites in the SBSdw1 subzone (Newsome et al. 2012).
- For optimal pine growth in 9-15 year-old stands in the SBSdw1 subzone, all aspen trees with a diameter greater than 0.75 times the pine diameter should be removed (Newsome 1995).
- Below an aspen density of 2000 SPH, pine diameter and diameter growth were not significantly reduced compared to pine growing free of competition. Therefore one or two aspen that are taller than the height of the pine can be left in a 1.8 m radius plot (10 m<sup>2</sup>) without seriously affecting pine growth. These results were obtained in 9-15 year-old stands in the SBdw1 subzone (Newsome 1995).

- In 9-15 year-old stands in the SBSdw1 subzone, pine leader growth and total height were not significantly reduced until aspen density exceeded 5000 SPH (Newsome 1995).
- In 15 year-old stands in the SBSdw1 subzone 37 km southwest of Horsefly, lodgepole pine vigour tended to be better where  $\leq 800$  aspen SPH are retained but there were no differences in mean stand-level pine height, stem diameter, quadratic mean diameter or basal area among treatments where 0 to 2800 SPH of aspen were left (Newsome et al. 2006a).
- In the SBSdw1 subzone, survival of 20-24-year old lodgepole pine declined significantly with increasing tall aspen density, with the threshold for 80% survival of pine at 7000 tall aspen SPH. The threshold for 80% fair to good vigour was 1000 SPH. Above 2000 SPH of tall aspen, 60-100% of pine had poor vigour or were dead (Newsome 2009).
- A threshold of 1000 SPH of tall aspen was associated with 90% open-grown lodgepole pine diameter growth in the SBSdw1 subzone in stands less than 23 years-old (Newsome 2009; Newsome et al. 2008).
- In 15 year-old lodgepole pine plantations in the SBSdw1 subzone, the greatest proportion of poor and moribund pine seedlings occurred where at least 1000 aspen SPH were retained. Above 1000 aspen SPH the proportion of unhealthy pine did not increase consistently as aspen density increased (Newsome et al. 2006a).
- Up to 500 SPH of aspen did not impact lodgepole pine growth in the SBSwk1 subzone according to a study at Vama Vama Creek in the Prince George Forest District (Lange et al. 2004).
- Based on a study in the SBSmk1 subzone 60 km northwest of Prince George optimal growth of lodgepole pine may not be achieved above a threshold density of 2500 SPH of aspen (DeLong 2007).
- In the SBPSxc subzone, 16 year-old lodgepole pine performed well when growing with up to 2500 SPH of tall aspen (Newsome et al. 2010).
- In Alberta, thresholds for diameter growth of lodgepole pine were broadleaf basal areas of 5 m<sup>2</sup>/ha for Lower Foothills and 9 m<sup>2</sup>/ha or 1700 SPH of aspen for Upper Foothills. When these levels were exceeded, diameter growth of pine was reduced by about 30%. Thresholds for pine height increment were about 15 and 20 m<sup>2</sup>/ha of aspen basal area for the Lower and Upper Foothills, respectively. These levels would reduce height increment to 80-85% of that of trees with no competition (Comeau 2010).
- In west-central Alberta, any aspen within 1.8 m of the crop pine stem (based on stem-to-stem distance) with a basal diameter greater than 75-100% of the crop pine's basal diameter should be removed regardless of aspen-pine distance (Navratil and MacIsaac 1993).
- In Alberta, 10 to 20% aspen cover had a positive effect on growth of 4-12-year old lodgepole pine growth. Higher levels of aspen cover adversely affected pine growth (Navratil et al. 1990a).

## 2.5 Carbon storage

Gower et al. (1997) evaluated carbon content, leaf area index and above ground net primary productivity for mature aspen (53-67 yrs old), black spruce (115-155 years-old), young jack pine (25-27 years-old) and older jack pine (60-65 years-old) stands in boreal forests in central Saskatchewan and

Manitoba. Leaf area index (defined as 1/2 of the total leaf surface area) was lowest for jack pine forests (1.8), highest for black spruce (5.6) and intermediate for aspen. The total ecosystem carbon content (vegetation + detritus + soil) was greatest in the black spruce stands with about 88% of the carbon in the soil, lowest in the jack pine stands with a similar distribution of carbon in the soil and vegetation, and intermediate in the aspen stands. Mean residence time of carbon ranged from 16-19 yrs for aspen to 28-39 yrs for jack pine. Above ground net primary production in mature stands differed significantly between forest types and was maximum for aspen and minimum for jack pine.

Cavard et al. (2010) calculated aboveground carbon content of boreal forests in western Quebec and northwestern Ontario. In Quebec, three stand types, all about 90 years-old, were examined: “pure” (>75%) black spruce, “pure” (>75%) trembling aspen and mixedwoods containing both species. In Ontario the stand types were “pure” jack pine, “pure” aspen, pine-aspen mixedwoods, and each of the types with a black spruce subcanopy. Tree age was 59-74 years for pine and aspen and 51-58 yrs for black spruce. The nearly pure trembling aspen stands contained the greatest amount of aboveground carbon, black spruce stands had the least and mixtures of conifers with aspen were intermediate. No carbon gain was found for species mixtures, but the researchers note that results could be different for different species proportions.

## **2.6 Resources required for tree growth**

### **2.6.1 Light**

Much research has been done that indicates that competition between conifers and broadleaf trees in mixedwood stands (at least stratified stands) primarily results from light limitations resulting from overstorey broadleaf trees (see Green 2004 for list of references). Although canopies of broadleaf trees such as trembling aspen can greatly reduce light transmitted to understorey trees, a partial decrease in light will not necessarily have a large impact on seedling growth (Wright et al. 1998). The light levels at which white spruce and lodgepole pine seedling growth becomes detrimental are provided in Section 2.4.3.10 and 2.4.4.5. Light limitations imposed by broadleaf trees not only impact trees but can affect other components of the ecosystem such as understorey vegetation (see section 2.9.5).

### **2.6.2 Soil moisture**

Broadleaf canopies can influence soil moisture. In the BWBSmw1 subzone, Coopersmith et al. (2000) looked at soil moisture in plots where 0, 5000, and 10,000 SPH of aspen were retained. In May, the 0 SPH plot had the highest soil moisture and the 10000 SPH treatment had the lowest, although differences were small. In July there were much larger differences between plots: soil moisture levels were much lower in 5000 and 10000 plots (18% and 14% respectively) than where aspen was removed (24%). Soils stayed drier in the retention plots than the open throughout the growing season. Similarly, in another BWBS study, soil moisture decreased steadily with increasing density of overstorey aspen (Hawkins 2005). Aspen densities were 0, 600, 1200, 1500 and 5000 SPH.

At a boreal Alberta site, glyphosate treatments were applied in various ways: complete control of all vegetation; complete control of woody plants only; spot control (2 m radius) of all vegetation; spot control of woody plants only; and untreated control (Man et al. 2008). In this study, soil moisture was not affected by aspen manipulation but precipitation levels in the area are relatively high.

### **2.6.3 Soil temperature**

Cold soil temperatures in spring may significantly reduce seedling photosynthesis and growth (Filipescu and Comeau 2011). Cold soil temperatures are known to reduce root growth (Camm and Harper 1991). However, Landhausser et al. (2003) observed minimal changes in white spruce growth when soil temperature was increased and other spruce species including Engelmann spruce, black spruce and Sitka spruce have demonstrated low sensitivity to soil temperature as well (Tryon and Chapin 1983, cited by Green 2004). In the BWBSmw1 subzone in northern British Columbia, plots with 0 and 5000 SPH of aspen had soil temperatures slightly warmer than where aspen was retained at 10000 SPH (Coopersmith et al. 2000).

In Quebec, Prevost and Pothier (2003) measured soil temperature under 5 partial cutting intensities in a mixed aspen-conifer stand. The treatments were removal of 35, 50 and 65% of basal area, a clearcut with careful logging around advance regeneration, and an uncut control. In the first year after treatment, summer soil temperature on the 35% cut was similar to on the control, while temperatures in other treatments increased by 2.4–3.2 °C in the 100% cut and 1.5–2.5 °C in the 50% and 65% cut.. After 5 years, mean summer soil temperatures were still 1.0–1.4°C higher in the 50%, 60% and 100% treatments than the control. The same magnitude of increases occurred for the summer maximum temperature, with no differences between the higher cutting densities. Mean winter temperature was not affected by the treatments.

In another study, growing season soil temperatures were about 3° lower under white spruce-dominated stands than aspen-dominated stands (Fenniak 2001, cited by Gradowski et al. 2008)

### **2.6.4 Soil nutrients and soil properties**

Nine studies from boreal forests were found that compared soil nutrients and/or soil properties under pure white spruce, pure trembling aspen and mixed spruce-aspen stands (Table 9). One study is from British Columbia.

Trembling aspen plays a role in enhancing nutrient cycling and site productivity in forest stands (Peterson and Peterson 1995). In their literature summary, they summarize the most important nutrient-related benefits of aspen, although the information is not necessarily from boreal or sub-boreal forests in British Columbia. The benefits include:

- Aspen leaves have a higher nutrient content than conifer needles on the same site; aspen functions as a nutrient pump

- Aspen rapidly takes up large quantities of nutrients which are stored in woody tissues especially bole bark and bole wood
- Aspen has rapid growth and high nutrient uptake in the early stages of stand development
- Aspen retains nutrients effectively within ecosystems; leaching losses are minimal and decrease quickly after fire or clearcutting
- Carbohydrates are stored below-ground in long-lived clonal root systems and the roots have high nutrient uptake rates
- Forest floor decomposition and nutrient turnover are faster under aspen than under spruce
- More biomass and litterfall of understorey vegetation occurs under aspen than under conifers
- A relatively high proportion of the above-ground nutrient content in broadleaf trees, especially N, is in the leaves so if whole aspen trees are removed from a stand in winter the foliage component of the nutrient pool stays on the site

### **Review papers**

Synthesis papers question the benefits of broadleaf trees to soils in conifer stands. Rothe and Binkley (2001) provide a synthesis of studies relating to nutritional interactions in mixed species forests. They note that for more than a century, scientists have considered whether mixtures of tree species differ in nutrition and yield relative to monocultures. They were unable to clear up this question very well because of the small number of directly applicable studies, the wide variety of observed interactions, and difficulties making interpretations because of differing methodologies and experimental conditions among studies.

Rothe and Binkley (2001) summarized 19 studies that looked at the impacts of species mixtures on rates of decomposition and nutrient release. The only study that looked at white spruce-aspen or lodgepole pine-aspen species combinations was written by Prescott et al. (2000) (discussed below and summarized in Table 9) who found no mixture effect. Rothe and Binkley's synthesis showed that mixtures in general (not necessarily broadleaf-conifer) usually did not have different rates of litter decomposition in the forest floor than monocultures, but a few cases demonstrated either less or more decomposition in the mixtures. Pools of soil nutrients generally did not differ between mixtures and monocultures. Four studies that examined the effect of conifer-broadleaf mixtures on foliar nutrient concentrations all showed no effect.

In their review of literature, Barbier et al. (2008) also questioned generalizations that have been made about the impacts of broadleaf trees on soils. They stated that it is commonly accepted that conifers produce more acidic topsoil than hardwoods but note that this generalization is sometimes wrong. For example, in Ontario, France et al. (1989) measured lower top soil pH under paper birch and sugar maple than under Eastern white pine and white spruce all planted at the same site.

### **British Columbia studies**

Prescott (2002) and Jerabkova et al. (2006) state that the long-held belief that nutrient cycling and availability is higher under broadleaved trees than conifers is not consistently supported by experimental evidence. Jerabkova and Prescott (2007) assessed northern Alberta boreal aspen and spruce-dominated forests four years after clearcutting and found that nitrate availability and production wasn't any higher in aspen-dominated forests than spruce forests, and clearcutting did not increase nitrate production or consumption.

Prescott et al. (2000) studied litter decomposition in 100 year-old aspen, spruce and mixed aspen-spruce stands in the BWBSmw1 subzone near Dawson Creek in northeastern British Columbia. The mixed stand was comprised of 56% spruce, 33% aspen and 11% lodgepole pine. Litter from the aspen and mixedwood forests decomposed slightly faster than that from spruce forests (or clearcuts), but the effect was short-lived, with little difference in decomposition rates by the third year. Aspen litter decomposed at about the same rate in the pure aspen and mixed forest, but spruce litter decomposed faster in a mixture with aspen than in the spruce plot.

However, some studies of trembling aspen that Prescott refers to (Flanagan and Van Cleve 1983, whose work was in in taiga ecosystems; and Stump and Binkley 1993, whose study was in the Rocky Mountains in Colorado) demonstrated higher rates of litter decomposition and N mineralization in aspen forest floors compared to those of conifers.

Jerabkova et al. (2006) found evidence that maintaining an aspen-balsam poplar component in white spruce stands may help keep a higher proportion of N in the available form. Mixtures were suggested to be especially beneficial since broadleaf stands had higher ammonium concentrations and spruce is believed to prefer ammonium as a N source. They studied N availability in soil and forest floors of 70-125-year-old boreal mixedwoods dominated by varying proportions of broadleaf species (trembling aspen and balsam poplar) and white spruce in northwestern Alberta. Broadleaf-dominated stands had >75% broadleaf trees, conifer-dominated stands had > 75% conifer species, and mixed stands had proportions in between these. Of the three stand types, broadleaf ones had the highest N availability, reflected by higher amounts of  $\text{NH}_4\text{-N}$  and inorganic N in the forest floor, and tended to have higher concentrations of microbial N (an indication of N availability), but levels of  $\text{NO}_3\text{-N}$  and net nitrification were not higher. pH was higher and soil C: N ratio lower in the broadleaf stands. Mixed stands had the highest rates of net N mineralization, which coincided with the highest volume, basal area, and tree size of the three forest types. Availability of N was related more to the amount of N added to the litter than the litter decomposition rate. The sites with low inorganic N concentrations and faster spruce litter decomposition rates were often spruce stands.

In the SBSwk subzone in British Columbia, Sanborn (2001) examined the influence of broadleaf trees on soil properties under a 23-year-old mixedwood lodgepole pine stand. He compared soils under a range of broadleaf-conifer proportions. Between one and 86% of the basal area was comprised of broadleaf trees, with about two-thirds of the broadleaf basal area from paper birch and the remainder from black cottonwood and trembling aspen. Soil chemical properties in the mineral soil were not correlated significantly with the amount of broadleaves in the stand. As well, no relationship was detected

between the degree of broadleaf occupancy and total forest floor accumulation (mass), which represents the balance between litterfall and decomposition. However, in the forest floor higher pH, higher mineralizable N concentration, higher concentrations of available N, available P and extractable  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$  and  $\text{K}^{+}$ , and lower C: N ratios were associated with an increasing proportion of broadleaf species. Sanborn notes that these have not been consistent patterns in other birch studies. Perhaps as suggested by Perry et al. (1987) it is not possible to explain nutrient dynamics of mixed species communities simply as an additive function of the component species.

### **Alberta studies**

In northern Alberta boreal forests, Hannam et al. (2006) looked into whether or not forest floor structure and microbial community biomass differed among 70-130 year-old spruce, aspen and mixed stands. The “pure” stands were comprised of greater than 70% of the one species. Untreated mixed stands had approximately equal proportions of conifers and broadleaf trees, with small patches dominated by either species. The researchers also investigated whether partial cutting mitigated post-harvest changes in the microbial community structure and biomass compared with clearcutting. Lastly, they investigated whether stand type affected post-harvest changes in the forest floor microbial communities. Treatments that were carried out in each stand type were: (1) Undisturbed control, (2) Partial cutting: In the first pass all trees were removed in 5 m wide strips spaced 10 m apart, and in the second pass 20% and 50% of the stand was retained. No site preparation was done. Aspen forest floors supported a larger microbial biomass with very different community structure than spruce or mixed stands. Mixed and “pure” spruce stands may have been similar to each other because they had similar understorey vegetation, which along with the presence of spruce had a large influence on the microbial biomass and community structure. For the clearcut and retention treatments, pH was similar in mixed and spruce stands and higher in pure aspen stands. In the untreated control, pH was lowest in the spruce stands, then the mixed stands, then aspen. pH of the forest floor increased with harvesting in all forest types but forest floors were resilient to timber harvesting, maybe because soil disturbance was low. Partial harvesting had no benefit to the forest floor microbial community compared to clearcutting.

In northern Alberta, Hannam et al. (2004) compared forest floor composition among the same stands that were studied by Hannam et al. in 2006. There was much more moss under spruce than aspen. Aromatic C content was higher and carbonyl C was lower in the forest floor of spruce compared to aspen. Within stand types there were significant relationships between composition of the forest floor and soil temperature, mass of the Oi horizon and mass of the moss layer.

Lindo and Visser (2003) examined soils under the pure stands described by Hannam et al. in 2006. They did not study the mixed stands. Forest floor physical, chemical and biological properties differed between the spruce and aspen stands. The following results are for untreated stands. Forest floor bulk density, pH, and moisture content were lower and the forest floor was deeper under the spruce stands than under aspen. Total N, total P, available nitrate, basal respiration, and microbial and root biomasses were significantly higher in broadleaf forest stands than conifer stands. Conifer floors had significantly higher amounts of available P and significantly greater mesofauna and mite abundance compared with

broadleaf forest floors. Initial  $\text{NH}_4\text{-N}$  concentrations in forest floors and amounts of  $\text{NH}_4\text{-N}$  mineralized after 6 weeks of incubation were not significantly different between the spruce and aspen forest floors.  $\text{NO}_3\text{-N}$  availability and the amount of  $\text{NO}_3\text{-N}$  mineralized were greater in aspen than spruce stands.

### Quebec studies

Bauhus et al. (1988) studied 50- and 124 year-old stands of trembling aspen, paper birch, white spruce and balsam fir in a southern boreal forest in Quebec. Microbial C and N concentrations were on average lower in forest floors under conifers than birch or aspen. Average C: N ratios were only slightly different under conifers and broadleaf tree species.

In northwestern Quebec, Ste-Marie and Pare (1999) investigated the relationship between forest stand type and net nitrification in forest floors of fire-origin stands with no history of treatment. Five types were studied: 50 year-old trembling aspen, paper birch, and white spruce stands, 71 year-old jack pine stands, and 234 year-old white cedar stands. Mixed types were not looked at. Net accumulation of nitrate and ammonium was measured in six week laboratory incubations from samples that all came from well-drained lacustrine clay soils. Soil pH and net nitrification were highest under aspen and nitrate accumulation was rapid in forest floors under all broadleaf stands. Under spruce and white cedar net nitrification was low, and under jack pine it was non-existent, indicating stand type was influencing N transformation processes in the forest floors. However, because variability within forest types was high, net nitrification cannot be predicted only on the basis of stand type. Forest floors with no or low nitrification potential (e.g. jack pine) generally had high pH, low available P and high C:N ratios. Adding as little as 5% of aspen forest floor to the jack pine forest floor significantly increased nitrification and decreased ammonium accumulation compared with pure jack pine.

In an aspen-paper birch-white spruce stand in the southern boreal forest of Quebec, soil nutrient availability was assessed around stems of each of the three tree species in stands that had established 49, 77 and 123 years after a fire (Pare and Bergeron 1996). For all stand ages, forest floor pH was 0.5 units higher under aspen trees than the other species, and the accumulations of organic matter and nutrients in the forest floor were generally greatest under spruce. Net N mineralization and nitrification in the forest floor of the youngest stand, but not the older stands, were higher under the broadleaved species than under spruce.

Trembling aspen and jack pine were found to have contrasting effects on soil nutritional properties in another Quebec study (Ste-Marie et al. 2007). On both coarse-textured (>70% sand) and more fertile fine-textured soils (>70% silt and clay), the forest floor under aspen had a greater accumulation of almost all total and available nutrients than was found under pine. This was due to a significantly thicker FH layer under aspen than jack pine (on the sandy soil), and higher nutrient concentrations under aspen. The FH layer under aspen had significantly higher pH and lower C: N ratio than under pine on both soil types. Soil properties did not differ in the upper (0-20 cm) mineral soil, including soil pH, C: N ratio, and total and available N, P, K, Ca and Mg concentrations.

Legare et al. (2005a) looked at the influence of aspen on forest floor properties in 70-80 year-old fire-origin black-spruce dominated stands in northwest Quebec. Soils were examined under three stand types: plots dominated by black spruce with <15% of the basal area in aspen; plots with 15-20% of the basal area in aspen, and plots with 50-75% of the basal area in aspen. The presence of aspen accelerated nutrient cycling because of differences in total N, C: N ratio, organic matter depth, exchangeable cations, pH and CEC of the forest floor with varying proportions of aspen. There was a decrease in organic matter thickness with increasing aspen abundance.

In boreal Quebec, Cote et al. (2000) studied the influence of forest composition on the quality of soil N and carbon as determined by C and N mineralization in a long term (282 days) in vitro incubation. Soil was examined under three stand types: aspen, paper birch, and coniferous (white spruce and balsam fir mixtures). Stand ages were 50 and 124 years. The mineralization rate of C in the FH horizon differed significantly between stand types and was higher in birch than aspen or the conifer stand. Expressed on an organic C basis, the amount of N mineralization in both the forest floor and mineral soil over the course of the experiment was significantly higher under aspen and birch stands than in conifer stands. The ratio of C mineralized: N mineralized was greater in coniferous than broadleaf soils indicating lower quality of organic matter under coniferous soils. The pool sizes of mineralized (or mineralizable) N and C were generally not significantly different between the different forest types because of an inverse relationship between quality and quantity of soil organic matter.

Brais et al. (1995) obtained results that they say stress the need to evaluate the long-term impacts of successive rotations of conifer species where broadleaf competition is eliminated. Their work was in forests covering an age range of 27 to 231 years in boreal forests in Quebec. Changes in  $\text{NO}_3$  concentrations were related to stand age and the amount of aspen and birch in the stands. Both species had a negative effect on  $\text{NO}_3$  concentrations.

### **Minnesota studies**

Alban et al. (1978) compared biomass and nutrient distributions in 40 year-old pure trembling aspen, white spruce, jack pine, and red pine stands growing on very fine sandy loam soils in north-central Minnesota. Mixed stands were not looked at. The amount of organic matter in the soil was lowest under aspen. Aspen trees contained more of each nutrient (N, P, K, Ca, Mg) than the other tree species. Nutrient concentration in the bark were highest for aspen and nutrient concentrations in the branches and foliage were highest for spruce. Aspen and spruce trees had more Ca in their biomass and less in their surface soil than the pines. The lower Ca levels under aspen and spruce resulted in lower pH values than in the pine stands.

At the site where Alban et al. (1978) did their work, Alban (1982) conducted nutrient analysis to determine the effects of tree species on soil properties. On both soils (very fine sandy loam and loamy sand) aspen and spruce stands accumulated more nutrients than pine stands and the species differences were reflected in their litterfall although the weight and bulk density of the forest floors did not differ among species. Mineral soil differences were most pronounced in the top 10 cm with few differences

below this. Accumulations of N and P in the forest floor were about the same under aspen and spruce and were lower under the pines. Ca content in the forest floor was about twice as high under aspen and spruce versus the pines. In the mineral soil, the highest amount of Ca was under the pines. Although major species-related Ca differences were found in both the forest floor and mineral soil, the total amount of Ca in the ecosystems did not differ among species (because of Ca in the vegetation). Mineral soil pH was highest under the pines; forest floor pH was lowest under the pines. The pH differences were directly related to soil Ca content (a lower Ca level gives a lower pH). The amounts of Mg and K in the forest floor were similar among the different stand types. N, organic matter and Mg levels in the mineral soil were lowest under aspen while the amount of P and K showed little difference among species. The amount of P and K in the ecosystem decreased in the order aspen>spruce>pines and this largely reflects the different vegetation under these stands since differences in the soil were minimal.

## **2.7 Hydrology**

In boreal mixedwood forests white spruce seedlings are frequently affected by a rise in the water table and flooding after logging, especially on wet sites (three references cited by Man and Lieffers 1999b). The presence of young aspen, with their high leaf area, can help alleviate this problem through transpiration and interception of precipitation. The aspen can therefore potentially improve white spruce establishment success on wet sites.

Broadleaf canopies are well known to result in different degrees of snow and water interception and water use than conifer canopies (R. Winkler, pers. comm., Dec. 6, 2012). Pomeroy and Goodison (1997, cited by Pike et al. 2010) reported that snow accumulation in the boreal forest was greater in stands of aspen than of jack pine because of the lack of foliage during winter in aspen stands. Pomeroy et al. (1998) stated that up to 70% of the spatial variation in snow water equivalent under forest cover is related to winter leaf area. In a review of the interception loss literature, Carlyle-Moses (2004), cited by Pike et al. 2010) reported that, on average, canopy interception loss from coniferous forests was double that of deciduous stands, averaging 26% versus 13% of incident rainfall, respectively, during the growing season. A study in the IDF zone near Kamloops, British Columbia was carried out to compare snowpacks in a clearcut with neighbouring mature aspen and mature lodgepole pine stands. Snow accumulation was greatest under the aspen due to aspen acting as a windbreak and having no winter canopy, and it melted more slowly (Misener 2009). Thus it would be wetter under the aspen canopy in early summer. Possible impacts of this are unsuitability of the site for early summer harvest and on dry sites the extra soil moisture could promote crop tree growth and vigour.

## **2.8 Root stratification**

Distribution of white spruce roots in spruce stands and aspen-spruce mixtures were compared in a transitional boreal-Great Lakes-St. Lawrence forest in northwestern Ontario (Lawrence et al. 2012). The stands were 20-year-old white spruce plantations and matching even-aged mixtures of aspen and spruce, with varying proportions of aspen (up to 4049 SPH aspen and 1840-2901 SPH spruce). Mixed white spruce-aspen forests may have the ecological advantage over pure white spruce stands in that

belowground competition is reduced because of vertical stratification of the roots, allowing for greater exploitation of soil resources. If white spruce roots are located closer to the surface than aspen roots competition could be reduced through avoidance strategies. A subtle trend of wider lateral reach of white spruce's roots was also observed in the mixed spruce-aspen plots compared to pure white spruce plots. This may be related to less competition in the upper soil because of the vertical root stratification. As well, aspen litter decomposes faster than that of spruce and was measured to be less acidic which may improve the growing environment for spruce, especially in the upper soil layers, which would promote lateral root growth.

Brassard et al. (2011) investigated fine root productivity of mature (85-92 year-old) aspen-spruce-balsam fir stands compared to relatively pure aspen stands in boreal forests at six sites in each of two study regions (Ontario and Quebec). The aspen stands contained 0-9% basal area of spruce and balsam fir. They found that fine root production, measured by annual production and total biomass, was significantly higher in mixed than the single species stands at both study regions. The biomass of aspen fine roots did not differ between stand types but the biomass of spruce and balsam fir fine roots was significantly higher in mixed stands. They found that the soil space was more fully occupied by fine roots in the mixed versus single-species stands.

Several other studies suggest that broadleaf and conifer species may have spatial separations in their rooting zones in mixedwood stands, allowing them to exploit different edaphic niches (e.g., Kabzems and Lousier 1992; Man and Lieffers 1999a)

## **2.9 Biodiversity**

### **2.9.1 Overview**

Peterson and Peterson (1995) state that "one of the strongest incentives to manage aspen in mixedwood rather than pure stands is to enhance the habitat diversity that would be achieved by managing only pure aspen or pure spruce." They provide the following reasons why aspen is important in maintaining biodiversity in western Canada:

- Some cavity nesters prefer aspen. Broadleaf trees die before conifers, are more susceptible to stem decay than conifers, and decay faster so they create snags and forage for species that feed on decayed wood at relatively early stages of stand development.
- Cavity-nesting birds prefer mature live aspen for feeding and nesting.
- Dead or downed wood helps maintain the nutrient capital of sites and provides shelter and habitat for small mammals and invertebrates.
- As the aspen grows taller, the diversity of bird species increases.
- The first 20 years of aspen stand development provides abundant browse for deer, moose, beaver and snowshoe hares.

Aspen is important for conserving biodiversity across a variety of stand ages (Misener 2009). Roy et al. (1995) describe the relationships between stand age, stand structure and biodiversity in aspen mixedwood forests in Alberta. The paper compares three categories of aspen mixedwood forests: young (20-30 years), mature (50-65 years) and old (120+ years). Overall, a rich biota was identified in the aspen mixedwood forests, including 47 lichen species, 39 moss species, 7 liverwort species, 24 fungi species, 11 pteridiophyte species (horsetails, club mosses and ferns), 55 herb species, 27 shrub species, 6 tree species, 3 amphibian species, 76 bird species and 33 mammal species.

Roy et al. (1995) indicate that clearcut logging with 60-70 year rotations in boreal mixedwood stands simplifies the structure of young stands and reduces the frequency of older stands, and will not maintain levels of flora and fauna abundance found in unmanaged mixedwood forests. They say that "unmixing" the mixedwood forests may jeopardize wildlife species and ecological processes that rely on a mixed-species canopy.

Cavard et al. (2011) reviewed the potential benefits of northern mixedwoods on biodiversity, including understorey plants, birds, soil fauna and ectomycorrhizae. The review looked at both stand-level and landscape-level biodiversity. They define stand level mixedwoods as those in which no single species makes up more than 80% of the stand basal area. At the landscape scale, a mixedwood contains stands dominated by different tree species and mixed or mosaic landscapes may or may not include mixed stands. Highlights of the review are found in the soil biota, ectomycorrhizae, understorey plants and bird sections below.

### **2.9.2 Soil biota**

Soil biota are important for biodiversity in forest ecosystems because they facilitate the processes of energy flow, nutrient cycling, water infiltration and storage in the soil (Whitford 1996). Soil biota includes the microflora (bacteria, algae, fungi) and the soil fauna.

In their review of the importance of mixedwoods for biodiversity in northern forests, Cavard et al. (2011) include a table summarizing ten studies that compared soil fauna composition and diversity between mixed and pure stands or litters. The studies were done in North Carolina, France, Germany, Sweden, Japan and New Zealand. None of them were conducted in stands that included white spruce, lodgepole pine, or trembling aspen or other species found in boreal or sub-boreal British Columbia such as black spruce, balsam poplar, or paper birch so the findings are not discussed in depth here. The authors conclude that a few studies indicate mixed stands or mixed litters support greater biodiversity of soil organisms but results have been highly variable. Overall, empirical evidence for the existence of soil fauna species that are associated with mixed stands is limited and weak, and ultimately forest canopy diversity itself does not affect soil fauna diversity.

### **2.9.3 Ectomycorrhizae fungi**

Increasing diversity of ectomycorrhizal fungi is associated with increased plant productivity and plant diversity (Kernaghan 2005). Cavard et al. (2011) reviewed the importance of mixedwoods for biodiversity in northern forests and summarized information on ectomycorrhizal fungi composition and diversity in mixedwoods versus pure stands. Included is a table summarizing the eight relevant studies that they found. Two are greenhouse experiments, two are from southern interior British Columbia and one each are from northwestern Quebec, Wyoming, southwestern Oregon, and Germany.

The Quebec study referred to by Cavard et al (2011) was conducted far from British Columbia's boreal forests, but is the only ectomycorrhizae study that was found in which the stands included boreal British Columbia broadleaf and conifer species. The tree species in the forest were balsam fir, white spruce, jack pine, paper birch, trembling aspen, and balsam poplar (Kernaghan et al. 2003). Mixed stand ectomycorrhizal communities were the accumulation of fungi types associated with each trees species. Based on all of the studies they reviewed, Cavard et al. (2011) concluded that there is evidence that diversity of ectomycorrhizal fungi increases with host species diversity. Several studies from around the world showed that ectomycorrhizae with multiple hosts are more abundant under mixedwoods than pure stands.

#### **2.9.4 Coarse woody debris**

Coarse woody debris (CWD) is important for biodiversity because it:

- Contributes to stand level structural diversity of old growth and mature forests.
- Provides feeding, breeding, and shelter substrate for many organisms (invertebrates, small mammals, amphibians).
- Provides habitat for many forest plants, animals, (both vertebrates and invertebrates), and microorganisms.
- Provides a nutrient source and growing substrates for various bacteria and fungi (including beneficial mycorrhizal fungi), as well as saprophytic plants, lichens, and mosses that are important in decay, N production, and other nutrient and moisture cycling.
- Influences stream habitat quantity by dispersing stream energy, releasing nutrients, and creating gradual steps, gravel bars and pools for resident and spawning fish.
- Shapes and stabilizes stream banks. It increases channel complexity and habitat quality by creating pools and riffles.
- In streams, CWD increases litterfall retention by up to 70%, which is then decomposed by stream organisms.

(Source: British Columbia Ministry of Forests:

<http://www.for.gov.bc.ca/hfp/training/00001/module03/cwd.htm#cwd>)

A few studies from boreal forests were found that compared CWD levels and characteristics among mixed, conifer and broadleaf stands, but they are not from British Columbia. These results are not necessarily transferrable to boreal and sub-boreal forests in British Columbia.

Brassard and Chen (2008) sampled 72 boreal fire-origin forest stands in Ontario that ranged in age from seven to 201 years and represented jack pine, aspen, and mixedwood (jack pine-aspen) overstorey types. Species diversity of CWD was generally highest in mixedwoods but decay diversity was not significantly affected by overstorey type. The CWD volume in conifer stands was greater than or equal to that in mixedwood or broadleaf stands except in seven year-old stands where mixedwoods had the most. Higher CWD levels in conifer stands was attributed to higher prevalence of spruce budworm host-specific balsam fir and white spruce in these stands, slower decay rates, greater stand breakup in the 124-139 yr old age class than the other two overstorey types, and possibly differences in pre-disturbance CWD levels.

In a study in the boreal forest of northwestern Ontario, Pedlar et al. (2002) measured and compared the volume of CWD in three mature forest types: conifer (average 88 years-old), mixedwood (75 years-old) and broadleaf (67 years-old) with two disturbance types (burning and clearcutting of mixedwoods). The main tree species in the study area were black spruce, jack pine, trembling aspen, balsam fir, white birch, tamarack and eastern white cedar. The CWD level was higher in mixed (161 m<sup>3</sup>/ha) and broadleaf (105 m<sup>3</sup>/ha) stands than coniferous ones (18 m<sup>3</sup>/ha). Most of the CWD was downed woody debris not snags. Mixed and pure forest types had similar proportions of CWD in the different decay states with most wood in early and mid-stages of decay. The different forest types also had similar proportions of CWD in the different size classes but the conifer plots had no large pieces because the trees were small.

Alban and Pastor (1993) looked at sites in Minnesota occupied by aspen, white spruce, red pine and jack pine. Boles were allowed to decompose on the forest floor for 11-17 years. The decomposition rate was fastest for aspen, then spruce, then red pine, then jack pine. N release was not occurring for any species in that time period; the logs still had low concentrations of N and high C: N ratios.

## **2.9.5 Understorey vegetation**

### **2.9.5.1 Overstorey-understorey relationships**

Seven studies conducted in boreal forests were found where understorey vegetation was compared among conifer, trembling aspen, and mixed conifer-aspen stands (Table 10). None of the studies are from British Columbia. At all of the study sites, white spruce is included in the conifer and mixed conifer-aspen stands. No studies that include lodgepole pine were found, but jack pine is a stand component in 2 of the studies. Several reviews that are not specific to white spruce, pine, or aspen have summarized the effect of forest overstories on understorey plants and are described first.

#### **Overview**

Cavard et al. (2011) reviewed the importance of mixedwoods for understorey vegetation biodiversity in northern forests. They summarized diversity of vegetation in mixed compared with pure stands for 11 studies. Six of the studies are Canadian but none are from British Columbia. They report that some studies indicate that mixed stands have higher understorey plant diversity than “pure” stands of the

component species. There is evidence that understorey plant diversity increases with the proportion of early-successional broadleaf trees in conifer-dominated stands. Greater diversity in mixed stands may be because having more than one tree species in the canopy creates a greater diversity of microhabitats, and so in mixed stands plants that are associated with the microhabitats of each tree species are found. However, even though a diversity of niches occur in mixedwoods which should allow for the addition of additional species, there is limited evidence that there are understorey plant species that are actually unique to mixedwoods.

Hart and Chen (2006) conducted a review which included a comparison of understorey vegetation in mixed versus “pure” conifer and “pure” broadleaf stands in North American boreal forests. They determined that overstorey composition has a strong effect on composition of the understorey. Broadleaf stands tend to have vascular species in the understorey and conifer stands are associated more with bryophytes. Total species richness is about the same for broadleaf and conifer stands. Mixedwood canopies support understorey communities that are intermediate between pure conifer and pure broadleaf stands. They may be more diverse than plant communities under pure tree stands, depending on the proportion of conifers and broadleaf trees in the overstorey.

Barbier et al. (2008) reviewed the influence of tree species on understorey vegetation diversity and mechanisms involved for temperate and boreal forests. Very little, if any, mention of white spruce, lodgepole pine, trembling aspen, balsam poplar and paper birch are made in the paper. They initially selected 700 papers for review. Their conclusions are: Coniferous forests generally provide less diversified vascular species than hardwood forests, but one must be careful in reducing tree species effects to a “coniferous” or “hardwood” effect. Data was considered too limited to draw firm conclusions on the effect of any particular tree species on the understorey. Mixing of broadleaf and coniferous species generally affects understorey diversity but in almost all cases maximum diversity is observed in one of the pure stands not in the mixed stands (even though mixed stands are often *assumed* to have more heterogeneous and species rich understorey vegetation than pure stands). The degree of mixing has been found to influence vascular diversity, but effects vary among studies. In their analysis of the studies they tested whether the ratio of vascular species richness under broadleaf trees to vascular species richness under conifers was greater than one. In the published data for understorey vascular species richness, ten sources indicated higher species richness under broadleaf stands and four sources indicated it was higher under conifer stands. The resulting ratio was significantly greater than one, but values from the studies were generally less than two, indicating that species richness is often higher under broadleaf canopies, but rarely doubled.

The way that overstorey composition and structure influences the understorey vegetation includes modifications of resource availability (light, water, and soil nutrients) (Barbier et al. 2008). In an Alberta study Roy et al. (1995) found that vegetation cover in boreal mixedwoods was related to air and soil temperature and photosynthetically active radiation under the stands, which varied with age of the forest. The type of overstorey also influences the understorey through physical characteristics of the litter layer (e.g. depth), and throughfall water quantity and chemistry. Overstorey composition is not the only factor impacting the understorey: management practices, forest age, forest density, whether

there is a subcanopy, and site characteristics all play a part. Chipman and Johnson (2002) assessed understorey vascular plants in 121 upland white spruce-balsam fir-aspen boreal mixedwood stands in central Saskatchewan and concluded that hillslope position and surficial geology were the most important factors accounting for species richness, evenness and diversity. Of secondary importance was the interaction between time since fire and canopy coverage.

### Alberta studies

Macdonald and Fenniak (2007) examined richness, diversity and composition of understorey vegetation in mixedwood boreal forests in northwestern Alberta. They compared the understories of conifer-dominated (>75% conifer canopy cover), broadleaf-dominated (>75% broadleaves), and mixedwood (35-65% broadleaf trees and conifers) stands. Trembling aspen was the most abundant broadleaf tree and white spruce the dominant conifer species. Mixed and conifer stands had similar understorey characteristics and differed significantly from broadleaf stands. Broadleaf-dominated stands had greater shrub cover, herb and shrub richness and diversity at the plot scale than conifer forests, while mixed stands were intermediate. However, conifer, and to a lesser degree mixed stands, had higher species turnover than broadleaf stands at a larger scale. Understorey community composition did not significantly differ between conifer and mixed stands but both differed from broadleaf stands. There were many indicator species for broadleaf dominated forests but few for conifer or mixed stands, although few species were exclusive to any particular forest type.

Chavez and MacDonald (2012) compared understorey vegetation in 100 year-old fire origin “pure” white spruce, “pure” aspen, mixed spruce-aspen, and canopy gaps. The “pure” stands had >70% of the one species based on tree density and canopy cover and the mixed stands were 40-60% conifer. Canopy gaps were big enough to locate a 50 m<sup>2</sup> circular plot without any of it being under a tree canopy. The study took place at two sites located in the Boreal Mixedwood Ecoregion in Alberta and 23-26 patches per type were examined. Total species richness was greatest for mixed patch types (63 species), followed by gaps (60) then conifer (54) and broadleaf (55) patch types. A total of 78 species were seen altogether. The conifer and broadleaf patches each showed strong dominance by particular species (*Aralia nudicaulis* for conifer and *Rosa acicularis* for broadleaf patches). Mixed patches were dominated by *Viburnum edule*, closely followed by *A. nudicaulis*; canopy gaps were dominated by *Calamagrostis canadensis* but *R. acicularis* and *V. edule* were almost as abundant. The study shows that it is important for biodiversity to maintain the mosaic of different canopy patch types in mixedwood forests.

Kembel and Dale (2006) compared understorey vegetation in white spruce (>70% conifer canopy cover), aspen and balsam poplar (>70% canopy cover) and mixed (both conifer and broadleaf cover <70%) stands. The study was at the Ecosystem Management Emulating Natural Disturbance (EMEND) experimental site located in the Upper Boreal Cordilleran Ecoregion northwest of Peace River in Alberta. Understorey vascular plant cover was generally positively associated with broadleaf canopy cover and negatively associated with conifer canopy cover at scales of 5-15 m. Mean vascular plant cover, understorey species richness, and diversity were highest in the aspen plots. Non-vascular plants were

uncommon in aspen plots and much more common with higher cover in the mixedwoods and conifer plots.

### **Ontario and Quebec studies**

Canopy-understorey affinities were examined in 197 boreal forest stands in Ontario and Quebec by Carleton and Maycock (1981). Nine overstorey species were abundant in the stands: trembling aspen, balsam poplar, paper birch, white spruce, black spruce, jack pine, balsam fir, tamarack, and white cedar. Certain understorey species had affinities for broadleaved versus upland conifer stands versus lowland conifer stands but of the 410 understorey taxa included in the study, only 121 appeared to show any specificity to forest type. The majority of vegetation species were widespread throughout the forest types. Few species showed affinity for any of the upland conifer stand groups and few were associated with the aspen and paper birch groups. On the other hand, balsam poplar stands had a long list of associated understorey species. This suggests that the actual tree species may be more important than a broad "broadleaf" overstorey category in determining the number of understorey species specific to a stand.

Bartemucci et al. (2006) compared understorey vegetation in pure aspen stands with mixed aspen-conifer stands and old-growth white cedar. The cedar type is not discussed here because it is not found in boreal or sub-boreal stands in British Columbia. The stands were in northwestern Quebec on high productivity sites at the southern limit of boreal forest. Stand ages were 50-75 years for aspen and 75-80 years for the mixed forests. Forty-six percent of the mixed stand composition was balsam fir, white spruce, and black spruce and the remainder aspen. The mixed and pure aspen stand types had similar light transmission levels (18-19% full sunlight). Species diversity was higher in aspen forests and was weakly correlated with overstorey light transmission. Species richness did not differ between the two types. In all layers of the understorey, plant species composition was influenced by forest type and overstorey light transmission, but understorey composition and light transmission were correlated more highly in the aspen forest than the mixed forest. Total height of the understorey vegetation was very similar in the two types and was positively related to understorey light transmission. Two layer 1 (0-1 m height) species were associated with mixed forests and three layer 1 species were associated with aspen forests.

Hart and Chen (2008) tested the effects of overstorey composition (conifer, mixed wood and broadleaf) and stand-initiating disturbance type (logging and fire) on understorey vegetation dynamics in Ontario. Sixty-eight stands were visited in the boreal mixedwood region of Ontario, 100 km north of Thunder Bay. The fire origin stands ranged in age from 7-201 yrs old and the logged stands were 7-31 years-old. The basal area of conifer stands was at least 70% conifer, the basal area of broadleaf stands less than 70% conifer, and mixedwoods had approximately equal proportions of conifers and broadleaf trees. Jack pine, black spruce, aspen, and paper birch dominated the mixtures, with some white spruce and balsam fir. Total ground vegetation cover did not differ among overstorey types or stand age class, but understorey cover of individual plant groups did. For fire origin stands, total understorey cover and species richness were highest in 72-90 yr old stands for all three forest types. Species richness and

vascular plant cover were generally higher under broadleaf stands (richness 22; cover 58%) and lower in conifer stands (richness 19; 42% cover). Mixedwoods were in between the two except in 7 year-old stands where cover was higher than for the other two stand types. Broadleaf stands had significantly higher shrub-layer cover (62%) than mixedwoods (48%) and conifer stands (37%). Non-vascular species richness was significantly higher under conifer stands (12) versus broadleaf stands (10) and increased with stand age. Mixedwoods fell in between broadleaf and conifer stands except at age 72-90 where mixedwoods had greater nonvascular richness. Nonvascular cover was significantly higher for conifer stands (28%) than mixedwoods (12%) which was significantly higher than that of broadleaf stands (5%). Understorey communities were compositionally distinct for all overstorey types with some species specific to each forest type. Mixedwoods had a composition intermediate between the other two forest types. Mixedwood stands had only a few indicator species compared with conifer and broadleaf stands but all overstorey types had their own specific species. Post-logging stands had similar species richness and cover to post-fire stands but different plant communities. Post-logging stands had more indicator species for the different stand types than fire-origin stands. In the 7-year age class of logged stands, vascular species richness was highest in the mixedwood.

The influence of stand composition on understorey cover and biomass was investigated on 2 soil types (clay and till deposits) in northwestern Quebec using ninety-four 10 x 10 m plots (Legare et al. 2001; 2002). Understorey vegetation was compared among four 36-130 year-old forest types: aspen, paper birch, jack pine and balsam fir-white spruce. Mixed conifer-broadleaf stands were not part of the study. Only a few understorey species were restricted to a specific forest composition. Four species were strongly associated with aspen stands and four with jack pine stands. There were no indicator species for fir-spruce stands. Understorey species richness, diversity, and evenness did not vary with cover type but species richness and evenness were affected by surface deposits. Stand composition had a significant effect on mountain maple biomass and shrub cover, but not large-leaved aster biomass or herb cover (mountain maple and aster were the only individual species for which biomass was measured). Total understorey cover was lower under spruce-fir stands than any of the other stand types. Shrub cover was lower under coniferous stands than birch, aspen and jack pine stands. On clay deposits, mountain maple biomass was significantly greater under jack pine and aspen stands than spruce-fir stands. On till deposits, mountain maple biomass was lower under spruce-fir stands than under both broadleaf stands. It was also lower in jack pine stands than birch stands. Contrary to what they expected, the variation in plant biomass associated with forest composition was weakly related to soil nutrient availability and more strongly related to stand structural attributes (overstorey basal area and stand height).

### **Minnesota studies**

In northeastern Minnesota in the southeastern ecotone of the boreal forests of North America, Reich et al. (2012) assessed understorey vegetation in a total of 81 aspen, jack pine and black spruce stands, aged 19-133 years. The study did not include broadleaf-conifer mixtures. Light heterogeneity, which is linked to a higher diversity of microsites, enhanced stand-scale species richness. Understorey species richness was higher but cover was lower at reduced light levels (higher tree basal area). At the higher

light levels an increase in abundance of large common plants had a negative effect on species richness at the plot-scale. N availability also influenced species richness at the plot level. Low productivity aspen stands which tend to be open and relatively nutrient-rich generally had the highest species richness at both the plot (5 x 5 m) and stand scales. High productivity sites of all species had the lowest understorey light levels and these ranked intermediate in stand-scale species richness. The lowest stand-level species richness was in low productivity black spruce stands, where understorey light levels were higher but light heterogeneity was lower than in higher productivity spruce stands. Species richness in the black spruce stands was also likely reduced by the nutrient poor, waterlogged, acidic soils.

### 2.9.5.2 Impacts of removing aspen on understorey vegetation

Seven studies were found in which the vegetation understorey was assessed after an aspen overstorey was removed (Table 11). Five of the studies are from the BWBS zone in British Columbia, one from the SBS zone in British Columbia, and two from boreal forest sites in Alberta. Two studies indicate minimal effect of removing the aspen while five show either an increase in cover or shift in vegetation species.

#### British Columbia studies

An aspen overstorey can enhance white spruce regeneration and growth by suppressing *Calamagrostis canadensis* and *Epilobium angustifolium*, as demonstrated at a mesic BWBSmw1 site located 110 km northwest of Fort St. John (Maundrell and Hawkins 2004). The stand here was a 45-old mixedwood dominated by even-aged aspen in the overstorey (3900 SPH and 32 m<sup>2</sup>/ha BA aspen) and multi-aged white spruce in the understorey (1050 SPH). At this site, *C. canadensis* and *E. angustifolium* were considered the only understorey competitors with white spruce. The canopy was incrementally opened with 10 treatments, to give aspen basal areas of 10, 20, 30...100% of the original stand basal areas. Two years after the thinning treatments, light levels at 1.3 m above the ground were increased and a significant positive relationship was observed between light transmitted through the aspen canopy and the percent cover of the two plant species. *E. angustifolium* cover varied from <5% to about 30%, and *C. canadensis* grass cover from <5% to about 50% but the species were never completely eliminated. The researchers suggest a management treatment of first reducing the basal area of the stand by 20-25% to provide better growing conditions for the spruce while at the same time limiting vegetation competition, then once the spruce has reached 1 m in height make additional entries (to increase light to 40-50% of full sun) to further release the spruce.

Kabzems, Harper and Fielder (2011) looked at understorey vegetation seven years after several brushing treatments were applied to a three year-old aspen stand in the BWBS zone in northeastern British Columbia. The treatments were chemical complete control, manual complete control, chemical removal of aspen in 1.25 m spots, manual removal of aspen in 1.25 m spots, an untreated control, and spacing (done four years after the other treatments). There were no significant differences in cover of shrub or herb-fern-grass layers or frequency of occurrence of vegetation species three or seven years after treatment. Seven years after the treatments (three years after spacing), *Rubus pubescens* had greater cover in the chemical complete treatment than the untreated control and aspen spacing treatments. *C.*

*canadensis* cover increased most in the spaced plots, less where manual treatments were done, and least with chemical treatments.

### **Alberta studies**

Aspen canopy removal increased understorey vegetation production at a boreal site in west-central Alberta (Powell and Bork 2006). The aspen stand was 18-20 years-old, 5.7 m tall and had a basal area of 23 m<sup>2</sup>/ha when the experiment began. Three levels of aspen canopy removal were used: complete removal; partial removal (equal to the amount needed to double light in the understorey); and no treatment (control). In the partial canopy removal treatment, the residual stems were left evenly spaced with an average post-thinning density of 6770 SPH. The cut trees were removed from the site and resprouting aspen was removed biweekly. Two years after the treatments, partial canopy removal had resulted in a shift to more shrubs, and complete overstorey removal gave a further shift towards greater productivity from graminoids. Complete canopy removal substantially increased grass production but partial canopy removal did not. Greater understorey production with a partial canopy may be attributed to the combination of more favourable microclimate conditions in a closed forest but increased light penetration.

In another Alberta study, removing aspen and woody vegetation stimulated growth of herbaceous plants, which were dominated by *C. canadensis* (Man et al. 2008). The increase of this species may have offset the reduction in competition from aspen and woody plants. *C. canadensis* was taller than the spruce, resulting in a delay in soil warming and low light levels (<40%) reaching the seedlings.

### **2.9.6 Birds**

#### **Overview**

There is limited evidence that mixed stands have greater avian diversity at the habitat level than comparable 'pure' stands or that some species are mixed stand specialists, but some bird species have greater abundance or frequency of occurrence in mixed stands. Some bird species seem to require the presence of two distinct types of habitat within a landscape indicating that mixed forest landscape mosaics are important for conserving avian communities.

Six studies were found in which avian composition and diversity was compared between mixedwoods and pure stands. Most of the studies that were identified correspond to ones that Cavard et al. (2011) summarized.

A meta-analysis conducted by Schieck and Song (2006) for >125 year-old boreal forests in western North America indicated that bird communities differ among old aspen, old white spruce, and old mixed aspen-white spruce forests. Old aspen and old spruce forest had bird communities that were least similar to each other. Bird communities in mixedwood forests were intermediate between the two pure forest types. No bird species were unique to mixedwoods but these stands had higher species richness

than the pure ones because most bird species from both pure stand types were found in the mixedwoods. The authors suggest maintaining the diversity of forests from pure aspen to various mixtures to pure spruce may be important for bird communities.

### **Northwest Territories studies**

Songbird communities in aspen, conifer and mixedwood stands in the Liard Valley, Northwest Territories were investigated by Machtan and Latour (2003). One hundred and ninety-five point stations were placed in various forest types including old mesic forests (broadleaf, coniferous and mixed), young forests (<90 years-old), clearcuts, and wooded bogs. Statistical analysis was only performed for the old mesic forests. The broadleaf stands were dominated by 50-150 year-old aspen, usually with <10% of the canopy coniferous. Conifer stands typically had <25% broadleaf canopy with white spruce a dominant species, and they were 90-150 years-old. The mixedwoods had a nearly even mix of broadleaf trees and conifers and were 110-150 years old. The mixedwood forests had slightly more species of songbirds than the coniferous forests. Broadleaf stands had 14% fewer observed species than both coniferous and mixedwood forests. There was a high degree of overlap in the dominant bird species in mixedwood and coniferous forests: 39 species were common to the two habitats. Only two species were completely restricted to one stand type: the palm warbler was only in wooded bogs and the black-backed woodpecker in coniferous forests. As well, four other species were essentially specialists (occurring in just one stand outside of their usual type), but none were specific to mixedwood types. All other species were found in several stand types. Some species increased in abundance as the percent broadleaf canopy increased and some reached their peak abundance in mixedwoods. The mixedwoods contained 30% more individuals than coniferous or broadleaf stands. Hobson and Baynes (2000) discuss this in detail and attribute it the increased floristic and structural diversity in the mixedwoods, resulting in more nesting sites, foraging areas and other factors. Evenness in the three types was similar. The study demonstrates the importance of maintaining mixedwood forests rather than replacing them with monotypic stands after they are logged.

### **Alberta studies**

Black-throated green warblers breeding in 115-135 year-old pristine broadleaf-dominated mixedwood stands preferred the less abundant conifer trees over trembling aspen or balsam poplar (Rochibaud and Villard 1999). In this study in northern Alberta, the stands were dominated by aspen and balsam poplar, and white spruce and paper birch were present at low densities in the canopy. Few smaller spruce were present. The warblers clustered their territories where conifers were at their highest densities and tended to avoid areas where conifers were rare or absent. They preferred white spruce over trembling aspen and balsam poplar for songposts (singing Type A and B songs) and for foraging. They did not avoid paper birch in the same way as the more abundant broadleaf species. The reason for preference of white spruce was thought to be related to its larger diameter but species was concluded to be an important factor by itself. The authors conclude that the conversion of mixedwood forests into pure broadleaf stands or pure conifer plantations could have negative impacts on this and other ecologically similar species in the boreal forest.

Roy et al. (1995) found that old boreal mixedwoods in Alberta had greater bird species richness than young stands, which had greater richness than mature stands. Of 33 bird species that were encountered at least ten times, 21 species had their highest abundance in old stands, 9 in young stands, and 3 in mature stands. The variation in abundance of bird species among stand ages was probably caused by changes in the stand as succession proceeded: greater density of live trees, large live trees, large snags and large downed woody debris and an increase in the height of canopy trees was found in older successional stages. Bird abundance was likely also related to differences in heterogeneity of the canopy and understorey among different stand ages. Heterogeneity was greatest in oldest stands followed by young stands, then mature stands, and heterogeneity was correlated with many attributes of snags and downed woody debris. Abundance of 20 bird species was correlated with successional stage and abundance of 14 species was correlated with canopy heterogeneity. Ten of the 21 species that were most abundant in old stands preferred conifer-dominated mixedwoods during the breeding season. The old stands had more conifers than younger stands. This study demonstrates the importance of retaining mixedwoods stands across the landscape.

Use of a model to simulate potential conflicts between timber supply and habitat protection in the boreal forest of northern Alberta predicted that if mixed stands are eliminated, optimal habitat for some wildlife species (birds and mammals) will be eliminated from the region or greatly reduced in extent (Cumming et al. 1994). The scenarios that were tested with the model were: (1) Unlogged forest (2) Systematic elimination of mixedwoods with no logging of pine or black spruce, (3) same as (2) but with 10% cut reduction, (4) same as (2) but with protected areas of mature and old aspen and white spruce, (5) same as (2) but with protected areas of mature and old aspen and mixed types.

### **Saskatchewan studies**

In the southern boreal ecoregion in central Saskatchewan, mixed stands (white spruce-aspen and jack pine-aspen) had significantly higher species richness and higher abundance of birds at both the stand and landscape scale than pure stands of spruce or pine (Hobson and Bayne 2000). Certain bird species were affiliated with pure and mixed stands. The counts were done in 27 pure aspen, 27 mixedwood aspen, 21 pure jack pine, nine mixedwood jack pine, 13 pure white spruce, 17 mixedwood white spruce stands, six pure black spruce and five mixedwood black spruce naturally occurring forests. Pure stands had >75% of the canopy in the dominant species. Mixed and pure stands were of similar age (90-100 years-old), canopy height and crown closure. Considering all forest species together, at the stand scale mixedwoods supported 20 bird species compared to 15 species in the pure stands. This pattern was consistent among the different tree species. At the landscape scale there was no difference in species richness between pure and mixed stands when all stand types are considered together but richness was higher for aspen (53) than white spruce (47), jack pine (40) or black spruce (38). When individual stand types were considered separately pure and mixed aspen stands had similar species richness at the landscape level but mixed stands of white spruce, black spruce or pine had more species than pure stands of these species. Mixedwoods supported more individuals (total abundance) than pure stands (90 versus 62 at the stand level and 571 versus 393 at the landscape level). The pattern was consistent

for each tree species at the stand scale, but at the landscape level pure aspen and mixed aspen had similar total abundance of birds. Altogether 87 bird species were seen and 57 were common. Of the common species, 32 showed significant differences among stand types. Chipping sparrow, pine siskin, white-winged crossbill, red-breasted nuthatch, Swanson's thrush and Tennessee warbler were more abundant in mixedwood stands than pure ones. Black-throated green warbler, magnolia warbler, and blackburnian warbler were abundant in stands dominated by white spruce (but absent from black spruce or pine stands). Other species such as American redstart and chestnut-sided warbler relied exclusively on pure aspen stands. Forty-three percent of the species were found in all stand types. Mixed stands had more shrub-, cavity- and canopy-nesting birds than pure stand and the pattern was consistent among tree species. Long distance migrants, residents and irruptive species had higher abundance in mixedwoods than pure stands and the pattern was consistent among tree species. Short-distant migrants were equally abundant in pure and mixed stands. The author suggests that higher species richness and abundance in mixedwood stands versus pure stands was likely due to greater floristic and structural diversity in the canopy and subcanopy of the mixed stands. All of this indicates that several bird species in the boreal forest would be adversely affected by reducing mixedwood composition, especially converting old aspen and white spruce mixedwoods to pure stands.

Mature pure jack pine forests in the Southern Boreal ecoregion in central Saskatchewan had limited avian diversity compared to jack pine mixed stands (Kirk and Hobson 2001). For overmature stands there was no difference in species richness among the pure or mixed stand types. Some bird species were found in greater abundance or exclusively in mixedwoods. Surveys were done on two sites in 44 forest stands aged 14-145 years and 80 bird species were observed altogether. The study implies that planting or encouraging monocultures of jack pine to replace jack pine mixedwoods will not maintain avian biodiversity.

Bird communities differed among stand types across boreal forests in Alberta, Saskatchewan, Manitoba, Northwest Territories (Kirk et al 1996). The distribution of 80 species of birds was looked at in upland black spruce sites, riverine deciduous forests and wet marshy bogs. In aspen mixedwoods, 23 species occurred at higher abundance or were restricted to old stands (80 years-old) and another 28 species were most abundant in or restricted to young or very young stands (0-20 years-old.). Variations in densities of bird species across a range of habitat types indicated that a continuing supply of forest types varying in age composition (even-aged and uneven-aged), tree species composition, and the shrub layer is needed to support populations of the bird species in this study.

Barred owls preferred old (80+ years-old) and mature (50-79 years-old) mixedwoods within their non-breeding home ranges and avoided young forests (<50 yrs old) and coniferous forests in boreal forests in central Saskatchewan (Mazur et al. 1998). The dominant tree species in the study area included trembling aspen, balsam poplar, paper birch, white spruce, black spruce, jack pine and balsam fir. The preferred breeding home ranges contained high proportions of old mixedwoods, where tree cavities needed for nesting which occur in large trees and snags are especially common. Timber management practices that ensure a continuous supply of old mixedwood forests are essential for survival of the barred owl.

## Quebec studies

Bird community responses to landscape scale and local scale forest cover were determined in a study at the southern limit of the boreal forest in northwestern Quebec (Drapeau et al. 2000). In this study, birds were sampled at 459 stations across 3 landscape types: (1) 66% of the landscape in broadleaf stands (mature trembling aspen), 17% in mixedwood, and 17% in coniferous stands (pre-industrial landscape); (2) 37% broadleaf stands, 40% mixedwood, and 23% coniferous stands (industrial timber managed forest); and (3) 16% broadleaf stands, 65% mixedwood, 18% coniferous stands (forest dominated by natural disturbances). The main tree species in the study area were white spruce, black spruce, jack pine, red pine, balsam fir, white cedar, and tamarack. Eighty-four bird species were detected that were associated with forest habitats. Alpha diversity (station level) did not differ among landscape types, but at a landscape scale, diversity was lower in the natural landscape (where there were more mixedwoods) than the human-disturbed landscapes. There were no significant differences in species richness/station among the three landscape types. This was true for the three bird categories (Neotropical migrants, short-distance migrants, and residents). Although there were some significant differences, the abundance (mean number of individuals per station) was generally similar among the three landscape types, for each of the three bird categories. There were important differences in bird species composition across the three landscapes. The natural landscape had higher abundance of several bird species identified as having an affinity for mixed stands. The researchers note that large scale conversion of forests from mixed to broadleaf cover may be a very an important threat to the integrity of bird communities. Maintenance of a mosaic of forest types (broadleaf, coniferous and mixed) similar to that occurring under natural conditions is likely a good strategy in managed landscapes.

### 2.9.7 Mammals

No published data were found comparing mammal use of mixed spruce-aspen or lodgepole pine-aspen stands compared to pure conifer stands for boreal or sub-boreal forests. Roy et al. (1995) has some information about how mammal species richness compares among mixedwoods of different ages but not species composition. He found that for boreal mixedwood forests in Alberta mammal species richness in summer was significantly higher in old stands than young or mature ones, and in winter it was highest in the old and young stands. Of 19 mammal species that were detected ten or more times, nine had their highest abundance in old stands, four in young stands and three in mature stands. In winter, two, three, and one species had their highest abundance in old, young and mature stands, respectively.

### 2.10 Forest damage

#### 2.10.1 Frost and air temperature

Cold temperatures can be a major limitation to seedling growth in the growing season (Filipescu and Comeau 2011). Temperature fluctuations, which typically increase with reductions in the overstorey,

may also impact growth. Cold temperatures are an especially relevant issue in boreal climates where the growing season is short and freezing conditions can occur at any time of year. Frost damage is an important concern in these areas particularly in open areas compared to under canopies of aspen (Table 13).

A number of studies in boreal forests describe temperature differences under varying levels of aspen. For example, in the BWBS zone in British Columbia, Coopersmith et al. (2000) found that air temperatures were lower in the open than where 5000 or 10000 SPH of aspen were retained. In another study, Filipescu and Comeau (2011) looked at the influence of varying amounts of aspen cover on air and soil temperature and frost incidence on white spruce seedlings in boreal mixedwood stands near Peace River and Grande Prairie in Alberta. Aspen and spruce were established at the same time and at age 11 the aspen was thinned to 0, 500, and 1500 SPH and a natural untreated control was left (6000-9000 SPH at age 11). At Grande Prairie, where the site was in a low-lying basin, frost incidence increased with decreasing aspen cover. The amount of frost in the zero aspen plot was higher than in the natural untreated plot but frost incidence was similar in the 500 and 1500 SPH plots. At Peace River, the incidence of frost was similar across the gradient of aspen densities. Here the site was located on a rise, where there would be more wind and air mixing, indicating that the frost protection benefits of retaining aspen will be realized only on sites with topography such that there is an actual risk of frost injury. Reducing aspen density increased air temperature extremes and soil temperature. Air temperature during a frost event was 1.5°C colder where there was no aspen than in the natural plot, and intermediate between the two in the 500 and 1500 SPH plots.

Also in Alberta, Voicu and Comeau (2006) found that the frequency of summer frost increased rapidly moving from the edge of an aspen stand into an adjacent opening. The results suggested that some degree of frost protection occurred within one tree length (5-7 m) of 11-13 year old aspen patches. Pritchard and Comeau (2004) also found that the incidence of frost to white spruce increased as opening size in aspen canopies increased.

In Ontario, Groot and Carlson (1996) compared frost damage and bud-break phenology on planted spruce and aspen suckers in forest openings of different sizes and configurations (1.5 ha clearcut, 9 and 18 m wide strips, 9 and 18 m diameter circular openings, and an intact 19-m tall 40 year-old aspen forest with a basal area of 36 m<sup>2</sup>/ha. Damage and bud burst measurements were combined with measures of minimum air temperature and long wave radiation. The trembling aspen stand strongly influenced minimum near surface temperatures and the canopy provided almost complete protection from frost, but only where the canopy was intact or openings were very small. Nearly 75% of seedlings in the clearcut had medium or heavy frost damage versus only 2% in the 9-m circle and forest. About 50% of seedlings in the 18-m strip, 18-m circle and 9-m strip had medium to heavy frost damage indicating that damage in these areas not much less than in the clearcut even though the openings were much smaller with lower view factor values.

The difference in minimum air temperature in May-July between the clearcut and intact forest averaged almost 3°C (Groot and Carlson 1996). When the sky was clear, warmest temperatures were under the

tree canopy where the temperature was 5-6 °C higher in the forest but still below freezing. The difference in temperature between the forest and the 18-m strip opening was 3-4 °C and between the forest and the 18 m wide circle was 2-3 °C. Minimum air temperatures in the 9-m openings were similar to the forest under all conditions. On a night when skies were cloudy, night temperatures averaged 15-20 °C higher than 2 days earlier when it had been clear; the temperature variation between treatments was about 1 °C on that night.

Opening size and configuration had no significant effect on flushing date or timing of bud break of aspen suckers or spruce (1-2 day differences). However, aspen bud break occurred about 5 days before spruce bud break so in spruce-aspen mixtures a substantial canopy of aspen foliage may be present during and after white spruce bud break. This shelter isn't available in recently logged clearcuts.

### 2.10.2 Insects

A meta-analysis of boreal and northern temperate studies indicated a positive effect of mixing tree species on resistance against insects (Griess and Knoke 2011). The cumulated effect size was -0.26 with confidence limits of -0.19 and -0.34. Three of the five studies used in the analysis were from eastern Canada and two were European. Conifer-broadleaf combinations found in boreal and sub-boreal British Columbia forests were included in the analysis. In contrast to Griess and Knoke (2011), Koricheva et al. (2006), in their review of diversification of boreal forests to manage pests and diseases, concluded that experimental data from published studies provide no overall support for the hypothesis that diversifying forest stands can prevent pest outbreaks and epidemics, although they acknowledge that benefits are observed in some cases.

There is evidence from British Columbia that mixing broadleaf trees in with conifers can reduce attack by some insects. Spruce leader weevil (*Pissodes strobi* (Peck)) attack on white spruce in the SBS zone was significantly less in an untreated birch-spruce stand than in a stand dominated by spruce where birch was killed with glyphosate (Nykoluk and Hawkins 2001). In the mixed species stand, spruce density averaged 1165 SPH and birch densities ranged from 500 to 3500 SPH (average 2365 SPH)

Taylor et al. (1996) also found that weevil attack on white spruce decreased significantly with increasing overstorey cover based on surveys in eight plantations in the SBSwk subzone. The rate of decrease was much greater in heavily versus lightly attacked stands. A 60% decrease in percent crown cover increased weevil attacks by 22% for heavily attacked stands and by 8% for lightly attacked stands. In this study, the major shade species that overtopped the spruce were, in descending order, trembling aspen, willow, paper birch, subalpine fir, alder, lodgepole pine and white spruce. However, the low-lying brush species (alder and willow) caused greater reductions in weevil attack and leader growth than pine or cottonwood while aspen and birch had no relationship. This is probably because canopies of aspen and birch were higher, allowing more diffuse light to come through than with the shrubs. As well, alder and willow have a thicker branch pattern than aspen and birch, which may affect ambient air temperatures and affect weevil oviposition before maximum leaf extension. The optimum level of overstorey removal may be a compromise between volume loss due to overstorey competition (which was relatively small)

and volume gain due to decreased weevil attacks. Results are similar to Taylor and Cozens (1994) who suggest weevil attack will increase by about 7% for at least 7-8 years when overstorey species are partially removed.

There is also evidence that a component of broadleaf trees in a stand can reduce spruce budworm (*Choristoneura fumiferana* (Clem.)) damage (Su et al. 1996; MacLean 1980). Studies done more than 30 years ago in eastern Canada and Minnesota indicate that in general spruce budworm-caused mortality in mature stands with >20% broadleaf trees is slightly lower than that in pure stands (MacLean 1980). Su et al. (1996) found that defoliation due to spruce budworm is strongly linearly related to the proportion of broadleaf trees in balsam fir stands in northern New Brunswick. Broadleaf species were balsam poplar, yellow birch, white birch, red maple and sugar maple. Percent broadleaf content explained 57-81% of the variability in balsam fir defoliation over a five year period among 25 stands. Stands in the 0-20% broadleaf class sustained an average of 58-71% defoliation, versus 12-15% defoliation for stands with 81-100% broadleaves. No defoliation occurred where broadleaf content was >90%. The study indicated that mixed stand management with broadleaf content >40% could substantially reduce losses during spruce budworm outbreaks. Determining the mechanisms for the results would take another study but the authors think it is related to the populations of natural enemies of the budworm, which in turn are related to the presence of key host plant or tree species or plant diversity.

### 2.10.3 Diseases

Several studies in the Interior-Cedar Hemlock (ICH) zone in British Columbia have shown that conifer mortality rates due to root disease increase when the density of broadleaf trees is reduced (Woods 1994, cited by Baleschta 2005; Simard et al. 2001; Baleschta et al. 2005). Simard et al. (2001) found that Armillaria-caused mortality in lodgepole pine increased by four times from 0.4%/year in juvenile untreated lodgepole pine-paper birch stands to 1.8%/year where all paper birch was manually cut. In lodgepole pine-aspen mixtures however, Armillaria-caused mortality was about the same whether brushing was done or not.

In ICH Douglas-fir plantations, mortality rates due to Armillaria were higher (1.6%/year) where broadleaves (birch, aspen, and black cottonwood) were killed by girdling compared to the untreated control (0.6%/year), but this trend was not found where manual cutting or cut-stump glyphosate brushing treatments were conducted (Simard et al. 2001). Baleschta et al. (2005) found that in 10-15 year-old Douglas-fir stands, mortality due to Armillaria steadily increased as the intensity of manual cutting of birch increased. Over a three-year measurement period, mortality was 0.1%/year in an untreated fir-birch mixture (7200-19,400 birch stems/ha) compared to 0.7%/year where birch was completely removed. In 25 year-old Douglas-fir plantations conifer mortality was 1.8% in untreated conifer plantations compared with 8.5% where brushing was done (Woods 1994, cited by Baleschta 2005).

In two year-old plantations in Minnesota that included white spruce, mortality rates due to Armillaria decreased significantly with an increase in the proportion of aspen (Gerlach et al. 1997). Mortality of the

three most susceptible species (black spruce, balsam fir and tamarack) was reduced by 75% when they were grown in aspen-rich rather than conifer-rich plots.

#### **2.10.4 Animal damage**

Levels of hare damage in the BWBS zone are consistently higher under broadleaf canopies or under mixed broadleaf-conifer stands than in the open where broadleaves have been removed (Harper et al. 1997; Coopersmith et al. 2000; DeLong 2000; Comeau et al. 2009a) (Table 14). Newsome et al. (2004a) found that in the SBS zone, vole damage to lodgepole pine seedlings was most prevalent where aspen was denser (untreated lodgepole pine-aspen mixtures and plots where aspen was removed in a 50 cm radius around pine) than in clearcuts or where aspen was removed in a 100-cm radius around the pine.

#### **2.10.5 Whipping and windthrow**

Whipping from aspen branches can be a significant form of conifer damage (Lees 1966; Newsome 1997), which is one negative aspect of retaining aspen in conifer stands. In Alberta, 18% of released and 22% of unreleased white spruce stems had top damage from a combination of whipping and snow and ice. Lodgepole pine is also susceptible to whipping damage (Newsome et al. 2008) although it has not been a problem in juvenile pine-aspen stands in the MS and IDF zones in the southern interior (Simard et al. 2001). Newsome et al. (2008) found that whipping abrasion to branches increased with increasing tall aspen density.

In a meta-analysis of boreal and northern temperate biomes, Griess and Knoke (2011) found a positive impact of mixing tree species on resistance against windthrow. The cumulated effect size was -0.35 with confidence limits of -0.29 and -0.40. Data came from seven studies with stand ages of 60-149. None of the studies used in the meta-analysis included broadleaf-conifer combinations found in British Columbia. The species were all European, most commonly Norway spruce and European beech.

There is limited literature from boreal or sub-boreal areas comparing windthrow-caused mortality in spruce-aspen or lodgepole pine-aspen mixedwoods with that in pure stands. Solarik et al. (2012) is one reference that relates to this. They investigated tree mortality in a study of variable retention logging in different stand types (spruce, aspen, mixed) in a boreal forest in Alberta. Ten-year mortality rates in spruce where trees actually fell over (i.e. including windthrow) had a trend of being greatest in the mixed stand, then the conifer stand, and least in the aspen stands (with or without a spruce understorey). Aspen mortality rates where aspen fell over had a trend of being highest in the spruce stand, then the mixed stand, then the aspen stands. Mortality rates for spruce, where trees fell over, were greatest in the 10 and 20% retention treatments then the 50% retention and lowest in the 75 and 100% retention treatments. Mortality rates for aspen, where trees fell over, were greater in the 10 and 20% retention areas than the other treatments.

#### **2.11 Invasive plants**

Unpublished information based on expert opinion indicates that most invasive plants of concern in the Cariboo-Chilcotin, where the SBS zone is found, are shade-intolerant (Misener 2009). The current management strategy of creating large clearcuts and disturbing the soil has encouraged invasive plants. Retaining some aspen increases the amount of shade and is effective at decreasing their presence.

## **2.12 Fire hazard**

Aspen stands are documented to be the least flammable of any forest type in Colorado and only half as flammable as adjacent conifer stands, so they can act as a firebreak (Fechner and Barrows 1976). When fires reach aspen patches they drop to the ground or may extinguish themselves after burning into the stand for a few metres. Aspen patches are recommended to be 20–100 m wide for them to be effective fire breaks.

Misener (2009) interviewed fire management experts regarding the role of aspen in wildfire management in British Columbia. The experts agreed with Fechner and Barrows (1976) noting that aspen stands are used as “anchor points” when wildfires are managed. Mixed stands provide benefits too but clumping is better because it creates breaks in the overstorey that can slow fire spread in the canopy. However, under severe weather conditions or when fuel loads are high, aspen stands may not be very effective as fire breaks.

Hely et al. (2000a) sampled forty-eight 32-236 year-old boreal stands in northwestern Quebec of three stand types: broadleaf (trembling aspen and birch), mixed conifer-broadleaf, and conifers. There was significantly more flammable material (small woody materials, conifer pieces and aerated organic matter) under conifer and mixed stands than broadleaf ones. Simulations with the BEHAVE prediction system showed that in the mixedwood boreal forests, fires are less intense and spread more slowly in broadleaf than other stand types, under the same topography and weather conditions. Mixed stands fell between broadleaf and conifer stands. Differences were due to changes in quality not quantity of surface fuels.

## **2.13 Cultural values**

No specific articles were found on the different cultural uses of pure conifer or pure broadleaf stands compared to mixtures of the two, but information was found on the cultural values of single broadleaf species, especially paper birch. This section describes some of the cultural values of broadleaf tree species found in boreal and sub-boreal British Columbia stands. Table 15 lists some historic uses of trembling aspen, balsam poplar, black cottonwood, and paper birch in British Columbia.

There are many products made from birch besides its usual uses (e.g., lumber, veneer, firewood), such as those listed below, and they come from all ages of birch trees, not just at the end of the rotation. The products tend to be made by local entrepreneurs and First Nations peoples, rather than on a large scale, and in British Columbia use by entrepreneurs is particularly important in the boreal regions (Peterson et al. 1995). First Nations peoples consider birch one of the most valuable trees in British Columbia. Stands

do not need to be pure birch for these products to be derived, therefore including birch in managed stands provides a source of materials for many cultural products, compared with pure conifer stands.

The following information is summarized from Byrne and Dow (2006). Birch trees are currently used in British Columbia, often by First Nations people, to make many arts and craft items including: canoes and paddles; musical instruments; sleds and snowshoes; twig furniture; basketry; paper made from bark; bowl, platters, and serving utensils from wood; and shoe insoles. Commercial food and health products currently obtained or made from birch trees in British Columbia include: mushrooms and fungi; birch sap drinks; birch syrup which may be made into toffee, marinades, ice cream toppings and sauces; oils from the bark for cosmetics, salves and medicinal preparations; medicinal teas and tonics, and chemicals such as Xylitol used as a sweetener. In 2006 in central British Columbia two farm businesses were tapping birch trees for sap and using it for syrup, wine, and a health drink. Markets for the arts and crafts and food and health products tend to be local (e.g. retail shops, markets, and fairs), although there are indications of interest by international markets. However, supply may be a problem because many producers only create a small volume of product each year. Collaboration efforts between producers may help solve this.

#### **2.14 Visual values**

No publications were found comparing the visual quality of pure conifer, pure broadleaf, and mixedwoods but references to the positive effect of broadleaves on visual values is sometimes made in passing. Obviously the appearance of stands and the landscape would be altered if broadleaf tree abundance were reduced. Visually, broadleaf trees have a different texture than conifers. A wide range of proportions of broadleaves across the landscape would increase the visual variety. Variety is also obtained on a seasonal basis as leaves change colour in the fall and then fall off by winter.

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Table 1. List of abbreviations.

| Abbreviation         | Meaning                           |
|----------------------|-----------------------------------|
| <b>BA</b>            | Basal area                        |
| <b>BWBS</b>          | Black and White Boreal Spruce     |
| <b>CI</b>            | Competition Index                 |
| <b>DBH</b>           | Diameter at breast height (1.3 m) |
| <b>FG</b>            | Free-to-grow                      |
| <b>GLD</b>           | Ground level diameter             |
| <b>HA</b>            | Hectares                          |
| <b>HDR</b>           | Height: diameter ratio            |
| <b>LAI</b>           | Leaf area index                   |
| <b>M<sup>2</sup></b> | Square metres                     |
| <b>M<sup>3</sup></b> | Cubic metres                      |
| <b>MSP</b>           | Mechanical site preparation       |
| <b>RCD</b>           | Root collar diameter              |
| <b>SBS</b>           | Sub-Boreal Spruce                 |
| <b>SPH</b>           | Stems per hectare                 |
| <b>SW</b>            | White spruce                      |

Table 2. List of Latin and corresponding common names for trees and plants.

| Latin name                             | Common name         |
|----------------------------------------|---------------------|
| <b><i>Abies balsamea</i></b>           | Balsam fir          |
| <b><i>Athyrium felix-femina</i></b>    | Lady fern           |
| <b><i>Aralia nudicaulis</i></b>        | Wild sarsaparilla   |
| <b><i>Betula papyrifera</i></b>        | Paper birch         |
| <b><i>Calamagrostis canadensis</i></b> | Bluejoint           |
| <b><i>Epilobium angustifolium</i></b>  | Fireweed            |
| <b><i>Larix laricina</i></b>           | Tamarack            |
| <b><i>Lonicera involucrate</i></b>     | Black twinberry     |
| <b><i>Picea glauca</i></b>             | White spruce        |
| <b><i>Pinus banksiana</i></b>          | Jack pine           |
| <b><i>Pinus contorta</i></b>           | Lodgepole pine      |
| <b><i>Pinus mariana</i></b>            | Black spruce        |
| <b><i>Pinus resinosa</i></b>           | Red pine            |
| <b><i>Populus tremuloides</i></b>      | Trembling aspen     |
| <b><i>Populus balsamifera</i></b>      | Balsam poplar       |
| <b><i>Rosa acicularis</i></b>          | Prickly rose        |
| <b><i>Rubus pubescens</i></b>          | Trailing raspberry  |
| <b><i>Thuja occidentalis</i></b>       | White cedar         |
| <b><i>Viburnum edule</i></b>           | High-bush cranberry |

Table 3. A summary of measured white spruce responses to broadleaf manipulation in planting trials. Values identified by different letters are significantly different at the indicated p value.

| BEC unit & Location                                      | Measure ment period | Treatments                                                   | Broadleaf density at end of measurement period | Spruce responses                                               |                                                                |                              |       |                                                         | P value | Reference                        |
|----------------------------------------------------------|---------------------|--------------------------------------------------------------|------------------------------------------------|----------------------------------------------------------------|----------------------------------------------------------------|------------------------------|-------|---------------------------------------------------------|---------|----------------------------------|
|                                                          |                     |                                                              |                                                | Ht. (cm)                                                       | Diam. (cm)                                                     | Stem vol. (cm <sup>3</sup> ) | HDR   | Survival (%)                                            |         |                                  |
| <b>BWBSmw<br/>NE British<br/>Columbia</b>                | 7 years             | Manual complete removal                                      | 22,667                                         | 214 a                                                          | 3.2 a                                                          | 730 a                        | 71 ab | 93 a                                                    | 0.05    | Kabzems, Harper and Fielder 2011 |
|                                                          |                     | Chemical complete removal                                    | 267                                            | 227 b                                                          | 4.8 b                                                          | 1615 b                       | 48 b  | 96 a                                                    |         |                                  |
|                                                          |                     | Manual 1.25 m radii                                          | 13,467                                         | 219 a                                                          | 3.0 a                                                          | 675 a                        | 74 a  | 96 a                                                    |         |                                  |
|                                                          |                     | Chemical 1.25 m radii                                        | 16,200                                         | 231 a                                                          | 3.3 a                                                          | 855 a                        | 73 a  | 90 a                                                    |         |                                  |
|                                                          |                     | Aspen spacing                                                | 9,733                                          | 193 a                                                          | 3.4 a                                                          | 755 a                        | 59 ab | 88 a                                                    |         |                                  |
|                                                          |                     | Untreated control                                            | 22,800                                         | 195 a                                                          | 2.5 a                                                          | 333 a                        | 79 a  | 94 a                                                    |         |                                  |
| <b>BWBSmw1<br/>Siphon Cr<br/>NE British<br/>Columbia</b> | 17 years            | No aspen                                                     | 0                                              | 940                                                            | 10.8                                                           |                              |       | 95-100% for all treatments                              | 0.05    | Kabzems et al. 2007              |
|                                                          |                     | Aspen thinning to 5000 SPH                                   | 5000                                           | Ht of Bareroot                                                 | Diam of Bareroot                                               |                              |       |                                                         |         |                                  |
|                                                          |                     | Aspen thinning to 10,000 SPH                                 | 1000                                           | Sw with 0 SPH                                                  | Sw with 0 SPH                                                  |                              |       |                                                         |         |                                  |
|                                                          |                     | Further aspen thinning to 1000 & 2000 SPH 2 yrs before meas. | 1000 & 2000                                    | aspen 23-61% greater than other tmnts                          | aspen 43% greater than 10,000 SPH & 112% greater than 5000 SPH |                              |       |                                                         |         |                                  |
| <b>BWBSmw1<br/>Siphon Cr<br/>NE British<br/>Columbia</b> | 8 years             | No aspen                                                     | 0                                              | Ht of Container                                                |                                                                |                              |       | 80-100                                                  | 0.05    | Kabzems et al. 2007              |
|                                                          |                     | Aspen thinning to 5000 SPH                                   | 5000                                           | Sw greatest with                                               |                                                                |                              |       | 40-95                                                   |         |                                  |
|                                                          |                     | Aspen thinning to 10,000 SPH                                 | 10,000                                         | 0 SPH aspen; less                                              |                                                                |                              |       | 75-95                                                   |         |                                  |
|                                                          |                     | Further aspen thinning to 1000 & 2000 SPH 2 yrs before meas. | 1000 & 2000                                    | in 5000 plot than 10,000 plot                                  |                                                                |                              |       |                                                         |         |                                  |
| <b>BWBS1<br/>Bear Mtn<br/>NE British<br/>Columbia</b>    | 11 years            | No aspen                                                     | 0                                              | Ht of Sw sig                                                   | Same trend as for                                              |                              | 47    | 78-100                                                  | 0.05    | Coopersmith et al. 2000          |
|                                                          |                     | Aspen thinning to 5000 SPH                                   | 5000                                           | greater with 0                                                 | ht                                                             |                              | 56    | 49-95                                                   |         |                                  |
|                                                          |                     | Aspen thinning to 10,000 SPH                                 | 10,000                                         | SPH aspen than                                                 |                                                                |                              | 33    | 61-84                                                   |         |                                  |
|                                                          |                     | Further aspen thinning to 1000 & 2000 SPH 2 yrs before meas. | 1000 & 2000                                    | 5000 and 1000 SPH aspen which are not sig diff from each other |                                                                |                              |       |                                                         |         |                                  |
| <b>SBSdw3<br/>Tsilcoh River<br/>British<br/>Columbia</b> | 10 years            | Glyphosate complete removal                                  | 1100                                           | 188 a                                                          | 3.7 a                                                          |                              | 53 a  | >84% in both plots but vigour better in glyphosate plot |         | Biring and Hays-Byl 2000         |
|                                                          |                     | Untreated control                                            | 20,200                                         | 133 b                                                          | 2.6 b                                                          |                              | 63 b  |                                                         |         |                                  |

|                                            |                     |                                      |        |                |        |       |                                                   |                                      |                                 |                 |
|--------------------------------------------|---------------------|--------------------------------------|--------|----------------|--------|-------|---------------------------------------------------|--------------------------------------|---------------------------------|-----------------|
| BWBSmw<br>Dawson Cr<br>British<br>Columbia | 12 years            | Glyphosate                           | 0      | 286 b          | 6.1 b  | 47 b  | Good in all plots but more hare damage in control |                                      | Harper et al. 1997 <sup>1</sup> |                 |
|                                            |                     | Hexazinone                           | 67     | 280 b          | 6.1 b  | 47 b  |                                                   |                                      |                                 |                 |
|                                            |                     | Control                              | 12,100 | 216 a          | 3.7 a  | 59 a  |                                                   |                                      |                                 |                 |
| Alberta                                    | 3 years             | Glyphosate complete removal          |        | 9 <sup>2</sup> | 0.25   | 0.56  | 33                                                | 91%, no sig diff among treatments    | 0.01                            | Man et al. 2008 |
|                                            |                     | Glyphosate 2 m radius spot (yr 1 &2) |        | 11             | 0.24   | 0.67  | 38                                                |                                      |                                 |                 |
|                                            |                     | Glyphosate 2 m radius                |        | 11             | 0.26   | 0.99  | 36                                                |                                      |                                 |                 |
|                                            |                     | Glyphosate complete woody only       |        | 10             | 0.14   | 0.22  | 47                                                |                                      |                                 |                 |
|                                            |                     | Glyphosate 2 m radius woody only     |        | 10             | 0.15   | 0.24  | 46                                                |                                      |                                 |                 |
|                                            |                     | Untreated control                    |        | 8              | 0.08   | 0.05  | 61                                                |                                      |                                 |                 |
| Alberta and Saskatchewan                   | 20 years            | Thinning to 0 SPH                    | 0      | 414 ab         | 9.8 a  |       | 44 d                                              | 0.05                                 | Bokalo et al. 2012              |                 |
|                                            |                     | Thinning to 200 SPH                  | 200    | 423 a          | 8.9 ab |       | 49 c                                              |                                      |                                 |                 |
|                                            |                     | Thinning to 500 SPH                  | 500    | 435 a          | 8.5 b  |       | 52 c                                              |                                      |                                 |                 |
|                                            |                     | Thinning to 1500 SPH                 | 1500   | 418 ab         | 7.3 c  |       | 8 b                                               |                                      |                                 |                 |
|                                            |                     | Thinning to 4000 SPH                 | 4000   | 375 b          | 5.8 d  |       | 65 a                                              |                                      |                                 |                 |
|                                            |                     | Untreated control                    | 22,800 | 298 c          | 4.5 e  |       | 66 a                                              |                                      |                                 |                 |
| Alberta                                    | Avg. 5 (range 1-12) | Broadcast glyphosate                 | <1000  | 114 a          | 1.9 a  | 700 a | 0.05                                              | Pitt, Mihajlovich and Proudfoot 2004 |                                 |                 |
|                                            |                     | Untreated control                    | 9000   | 107 a          | 1.5 b  | 470 b |                                                   |                                      |                                 |                 |
| Alberta                                    | 5 years             | Annual removal woody & herb.         |        | 62             | 2.0    | 81    | Similar for all treatments (89%)                  | 0.10                                 | Pitt et al. 2010                |                 |
|                                            |                     | Annual removal woody                 |        | 53             | 1.0    | 22    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal herb.                 |        | 56             | 0.9    | 15    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal woody in 2 m radius   |        | 62             | 1.1    | 27    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal all 2 m radius – 2yrs |        | 70             | 1.5    | 48    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal all 2 m radius – 4yrs |        | 76             | 1.7    | 68    |                                                   |                                      |                                 |                 |
|                                            |                     | Untreated control                    |        | 46             | 0.6    | 5     |                                                   |                                      |                                 |                 |
|                                            |                     | Untreated control – not planted      |        | -              | -      | -     |                                                   |                                      |                                 | -               |
| Ontario                                    | 5 years             | Annual removal woody & herb. Veg     |        | 61             | 2.2    | 88    | Similar for all treatments (89%)                  | 0.10                                 | Pitt et a l. 2010               |                 |
|                                            |                     | Annual removal woody                 |        | 68             | 1.8    | 64    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal herb.                 |        | 88             | 1.9    | 92    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal woody in 2 m radius   |        | 72             | 1.7    | 59    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal all 2 m radius – 2yrs |        | 83             | 2.0    | 93    |                                                   |                                      |                                 |                 |
|                                            |                     | Annual removal all 2 m radius – 4yrs |        | 77             | 2.1    | 96    |                                                   |                                      |                                 |                 |
|                                            |                     | Untreated control                    |        | 74             | 1.2    | 34    |                                                   |                                      |                                 |                 |
|                                            |                     | Untreated control – not planted      |        |                | --     |       |                                                   |                                      |                                 |                 |

|                |          |                                                 |                   |                                                                                         |                                                                                                              |      |                                                          |                                        |
|----------------|----------|-------------------------------------------------|-------------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|------|----------------------------------------------------------|----------------------------------------|
| <b>Ontario</b> | 7 years  | Manual cutting (suckered)                       |                   | Largest for<br>triclopyr; No sig<br>diff in ht of<br>dominant Sw<br>among<br>treatments | Largest for<br>triclopyr; No sig<br>diff in diam of<br>dominant Sw<br>among<br>treatments                    |      | 12% lower in<br>untreated<br>control than<br>other plots | Pitt and Bell<br>2005                  |
|                |          | Mechanical cutting (suckered)                   |                   |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Aerial glyphosate, patches untreated            |                   |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Aerial triclopyr (top kill only)                |                   |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Untreated control                               |                   |                                                                                         |                                                                                                              |      |                                                          |                                        |
| <b>Ontario</b> | 41 years | Herbicide – barrel MSP                          | 208               |                                                                                         |                                                                                                              | 53   | 60                                                       | Fleming and<br>Smith 2011 <sup>3</sup> |
|                |          | No herbicide – barrel MSP                       | 861               |                                                                                         |                                                                                                              | 44   | 73                                                       |                                        |
|                |          | Herbicide – blade MSP                           | 139               |                                                                                         |                                                                                                              | 59   | 66                                                       |                                        |
|                |          | No herbicide – blade MSP                        | 1041              |                                                                                         |                                                                                                              | 38   | 83                                                       |                                        |
| <b>Quebec</b>  | 5 years  | Leaf area index (LAI) 0 (no cover) <sup>4</sup> | Sw ht decreased   | Same trend as<br>height                                                                 |                                                                                                              | 1165 | 50 a                                                     | Jobidon 2000 <sup>5</sup>              |
|                |          | LAI 25                                          | as LAI increased; |                                                                                         |                                                                                                              | 351  | 56 b                                                     |                                        |
|                |          | LAI 50                                          | greatest drop was |                                                                                         |                                                                                                              | 164  | 66 c                                                     |                                        |
|                |          | LAI 75                                          | from LAI 0 to LAI |                                                                                         |                                                                                                              | 177  | 69 c                                                     |                                        |
|                |          | LAI 100 (complete cover)                        | 25                |                                                                                         |                                                                                                              | 122  | 75 d                                                     |                                        |
| <b>Ontario</b> | 10 years | Brush saw continuous removal                    | 0                 |                                                                                         | Gross total<br>volume:<br>glyphosate<br>continuous<br>removal 202% ><br>control; triclopyr<br>127% > control |      |                                                          | Bell, Dacosta et<br>al. 2011           |
|                |          | Brush saw                                       | 5333              |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Mechanical cutting                              | 6139              |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Triclopyr aerial spray                          | 3028              |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Glyphosate continuous removal                   | 0                 |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Glyphosate aerial spray                         | 1028              |                                                                                         |                                                                                                              |      |                                                          |                                        |
|                |          | Untreated control                               | 5083              |                                                                                         |                                                                                                              |      |                                                          |                                        |

- 1 Broadleaf tree on this site was balsam poplar
- 2 Height, diameter, and stem volume values are year 3 increments
- 3 Values in stem volume column are above ground biomass (kg)
- 4 Broadleaf tree on this site was paper birch
- 5 Values in stem volume column are above ground biomass (g)

Table 4. A summary of broadleaf tree responses to broadleaf manipulation treatments in white spruce-broadleaf stands.

| Location                                                 | Measurement period     | Treatments                                                                                                                                                                               | Broadleaf responses                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Reference                            |
|----------------------------------------------------------|------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|
| <b>BWBSmw<br/>NE British<br/>Columbia</b>                | 7 years                | Manual complete removal<br>Chemical complete removal<br>Manual 1.25 m radii<br>Chemical 1.25 m radii<br>Aspen thinning                                                                   | Seven years after treatment, aspen height and diameter did not differ significantly between any of the treatments (341-653 cm height and 2.0-5.2 cm diameter), although the trend was for smaller aspen in the manual complete control plot than the others.                                                                                                                                                                                                              | Kabzems, Harper and Fielder 2011     |
| <b>BWBSmw1<br/>Siphon Cr<br/>NE British<br/>Columbia</b> | 9 years                | No aspen<br>Aspen thinning to 5000 SPH<br>Aspen thinning to 10,000 SPH<br>Further aspen thinning to 1000 & 2000 SPH 2 yrs before meas.                                                   | Aspen survival over the measurement period was 91-100%. Following thinning, diameter growth of the remaining aspen stems increased, with a trend of increasing average diameter with decreasing aspen density, although the differences between treatments were not significant. There were no post-treatment differences in aspen height across the treatments.                                                                                                          | Kabzems et al. 2007                  |
| <b>BWBSmw1<br/>Bear Mtn<br/>NE British<br/>Columbia</b>  | 9 years                | No aspen<br>Aspen thinning to 5000 SPH<br>Aspen thinning to 10,000 SPH<br>Further aspen thinning to 1000 & 2000 SPH 2 yrs before meas.                                                   | Aspen survival over the measurement period was 96-100%. Following thinning, diameter growth of the remaining stems increased with a trend of increasing average diameter with decreasing aspen density. There were no post-treatment differences in aspen height across the treatments                                                                                                                                                                                    | Coopersmith et al. 2000              |
| <b>SBSdw3<br/>Tsilcoh River<br/>British<br/>Columbia</b> | 10 years               | Glyphosate complete removal<br>Untreated control                                                                                                                                         | At the end of the measurement period (11 years after planting), the untreated control was a two-storied mixedwood dominated by aspen (46% cover; 20,200 SPH). Height of the tallest aspen was 8.4 m, while the spruce were about 1.3 m tall on average. The glyphosate treated plot was close to a pure single-storied conifer stand, with only 3% cover of aspen (1100 SPH; height data not available).                                                                  | Biring and Hays-Byl 2000             |
| <b>BWBSmw<br/>Dawson Cr<br/>British<br/>Columbia</b>     | 12 years               | Glyphosate<br>Hexazinone<br>Control                                                                                                                                                      | Balsam poplar density was reduced to 00 SPH by glyphosate and 67 SPH by hexazinone. Density of balsam poplar in the control was 12,100 SPH in year 12.                                                                                                                                                                                                                                                                                                                    | Harper et al. 1997 <sup>1</sup>      |
| <b>Alberta</b>                                           | 3 years                | Glyphosate complete removal<br>Glyphosate 2 m radius spot (yr 1 & 2)<br>Glyphosate 2 m radius<br>Glyphosate complete woody only<br>Glyphosate 2 m radius woody only<br>Untreated control | No information on aspen development after treatment..                                                                                                                                                                                                                                                                                                                                                                                                                     | Man et al. 2008                      |
| <b>Alberta and<br/>Saskatchewan</b>                      | 9 years                | Thinning to 0 SPH<br>Thinning to 200 SPH<br>Thinning to 500 SPH<br>Thinning to 1500 SPH<br>Thinning to 4000 SPH<br>Untreated control                                                     | Aspen densities began to converge after age 10 (5 years after spacing) with the most mortality where initial aspen density was highest. Aspen spacing had little effect on height although 15 years after spacing height was significantly lower in the control (1030 cm) than the spaced plots (1131-1181 cm). Aspen root collar diameter, crown width, and height to live crown declined with increasing density. HDR of aspen increased with increasing aspen density. | Bokalo et al. 2012                   |
| <b>Alberta</b>                                           | Avg. 5<br>(range 1-12) | Broadcast glyphosate<br>Untreated control                                                                                                                                                | Untreated plots were dominated by aspen with the tallest trees just over 4 m in height and 3.8 cm stem diameter. Aspen stem densities were variable but averaged nearly 9000 SPH, giving an average stem volume approaching 30 m <sup>3</sup> /ha at age 8. The untreated plots also supported about 3000 of SPH balsam poplar and                                                                                                                                        | Pitt, Mihajlovich and Proudfoot 2004 |

|                            |          |                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                           |
|----------------------------|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
|                            |          |                                                                                                                                                                                                                                                                | 2000 SPH of white birch. Total basal area on untreated areas averaged 10.6 m <sup>2</sup> /ha; 70% of this was aspen and 88% was broadleaf. These could be considered “broadleaf stands.” Treated plots had about 10% of the aspen volume of untreated plots and less than 1000 SPH aspen. The aspen in the treated plots were less than half the size of aspen in the control.                                                                                                                                                                                                                                                               |                           |
| <b>Alberta and Ontario</b> | 5 years  | Annual removal woody & herb. veg<br>Annual removal woody<br>Annual removal herb.<br>Annual removal woody in 2 m radius<br>Annual removal all 2 m radius – 2yrs<br>Annual removal all 2 m radius – 4yrs<br>Untreated control<br>Untreated control – not planted | Control aspen cover increased linearly over time to reach just over 50% in year 5. Year 5 codominant aspen height in Alberta ranged from 285-333 cm across the different treatments and from 315-432 across the treatments in Ontario. The tallest aspen were in the controls where no spruce was planted. Average diameter ranged from 3.2 to 4.4 cm across the treatments with smallest diameters in the control where spruce was planted. Radial treatments reduced aspen cover and density by approx..50% and codominant aspen in these plots were 20% shorter than those in the control. Whole-plot treatments eliminated aspen.         | Pitt et al. 2010          |
| <b>Ontario</b>             | 7 years  | Manual cutting (suckered)<br>Mechanical cutting (suckered)<br>Aerial glyphosate, patches untreated<br>Aerial triclopyr (top kill only)<br>Untreated control                                                                                                    | Manual and mechanical cutting resulted in suckers that doubled aspen density. In year 7, aspen was twice as tall as the spruce in the control, aspen and spruce had similar heights to each other in the cut and triclopyr plots (but in the cut treatments aspen density was higher), and spruce was taller than the aspen in the glyphosate plot.                                                                                                                                                                                                                                                                                           | Pitt and Bell 2005        |
| <b>Ontario</b>             | 41 years | Herbicide – barrel MSP<br>No herbicide – barrel MSP<br>Herbicide – blade MSP<br>No herbicide – blade MSP                                                                                                                                                       | The herbicide treatments decreased year 41 broadleaf biomass by 6-10 times and density by 4-5 times compared to the non-herbicide plots. In the non-herbicide barrel scarified areas, year 41 aspen density was half that of the year 19 aspen density (2027 versus 861 SPH). In the herbicide areas aspen density decreased by about 4 times over the same period. (from 729 to 208 SPH) In the non-herbicide blade scarified areas, year 41 aspen density decreased by about 4 times from year 19 to year 41 (from 4165 to 1041 SPH). In the herbicide areas density was less than half (139 SPH) in year 41 compared to year 19 (305 SPH). | Fleming and Smith 2011    |
| <b>Quebec</b>              | 5 years  | Leaf area index (LAI) 0 (no cover)<br>LAI 25<br>LAI 50<br>LAI 75<br>LAI 100 (complete cover)                                                                                                                                                                   | In the first year of the study the site was occupied by 0.28 stems/m <sup>2</sup> of birch with a mean height of 66 cm (range 25-155 cm). By year 5 the control had a birch density of 0.93 stems/m <sup>2</sup> and a mean height of 175 cm (range 10-390 cm).                                                                                                                                                                                                                                                                                                                                                                               | Jobidon 2000 <sup>2</sup> |
| <b>Ontario</b>             | 10 years | Brush saw continuous removal<br>Brush saw<br>Mechanical cutting<br>Triclopyr aerial spray<br>Glyphosate continuous removal<br>Glyphosate aerial spray<br>Untreated control                                                                                     | No information on broadleaf development after treatment.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Bell, Dacosta et al. 2011 |

1 Broadleaf tree on this site was balsam poplar

2 Broadleaf tree on this site was paper birch

Table 5. A summary of the performance of white spruce seedlings underplanted beneath intact canopies.

| Location                                                               | Measure-<br>ment<br>period | Canopy<br>age &<br>species                  | Treatments                                                                                                                                                                    | Spruce growth responses                                |                                                                             |                                                                                                                                            | Reference                   |
|------------------------------------------------------------------------|----------------------------|---------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
|                                                                        |                            |                                             |                                                                                                                                                                               | Survival                                               | Damage                                                                      | Height, diameter, HDR                                                                                                                      |                             |
| <b>BWBS<br/>80 km SW of<br/>Dawson Cr<br/>British<br/>Columbia</b>     | 7 years                    | 40-80<br>years;<br>aspen                    | <ul style="list-style-type: none"> <li>Intact aspen canopy</li> <li>Clearcuts</li> </ul>                                                                                      | 94% under canopy; 88% in clearcut                      | More hare damage and less frost damage under intact canopy than in clearcut | Height and diameter greater in clearcut than under intact canopy.                                                                          | DeLong 2000                 |
| <b>BWBS<br/>Fort Nelson<br/>British<br/>Columbia</b>                   | 2 years                    | 120<br>years;<br>aspen-<br>white<br>spruce  | <ul style="list-style-type: none"> <li>Intact canopy</li> <li>"Clearcuts" with 0-75 SPH aspen &amp; 0-75 SPH spruce</li> </ul>                                                |                                                        |                                                                             | Height greater in clearcut but some vigorous trees under intact canopy. Root collar diameter did not differ in clearcut and intact canopy. | Kabzems and Lousier 1992    |
| <b>BWBS<br/>Dawson Cr &amp;<br/>Sierra Rd<br/>British<br/>Columbia</b> | 10 years                   | 39 years;<br>aspen                          | <ul style="list-style-type: none"> <li>Intact canopy</li> <li>Thinning to 1000, 2000 &amp; 3000 SPH</li> </ul>                                                                | High for all treatments                                | Hare damage close to protective cover                                       | Root collar diameter greater in 1000 & 2000 SPH than under intact canopy; 3000 SPH intermediate.                                           | Comeau et al. 2009a         |
| <b>BWBS<br/>Rice Property<br/>British<br/>Columbia</b>                 | 5 years                    | Old<br>growth<br>aspen                      | <ul style="list-style-type: none"> <li>Intact canopy</li> <li>Clearcut</li> <li>Thinning to 600, 1200, 2500, and 5000 SPH</li> </ul>                                          | 70% under intact canopy; 80-90% in other plots         | Rodent damage least under canopy & 2500 SPH                                 | No significant difference in height or diameter among plots in first 4 years. In year 5 best growth where 1200 SPH                         | Hawkins 2005                |
| <b>Ontario</b>                                                         | 5 years                    | 70 years;<br>aspen<br>and<br>paper<br>birch | <ul style="list-style-type: none"> <li>Intact canopy</li> <li>Clearcut</li> <li>50% partial cut, residuals not removed</li> <li>50% partial cut, residuals removed</li> </ul> | 46% under canopy, 85% in partial cuts, 90% in clearcut | Minimal mammal damage for all tmts                                          | Height sig higher in clearcut than partial cuts, which was sig greater than in intact forest                                               | MacDonald and Thompson 2003 |

Table 6. A summary of the performance of white spruce seedlings planted into shelterwood cuts.

| Location                                                                       | Treatments                                                                                                                    | Study period (yrs) | Spruce responses                                                   |                                                                                                                              | Reference                 |
|--------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|--------------------|--------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|---------------------------|
|                                                                                |                                                                                                                               |                    | Survival                                                           | Height and diameter                                                                                                          |                           |
| <b>BWBSmw2<br/>Hoffard Cr &amp; Fort<br/>Nelson River<br/>British Columbia</b> | 2 sizes of shelterwood gaps:<br>40 m & 113 m diameter                                                                         | 3 years            | No significant difference<br>among treatments                      | No significant difference<br>among treatments                                                                                | Kabzems 2001              |
| <b>West-central<br/>Saskatchewan</b>                                           | Spruce planted in & beside<br>80 x 340 m rectangular gaps<br>and under canopy                                                 | 4 years            | No significant difference<br>among treatments                      | Height growth initially<br>best at S edge of gaps; in<br>yr 4 best at gap centre                                             | Milakovsky et<br>al. 2011 |
| <b>Northern Alberta</b>                                                        | Clearcut, 50% retention,<br>75% retention, intact<br>canopy; each tmt done for<br>aspen and spruce forests                    | 7 years            | Survival greater under<br>aspen canopy than<br>spruce canopy       | Height and volume<br>greater under aspen<br>than spruce. Root collar<br>diameter greatest in<br>50% retention aspen<br>plots | Gradowski et<br>al. 2008  |
| <b>Northern Ontario</b>                                                        | Clearcut, 40% removal<br>uniform shelterwood, strip<br>shelterwood, narrow strips,<br>patch shelterwood, intact<br>overstorey | 2 years            | Survival 52% under<br>intact canopy, better in<br>other treatments | Height and diameter<br>growth least under<br>intact or nearly intact<br>canopies                                             | Groot 1999                |

Table 7. A summary of measured pine responses to broadleaf manipulation<sup>1</sup>. Values identified by different letters are significantly different at  $p \leq 0.05$ .

| BEC unit & Location                              | Measurement period | Pine age at end of measurement period | Treatments                                             | Aspen density at end of measurement period | Pine responses |                                                                             |                                         |                                    |                                                                                                                                 | Reference                          |
|--------------------------------------------------|--------------------|---------------------------------------|--------------------------------------------------------|--------------------------------------------|----------------|-----------------------------------------------------------------------------|-----------------------------------------|------------------------------------|---------------------------------------------------------------------------------------------------------------------------------|------------------------------------|
|                                                  |                    |                                       |                                                        |                                            | Height (cm)    | Diameter <sup>2</sup> (cm)                                                  | HDR                                     | Survival (%)                       | Vigour                                                                                                                          |                                    |
| <b>SBSdw2 Tyee Lake British Columbia</b>         | 9 years            | 9 years                               | Broadcast removal                                      | 0 <sup>3</sup>                             | 283 a          | 5.6 a                                                                       | 51 b                                    | 87 a                               | Vigour declined as aspen density increased                                                                                      | Newsome et al. 2004a               |
|                                                  |                    |                                       | Removal in 100 cm radius                               | 3(16)                                      | 265 a          | 4.6 a                                                                       | 58 ab                                   | 86 a                               |                                                                                                                                 |                                    |
|                                                  |                    |                                       | Removal in 50 cm radius                                | 4(19)                                      | 296 a          | 4.9 a                                                                       | 62 a                                    | 72 a                               |                                                                                                                                 |                                    |
|                                                  |                    |                                       | Untreated control                                      | 5(22)                                      | 189 a          | 4.7 a                                                                       | 63 a                                    | 74 a                               |                                                                                                                                 |                                    |
| <b>SBSdw1 McKinley Lk British Columbia</b>       | 4 years            | 15 years                              | Broadcast removal                                      | 2930 <sup>4</sup>                          | 389 a          | 4.4 a                                                                       | 107 a                                   | Data not available                 | Lowest where $\geq$ 1000 SPH aspen retained                                                                                     | Newsome et al. 2006a               |
|                                                  |                    |                                       | Thinned to 500-800 SPH                                 | 776                                        | 449 a          | 4.3 a                                                                       | 127 a                                   |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       | Thinned to 1000-1500 SPH                               | 1251                                       | 373 a          | 3.4 a                                                                       | 138 a                                   |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       | Thinned to 2000-2800 SPH                               | 1951                                       | 396 a          | 3.9 a                                                                       | 115 a                                   |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       | Untreated control                                      | 4737                                       | 424 a          | 4.2 a                                                                       | 116 a                                   |                                    |                                                                                                                                 |                                    |
| <b>SBSdw1 Cariboo-Chilcotin British Columbia</b> | 12 years           | 22-23 years                           | No treatments (naturally occurring densities)          | 0 <sup>5</sup>                             | Above          | No sig. diff. between 0 & 1000 SPH height was sig. less than in 0 SPH class | Increased with increasing aspen density | 95 <sup>6</sup>                    | >80% fair or good vigour for 0 and 1000 SPH classes. Above 1000 SPH class vigour declined steeply with increasing aspen density | Newsome 2009 & Newsome et al. 2008 |
|                                                  |                    |                                       |                                                        | 1000                                       | 4000 SPH       |                                                                             |                                         | 83                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 2000                                       | pine           |                                                                             |                                         | 88                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 3000                                       | height was     |                                                                             |                                         | 90                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 4000                                       | sig. less      |                                                                             |                                         | 77                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 5000                                       | than in 0      |                                                                             |                                         | 83                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 6000                                       | SPH class      |                                                                             |                                         | 90                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 7000                                       |                |                                                                             |                                         | 87                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 8000                                       |                |                                                                             |                                         | 71                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 9000                                       |                |                                                                             |                                         | 68                                 |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 10000                                      |                |                                                                             |                                         | 57                                 |                                                                                                                                 |                                    |
| <b>SBPSxc Clusko British Columbia</b>            | 4 years            | 15 years                              | Manual thinning & untreated control (14,200 aspen SPH) | 0                                          | 158 a          | 3.5 a                                                                       | 45 a                                    | At least 98% in all treatments     | Virtually all had good or fair vigour                                                                                           | Newsome et al. 2010                |
|                                                  |                    |                                       |                                                        | 1000                                       | 144 a          | 2.9 a                                                                       | 49 ab                                   |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 2500                                       | 158 a          | 3.2 abc                                                                     | 50 abc                                  |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 100 cm radius                              | 149 a          | 2.9 bc                                                                      | 52 bc                                   |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       |                                                        | 14,200                                     | 150 a          | 2.8 c                                                                       | 55 c                                    |                                    |                                                                                                                                 |                                    |
| <b>Alberta</b>                                   | 2 years            | 10-15 years                           | All aspen removed                                      | 0                                          | 172 a          | 3.1 a                                                                       |                                         | No sig difference among treatments | Trend of more mechanical and pest damage where all aspen removed                                                                | MacIsaac 1996                      |
|                                                  |                    |                                       | At BDR <1.0 removed                                    | 12000                                      | 171 a          | 3.2 a                                                                       |                                         |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       | At BDR <0.75 removed                                   | 10000                                      | 184 a          | 2.9 a                                                                       |                                         |                                    |                                                                                                                                 |                                    |
|                                                  |                    |                                       | Untreated control                                      | 18000                                      | 174 a          | 2.7 b                                                                       |                                         |                                    |                                                                                                                                 |                                    |
| <b>Northeastern Ontario</b>                      | 5 years            | 5 years                               | Clearcut                                               | Data not available                         | 130 c          | 9.0 d                                                                       |                                         | 81                                 | Less abiotic damage <sup>7</sup> in                                                                                             | MacDonald and Thompson 2003        |
|                                                  |                    |                                       | Partial cut, one entry                                 |                                            | 78 b           | 6.2 c                                                                       |                                         | 65                                 |                                                                                                                                 |                                    |

|                        |      |       |    |                                                                                          |
|------------------------|------|-------|----|------------------------------------------------------------------------------------------|
| Partial cut, 2 entries | 78 b | 4.5 b | 73 | control (1.5%)<br>than other tmts<br>(6-8%). Mammal<br>damage 1-4%;<br>least in clearcut |
| Untreated control      | 33 a | 1.3 a | 28 |                                                                                          |

- 1 Other references on the subject are not included in this table because they do not contain applicable quantitative information (e.g. Newsome et al. 2012; Bell, Dacosta et al. 2011; Comeau 2010; Harper et al. 2009; DeLong 2007; Landhausser and Lieffers 2001; Newsome 1995; Navratil and MacIsaac 1993; Navratil et al. 1990).
- 2 Ground level diameter except leader diameter for MacDonald and Thompson 2003
- 3 Values are no. of tall (total) aspen in 10 m<sup>2</sup> plots (r = 1.78 m)
- 4 Values are stems per hectare  $\geq$  1.3 m tall. Aspen stems in 0 SPH treatment were mainly sprouts or suckers and were relatively small compared with those in other treatments
- 5 Values are stems per hectare taller than subject pine
- 6 Values are approximate and were derived from Figure 3 (Newsome et al. 2008)
- 7 Breakage, wounding, or uprooting

Table 8. A summary of broadleaf tree responses in pine-broadleaf stands with varying broadleaf densities<sup>1</sup>.

| BEC unit & Location                                                  | Measurement period | Pine age at end of measurement period | Treatments                                             | Aspen density at end of measurement period | Aspen responses                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Reference                          |
|----------------------------------------------------------------------|--------------------|---------------------------------------|--------------------------------------------------------|--------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|
| <b>SBSdw2</b><br><b>Tyee Lake</b><br><b>British Columbia</b>         | 9 years            | 9 years                               | Broadcast removal                                      | 0 <sup>2</sup>                             | Aspen height, diameter, and density within the 1.78 m <sup>2</sup> subplots were similar across the 50 cm, 100 cm and control plots and aspen throughout the study. However, average density of “tall” aspen decreased from 23 to 4 stems per subplot between 1994 and 2002, and average density of “all” aspen decreased from 44 to 19 stems per subplot. The decreases were due to self-thinning and rapid height growth of pine relative to small, low-vigour aspen. Tall aspen was growing slightly faster than the pine (it increased in height from an average of 49 cm to 331 cm). Broadleaf tree cover within a 1.78 m radius around the crop pine increased from 10 to 29% in the control, from 10 to 19% in the 50 cm treatment and from 7 to 16% in the 100 cm treatment in the 9-year measurement period.. | Newsome et al. 2004a               |
|                                                                      |                    |                                       | Removal in 100 cm radius                               | 3(16)                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       | Removal in 50 cm radius                                | 4(19)                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       | Untreated control                                      | 5(22)                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
| <b>SBSdw1</b><br><b>McKinley Lk</b><br><b>British Columbia</b>       | 4 years            | 15 years                              | Broadcast removal                                      | 2930 <sup>3</sup>                          | Aspen suckering was much more prolific in the 0 retention treatment (28,187 suckers/ha 2 years after treatment) than the 500-800 SPH (5981 suckers/ha), 1000-1500 SPH (4084 suckers/ha) or 2000-2800 SPH (344 suckers/ha). Suckers were not assessed in the control in year 2 but in year 4 there were 264 suckers/ha. By year 4 sucker density had declined to 18,063 suckers/ha in the 0 retention area and 4,039 in the 500-800 and 1000-1500 SPH retention treatments. Sucker height did not significantly differ between treatments 2 or 4 years after cutting.                                                                                                                                                                                                                                                   | Newsome et al. 2006a               |
|                                                                      |                    |                                       | Thinned to 500-800 SPH                                 | 776                                        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       | Thinned to 1000-1500 SPH                               | 1251                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       | Thinned to 2000-2800 SPH                               | 1951                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
| <b>SBSdw1</b><br><b>Cariboo-Chilcotin</b><br><b>British Columbia</b> | 12 years           | 22-23 years                           | No treatments (naturally occurring densities)          | 0 <sup>3,4</sup>                           | Tall aspen height differed significantly between tall aspen density classes at stand ages 15 to 24 years. The height difference between pine and aspen generally increased with tall aspen density. Pine was growing faster than the aspen only where tall aspen density was 1000 SPH. Actual tall density in classes that were defined at age 12-13 remained relatively constant in the ≤ 3000 tall aspen density classes over the next 10 years, but decreased by 2-27% in higher tall density classes.                                                                                                                                                                                                                                                                                                              | Newsome 2009 & Newsome et al. 2008 |
|                                                                      |                    |                                       |                                                        | 1000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 2000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 3000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 4000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 5000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 6000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 7000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 8000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 9000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 10000                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
| <b>SBPSxc</b><br><b>Clusko</b><br><b>British Columbia</b>            | 4 years            | 15 years                              | Manual thinning & untreated control (14,200 aspen SPH) | 0                                          | Mean aspen density immediately after treatment was significantly higher in the control and 1-m radius treatments than the others (average 8507 SPH), and this trend continued for the 4 year measurement period. Sucker density decreased with increasing aspen retention. By the 4 <sup>th</sup> year after treatment an average of 144 suckers/ha in the broadcast treatment had grown taller than the pine but they were significantly shorter than in the other treatments.                                                                                                                                                                                                                                                                                                                                        | Newsome et al. 2010                |
|                                                                      |                    |                                       |                                                        | 1000                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 2500                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
|                                                                      |                    |                                       |                                                        | 100 cm radius                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |
| <b>Alberta</b>                                                       | 2 years            | 10-15 years                           | All aspen removed                                      | 14,200                                     | Aspen density before treatment was about 25,000 SPH with 38-50% cover                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | MacIsaac 1996                      |
|                                                                      |                    |                                       |                                                        | 0                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |

|                             |         |         |                        |                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |
|-----------------------------|---------|---------|------------------------|--------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
|                             |         |         | At BDR<1.0 removed     | 12000              | and a height of 2-3 m(2 to 3 times the pine height).Removal of all aspen larger in diameter than pine decreased aspen density by 47-66%, cover by 87-92% and height by 50-66%. Results were similar for removal of aspen with BDR<0.75.Aspen density 1 year after treatment was high due to coppicing but in year 2 was well below control densities for the 3 treatments. In year 2 aspen height and cover for all treatments were well below levels at the time of treatment. |                             |
|                             |         |         | At BDR<0.75 removed    | 10000              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |
|                             |         |         | Untreated control      | 18000              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |
| <b>Northeastern Ontario</b> | 5 years | 5 years | Clearcut               | Data not available | Broadleaf density and height decreased with brushing frequency. Broadleaf density and height after harvesting generally increased with increasing harvest intensity for all brushing frequencies but decreased in the clearcut. Fifth-year broadleaf density was greater in the partial cut-2 entries treatment than any other treatment for all brushing frequencies. Mean broadleaf density in this treatment was 21,449 SPH compared to 8325 SPH in the clearcut.            | MacDonald and Thompson 2003 |
|                             |         |         | Partial cut, one entry |                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |
|                             |         |         | Partial cut, 2 entries |                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |
|                             |         |         | Untreated control      |                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |

- 1 Other references on the subject are not included in this table because they do not contain applicable quantitative information (e.g. Newsome et al. 2012; Bell, Dacosta et al. 2011; Comeau 2010; Harper et al. 2009; DeLong 2007; Landhauesser and Lieffers 2001; Newsome 1995; Navratil and MacIsaac 1993; Navratil et al. 1990).

Table 9. Soil differences under stands of pure conifers, trembling aspen and conifer-aspen mixtures.

| Location                                                | Stand composition and age                                                                           | Soil differences among stand types                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | Reference                   |
|---------------------------------------------------------|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| <b>BWBSmw subzone Dawson Creek British Columbia</b>     | 100-yr-old boreal white spruce, aspen and mixed aspen-spruce                                        | <ul style="list-style-type: none"> <li>Litter from the aspen and mixedwood forest decomposed slightly faster than litter from the spruce forest but the effect was short-lived, with little difference in decomposition rates after 3 yrs.</li> <li>Aspen litter decomposed at about the same rate in the pure aspen and mixed forest, but spruce litter decomposed faster when mixed with aspen litter compared to on its own.</li> </ul>                                                                          | Prescott et al. 2000        |
| <b>Northern Alberta</b>                                 | Aspen and spruce dominated boreal forests                                                           | <ul style="list-style-type: none"> <li>Nitrate availability and production was not any higher in aspen-dominated forests than spruce forests</li> </ul>                                                                                                                                                                                                                                                                                                                                                             | Jerabkova and Prescott 2002 |
| <b>Northwestern Alberta</b>                             | 70-125 yr-old boreal pure white spruce, pure aspen-balsam poplar, and mixed spruce-broadleaf stands | <ul style="list-style-type: none"> <li>Broadleaf stands had the highest N availability (higher amounts of <math>\text{NH}_4\text{-N}</math> in the forest floor) and tended to have the highest concentrations of microbial N, but levels of <math>\text{NO}_3\text{-N}</math> and net nitrification were not higher</li> <li>pH was higher and soil C:N ratio lower in the broadleaf stands</li> <li>Mixed stands had the highest rates of net N mineralization</li> </ul>                                         | Jerabkova et al. 2006       |
| <b>Southern Quebec</b>                                  | 50 and 124 yr-old boreal aspen and white spruce stands                                              | <ul style="list-style-type: none"> <li>Microbial N concentrations were higher under aspen stands than spruce stands</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                      | Bauhus et al. 1998          |
| <b>Quebec</b>                                           | 49, 77 and 123 yr-old southern boreal aspen-white spruce-paper birch stands                         | <ul style="list-style-type: none"> <li>For all stand ages forest floor pH was 0.5 units higher under aspen than other species</li> <li>Accumulation of organic matter and nutrients in the forest floor was generally greatest under spruce</li> <li>Net N mineralization and nitrification in the forest floor of the youngest stand were higher under broadleaf species than under spruce but in older stands there were no sig. differences in these parameters between broadleaf and conifer stands.</li> </ul> | Pare and Bergeron 1996      |
| <b>Northwestern Quebec</b>                              | 50 yr-old boreal aspen and white spruce stands                                                      | <ul style="list-style-type: none"> <li>Faster turn-over and higher accumulations of <math>\text{N-NO}_3</math> under aspen than white spruce stands</li> <li>High variability within forest types</li> </ul>                                                                                                                                                                                                                                                                                                        | Ste-Marie and Pare 1999     |
| <b>Northern Alberta</b>                                 | 70-130 yr-old boreal aspen and white spruce forests                                                 | <ul style="list-style-type: none"> <li>Aspen forest floors supported a larger microbial biomass with very different community structure than forest floors under white spruce or mixed spruce-aspen stands</li> </ul>                                                                                                                                                                                                                                                                                               | Hannam et al. 2006          |
| <b>Northern Alberta Same area as Hannam et al. 2006</b> | 80-140 yr-old boreal white spruce and aspen stands                                                  | <ul style="list-style-type: none"> <li>Forest floor bulk density, pH, and moisture content were lower under spruce stands than aspen stands</li> <li>Forest floors were deeper under spruce stands than aspen</li> <li>Total N, total P, available nitrate, basal respiration and microbial and root biomass sig. higher in aspen forest floors than spruce</li> <li>Conifer forest floors had sig. higher amounts of available P and sig. greater mesofauna and mite abundance compared with</li> </ul>            | Lindo and Visser 2003       |

|                                 |                                                                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                        |
|---------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|
|                                 |                                                                          | <ul style="list-style-type: none"> <li>• aspen forest floors</li> <li>• Initial <math>\text{NH}_4\text{-N}</math> concentrations in forest floors and amounts of <math>\text{NH}_4\text{-N}</math> mineralized after 6 weeks of incubation were not sig. diff. between spruce and aspen forest floors</li> <li>• <math>\text{NO}_3\text{-N}</math> availability and amount of <math>\text{NO}_3\text{-N}</math> mineralized were greater in aspen than conifer forest floors</li> </ul>               |                        |
| <b>Quebec</b>                   | 50 and 124 yr-old boreal aspen, birch and balsam fir-white spruce stands | <ul style="list-style-type: none"> <li>• Amount of N mineralized (expressed on an organic C basis) over the course of the experiment (282 days) was sig. higher in aspen and birch forest floors and mineral soils than under balsam-fir-white spruce stands</li> <li>• Ratio of C mineralized: N mineralized was greater in coniferous than broadleaf soils</li> </ul>                                                                                                                               | Cote et al. 2000       |
| <b>North-central Minnesota</b>  | 40-yr-old pure aspen and white spruce stands                             | <ul style="list-style-type: none"> <li>• Forest floor weight and bulk density did not vary between aspen and spruce</li> <li>• Similar N and P nutrient accumulations under spruce and aspen</li> <li>• Small to no differences in Mg and K nutrients in forests floors</li> <li>• In mineral soil P and K amounts were similar among the 2 species</li> </ul>                                                                                                                                        | Alban 1982             |
| <b>Northwestern Quebec</b>      | 70-80 yr-old black boreal spruce and aspen-black spruce stands           | <ul style="list-style-type: none"> <li>• Aspen presence accelerated nutrient cycling because of changes in total N, C:N ratio, forest floor depth, exchangeable cations, CEC, pH</li> <li>• Aspen presence was associated with higher exchangeable cations, CEC and pH of the forest floor and shallower forest floors</li> </ul>                                                                                                                                                                     | Legare et al. 2005a    |
| <b>Rocky Mountains Colorado</b> | Lodgepole pine and aspen                                                 | <ul style="list-style-type: none"> <li>• Higher rate of litter decomposition and N mineralization in forest floors under aspen than lodgepole pine</li> </ul>                                                                                                                                                                                                                                                                                                                                         | Stump and Binkley 1993 |
| <b>Quebec</b>                   | 56-89 year old aspen and jack pine stands                                | <ul style="list-style-type: none"> <li>• Forest floors under aspen had greater accumulations of almost all total and available nutrients than under pine on both coarse and fine-textured soils</li> <li>• FH layer was thicker, had a higher pH, and a lower C:N ratio under aspen than jack pine</li> <li>• In the upper (0-20 cm) mineral soil, there were no apparent differences in soil pH, C:N ratio, total and available N, P, K, Ca and Mg concentrations under aspen versus pine</li> </ul> | Ste-Marie et al. 2007  |

Table 10. A summary of studies comparing understorey vegetation composition and diversity among conifer, trembling aspen, and mixed conifer-aspen stands (after Cavard et al. 2011).

| Location                    | Conifer tree species                                                                     | Broadleaf tree species                                                                                                                          | Community composition (landscape level diversity)                                                                                                                                                                                                                                                                                                                                   | $\alpha$ diversity (stand level)                                                       | Reference                  |
|-----------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|----------------------------|
| <b>Alberta</b>              | <i>Populus tremuloides</i>                                                               | <i>Picea glauca</i>                                                                                                                             | Understorey composition of broadleaf, mixed and conifer different                                                                                                                                                                                                                                                                                                                   | S highest for mixed patches, then conifer, then broadleaf patches                      | Chavez and MacDonald 2012  |
| <b>Alberta</b>              | <i>Populus tremuloides</i> ,<br><i>Populus balsamifera</i>                               | <i>Picea glauca</i>                                                                                                                             | Non-vascular and shade-tolerant vascular plants associated with mixed and conifer plots. Heliophilous species associated with broadleaf-dominated plots.                                                                                                                                                                                                                            | S and H higher in broadleaf plots than mixed or conifer                                | Kembel and Dale 2006       |
| <b>Northwest Alberta</b>    | <i>Populus tremuloides</i> ,<br><i>Populus balsamifera</i>                               | <i>Picea glauca</i> , <i>Picea mariana</i>                                                                                                      | Understorey composition of broadleaved stands different from conifer and mixed. No indicator species for mixedwoods. Mixedwoods had greater total species richness across several stands.                                                                                                                                                                                           | $\alpha$ diversity higher in broadleaf than in conifer stands; mixedwoods intermediate | MacDonald and Fenniak 2007 |
| <b>Northwestern Ontario</b> | <i>Populus tremuloides</i> ,<br><i>Betula papyrifera</i>                                 | <i>Picea glauca</i> , <i>Picea mariana</i> , <i>Abies</i> ,<br><i>Balsamea</i> , <i>Pinus banksiana</i>                                         | Ground mosses associated with coniferous stands; vascular plant cover greater in broadleaf stands. Composition of mixedwoods intermediate between coniferous and broadleaf stands.                                                                                                                                                                                                  | Higher S in mixedwoods but only at stand age 72-90 years                               | Hart and Chen 2008         |
| <b>Ontario and Quebec</b>   | <i>Populus tremuloides</i> ,<br><i>Populus balsamifera</i> ,<br><i>Betula papyrifera</i> | <i>Picea glauca</i> , <i>Picea mariana</i> , <i>Pinus banksiana</i> , <i>Abies balsamea</i> , <i>Larix laricina</i> , <i>Thuja occidentalis</i> | Certain understorey species had affinities for broadleaved versus upland conifer stands versus lowland conifer stands but of the 410 understorey taxa included in the study, only 121 specific to a forest type and most vegetation species widespread throughout forest types. Upland conifer, aspen and birch stands had few species specific to them but balsam poplar had more. |                                                                                        | Carleton and Maycock 1981  |
| <b>Northwestern Quebec</b>  | <i>Populus tremuloides</i>                                                               | <i>Picea glauca</i> , <i>Abies balsamea</i>                                                                                                     | Vascular plant cover highest under broadleaf stands and decreased with increasing conifer content. Herb cover not related to stand composition. Shrub cover lower under conifer stands than aspen. Four species strongly associated with aspen; none with spruce-fir stands.                                                                                                        | S, H and J did not vary with stand type                                                | Legare et al. 2001;2002    |
| <b>Northwestern Quebec</b>  | <i>Populus tremuloides</i>                                                               | <i>Picea glauca</i> , <i>Picea mariana</i> , <i>Abies balsamea</i>                                                                              | Two species were specific to mixed conifer stands and 3 to aspen stands.                                                                                                                                                                                                                                                                                                            | S similar in mixed conifer and broadleaf stands. H highest in aspen stands             | Barthemucci et al. 2006    |

S = Species richness; H = species diversity (Shannon's index), J = species evenness

Table 11. Impacts of manipulating trembling aspen density in managed stands on understorey vegetation.

| Location                                                             | Treatment                                                                                                                                                                       | No. of years after treatment until vegetation assessment | Understorey vegetation response to aspen manipulation                                                                                                                                                                                                                                                                                                                                    | Reference                        |
|----------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|
| <b>BWBSmw<br/>75 km NW of Fort Nelson<br/>British Columbia</b>       | Complete aspen removal manual and chemical; 1.25 m radius aspen removal manual and chemical; aspen spacing; control                                                             | 7                                                        | Cover of shrubs and herb-fern-grass layers and frequency of occurrence of vegetation species not affected by treatment. <i>Rubus pubescens</i> had greater cover in chemical complete treatment than untreated control and aspen spacing treatments. <i>Calamagrostis canadensis</i> cover increased most where spaced, less where manual treatments and least with chemical treatments. | Kabzems, Harper and Fielder 2011 |
| <b>BWBSmw2<br/>Fort Nelson Forest District<br/>British Columbia</b>  | Shelterwood cut creating openings 40 and 113 m in diameter (1.25 and 3-4 times aspen height)                                                                                    | 3                                                        | Herb and moss cover not significantly altered after overstorey aspen removed in patches.                                                                                                                                                                                                                                                                                                 | Kabzems 2001                     |
| <b>BWBS<br/>Siphon Cr/ Bear Mtn<br/>British Columbia</b>             | Complete removal of aspen and thinning aspen to 5000 and 10000 SPH                                                                                                              | 17                                                       | Removing aspen did not increase herb or shrub cover. <i>C. canadensis</i> cover similar in all plots.                                                                                                                                                                                                                                                                                    | Kabzems et al. 2007              |
| <b>BWBSmw<br/>110 km NW of Fort St James<br/>British Columbia</b>    | 10 treatments involving incremental opening of a 45 yr-old aspen canopy to give aspen basal areas of 10, 20...100% of original stand                                            | 2                                                        | Cover of <i>C. canadensis</i> and <i>Epilobium angustifolium</i> increased as canopy opened up. <i>E. angustifolium</i> cover reached a maximum of 30% and <i>C. canadensis</i> 50% (vs. <5% where the most canopy cover)                                                                                                                                                                | Maundrell and Hawkins 2004       |
| <b>BWBS<br/>Fort Nelson<br/>British Columbia</b>                     | Removal of 120 yr-old aspen canopy                                                                                                                                              | 2                                                        | Removing aspen canopy increased understorey vegetation.                                                                                                                                                                                                                                                                                                                                  | Kabzems and Lousier 1992         |
| <b>BWBSmw<br/>Dawson Creek<br/>British Columbia</b>                  | Complete removal of balsam poplar with herbicide                                                                                                                                | 12                                                       | <i>C. canadensis</i> cover 58-73% where aspen removed with herbicide versus 39% in untreated control. Twice as much forage cover in control than herbicided areas but no. of forage species the same. Species diversity reduced after aspen removed with hexazinone. Species diversity not affected by aspen removal with glyphosate.                                                    | Harper et al. 1997               |
| <b>SBSdw3<br/>Ft. St. James Forest District<br/>British Columbia</b> | Complete removal of aspen with glyphosate                                                                                                                                       | 10                                                       | Removing aspen shifted plant community towards herbs. Species richness similar where aspen and no aspen.                                                                                                                                                                                                                                                                                 | Biring and Hays-Bayle 2000       |
| <b>Alberta</b>                                                       | 18-20 yr-old aspen canopy completely removed, partially removed (to double light transmission) and left intact                                                                  | 2                                                        | Partial aspen canopy removal shifted plant community towards more shrubs; grass production not substantially increased. Complete aspen removal shifted plant community towards graminoids                                                                                                                                                                                                | Powell and Bork 2006             |
| <b>Alberta</b>                                                       | Glyphosate used to completely remove all vegetation, remove woody plants only, remove all vegetation in 2- m radius circle, and remove woody vegetation in a 2-m radius circle. | 12                                                       | Removing aspen and woody vegetation increased <i>C. canadensis</i>                                                                                                                                                                                                                                                                                                                       | Man et al. 2008                  |

Table 12. A summary of studies comparing avian composition and diversity between mixedwoods and pure stands. (from Cavard et al. 2011)

| Region                                      | Conifer tree species                                                                                                                                                    | Broadleaf tree species                                                                | Community composition (stand or landscape level diversity)                                                                                                         | $\alpha$ diversity (stand level)                                                                                                         | Reference                |
|---------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| <b>Western North American boreal forest</b> | <i>Picea glauca</i>                                                                                                                                                     | <i>Populus tremuloides</i>                                                            | Bird communities of mixed forests intermediate between pure aspen and pure spruce forests. No bird species unique to mixedwoods.                                   | Higher S in mixedwoods                                                                                                                   | Schieck and Song 2006    |
| <b>Central Saskatchewan</b>                 | <i>Picea glauca</i> ,<br><i>Picea mariana</i> ,<br><i>Pinus banksiana</i>                                                                                               | <i>Populus tremuloides</i>                                                            | Most species generalists but some species found mainly in mixed stands or had greater abundance there.                                                             | Higher S in mixed stands                                                                                                                 | Hobson and Bayne 2000    |
| <b>Central Saskatchewan</b>                 | <i>Picea glauca</i> ,<br><i>Picea mariana</i> ,<br><i>Pinus banksiana</i>                                                                                               | <i>Populus tremuloides</i> ,<br><i>Populus balsamifera</i>                            | Some bird species found in greater abundance or exclusively in mixedwoods.                                                                                         | For mature stands, higher S in <i>Pinus-Populus</i> mixtures than pure pine. For overmature stands, no difference in S among stand types | Kirk and Hobson 2001     |
| <b>Central Saskatchewan</b>                 | <i>Picea glauca</i> ,<br><i>Picea mariana</i> ,<br><i>Abies balsamea</i> ,<br><i>Larix laricina</i>                                                                     | <i>Populus tremuloides</i> ,<br><i>Populus balsamifera</i> , <i>Betula papyrifera</i> | Home ranges of owls included higher proportions of mature and old mixedwoods.                                                                                      | None                                                                                                                                     | Mazur et al. 1998        |
| <b>Northwestern Quebec</b>                  | <i>Picea glauca</i> , <i>Picea mariana</i> , <i>Pinus banksiana</i> , <i>Abies balsamea</i> , <i>Pinus resinosa</i> , <i>Thuja occidentalis</i> , <i>Larix laricina</i> | <i>Populus tremuloides</i> , <i>Betula papyrifera</i>                                 | Natural landscapes, which had greater proportions of mixed stands, had higher abundance of several bird species identified as having an affinity for mixed stands. | No difference in diversity among landscapes differing in amount of mixed forests                                                         | Drapeau et al. 2000      |
| <b>Northwest Territories</b>                | <i>Picea glauca</i> , <i>Pinus banksiana</i> , <i>Larix laricina</i>                                                                                                    | <i>Populus tremuloides</i> ,<br><i>Populus balsamifera</i> , <i>Betula papyrifera</i> | Mixed and coniferous forests had bird communities similar to one another but distinct from deciduous forests.                                                      | Higher S in mixed than in pure deciduous, No difference in F.                                                                            | Machtans and Latour 2003 |

S = Species richness; H = species diversity (Shannon's index), J = species evenness

Table 13. Influence of trembling aspen cover on frost damage levels to white spruce.

| Location                                                           | Frost incidence                                                                                                                                                                         | Reference                    |
|--------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|
| <b>BWBSmw subzone</b><br>80 km SW of Dawson Cr<br>British Columbia | 14% of seedlings damaged in clearcut<br>0% damaged under 40-80 yr old aspen                                                                                                             | DeLong 2000                  |
| <b>BWBS subzone</b><br>Dawson Cr /Sierra Rd<br>British Columbia    | 5 frost events in clearcut<br>No events under 39 yr old aspen canopy or in thinned aspen plots<br>(1000,2000, 3000 SPH aspen)                                                           | Comeau et al.<br>2009a       |
| <b>BWBS subzone</b><br>Fort Nelson<br>British Columbia             | No frost damage under 120 yr-old aspen or in open but more potential<br>events in open (i.e. more times when air temp <0° C 100 cm above<br>ground)                                     | Kabzems and<br>Lousier 1992  |
| <b>Alberta</b>                                                     | Higher frost incidence where no aspen cover than in untreated aspen<br>stand. Frost levels intermediate and similar to each other where 500 and<br>1500 SPH aspen.                      | Filipescu and<br>Comeau 2011 |
| <b>Alberta</b>                                                     | Frequency of frost incidence increased rapidly from edge of an aspen<br>stand into adjacent canopy.                                                                                     | Voicu and Comeau<br>2006     |
| <b>Alberta</b>                                                     | No. of nights with frost 49 for clearcut, 27 for untreated mixedwood and<br>28 for shelterwood.                                                                                         | Man and Lieffers<br>1999b    |
| <b>Ontario</b>                                                     | 75% of seedlings damaged in clearcut<br>50% damaged in 18 m diameter circle, 18 m wide strip, and 9 m wide strip<br>2% damaged in 9 m wide circle and under uncut 40 yr old aspen stand | Groot and Carlson<br>1996    |

Table 14. Incidence of hare damage in mixed white spruce-broadleaf stands compared to in the open.

| Location                                                           | Broadleaf species | Conifer species | Stand age                       | % of spruce seedlings damaged                                          | Reference               |
|--------------------------------------------------------------------|-------------------|-----------------|---------------------------------|------------------------------------------------------------------------|-------------------------|
| <b>BWBSmw subzone</b><br>Dawson Creek<br>British Columbia          | Balsam poplar     | White spruce    | 12                              | 50% - untreated mixed stand<br>0 % - all aspen removed with glyphosate | Harper et al. 1997      |
| <b>BWBSmw subzone</b><br>Peace River<br>British Columbia           | Trembling aspen   | White spruce    | 10                              | 63% - 10000 SPH aspen<br>39% - 5000 SPH aspen<br>3% - 0 aspen          | Coopersmith et al. 2000 |
| <b>BWBSmw subzone</b><br>80 km SW of Dawson Cr<br>British Columbia | Trembling aspen   | White spruce    | Aspen 40-80 yrs<br>Spruce 7 yrs | 62% - under intact aspen<br>13% - clearcut                             | DeLong 2000             |
| <b>BSBS subzone</b><br>Dawson Cr/<br>Sierra Rd<br>British Columbia | Trembling aspen   | White spruce    | Aspen 39 yrs<br>Spruce 10 yrs   | Damage occurred only where adjacent to<br>protective cover             | Comeau et al. 2009a     |

Table 15. Some historic uses of broadleaf trees in interior and northern British Columbia (Source: Parrish et al. 1996; MacKinnon et al. 1999)

| Tree species            | Tree part                                                                                    | Uses                                                                                                                                                                                                                                        |
|-------------------------|----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Trembling aspen</b>  | Bole/wood                                                                                    | <ul style="list-style-type: none"> <li>• Dugout canoes</li> <li>• Tent poles</li> <li>• Drying racks</li> <li>• Fuel</li> </ul>                                                                                                             |
|                         | Rotten wood                                                                                  | <ul style="list-style-type: none"> <li>• Diapers</li> <li>• Cradle linings</li> </ul>                                                                                                                                                       |
|                         | Bark and roots                                                                               | <ul style="list-style-type: none"> <li>• Chewed and applied to wounds</li> </ul>                                                                                                                                                            |
|                         | Cambium                                                                                      | <ul style="list-style-type: none"> <li>• Food</li> </ul>                                                                                                                                                                                    |
| <b>Black cottonwood</b> | Wood                                                                                         | <ul style="list-style-type: none"> <li>• Canoes</li> <li>• Fuel</li> <li>• Masks</li> </ul>                                                                                                                                                 |
|                         | Bark                                                                                         | <ul style="list-style-type: none"> <li>• Temporary cabins</li> </ul>                                                                                                                                                                        |
|                         | Roots                                                                                        | <ul style="list-style-type: none"> <li>• Rope</li> </ul>                                                                                                                                                                                    |
|                         | Cambium and inner bark (early spring)                                                        | <ul style="list-style-type: none"> <li>• Food in spring</li> <li>• Medicinal tea</li> <li>• Soap</li> </ul>                                                                                                                                 |
|                         | Bud resin                                                                                    | <ul style="list-style-type: none"> <li>• Ointment for small cuts</li> <li>• Glue</li> </ul>                                                                                                                                                 |
|                         | Seed fluff                                                                                   | <ul style="list-style-type: none"> <li>• Pillow stuffing</li> </ul>                                                                                                                                                                         |
| <b>Balsam poplar</b>    | Bark                                                                                         | <ul style="list-style-type: none"> <li>• Wound poultice</li> <li>• Worm medicine</li> </ul>                                                                                                                                                 |
|                         | Cambium                                                                                      | <ul style="list-style-type: none"> <li>• Food</li> </ul>                                                                                                                                                                                    |
| <b>Paper birch</b>      | Wood                                                                                         | <ul style="list-style-type: none"> <li>• Digging and gambling sticks</li> <li>• Snowshoe frames</li> <li>• Other utensils</li> </ul>                                                                                                        |
|                         | Bark from pole-sized trees and larger (sheets stripped off trees & sewn together with roots) | <ul style="list-style-type: none"> <li>• Canoes</li> <li>• Toboggans</li> <li>• Baskets</li> <li>• Dishes</li> <li>• Snow goggles</li> <li>• Moose calls</li> <li>• Baby cradles</li> <li>• Food wrap</li> <li>• Envelop corpses</li> </ul> |
|                         | Leaves                                                                                       | <ul style="list-style-type: none"> <li>• Soap and shampoo</li> </ul>                                                                                                                                                                        |

**Appendix 1.** Growth and yield results based on planting trials where spruce and aspen are established together in intimate mixtures.

**Study no. 1** (Kabzems, Harper and Fielder 2011)

**Species combination:** White spruce-trembling aspen

**Location:** BWBSmw subzone; productive site; northeastern British Columbia.

**Aspen manipulation treatments:** Complete chemical control; complete manual control; creation of small gaps chemically or manually (1.25 m radius); aspen thinning; untreated control (20,600 SPH aspen (22,800 SPH total broadleaves) at end of measurement period). Treatments were done three years after planting except thinning which was done seven years after planting.

**Growth and yield results:** **White spruce:** Spruce survival was good on all treatment plots, even where aspen was dense. Spruce height growth, diameter growth, volume, and HDR did not differ among treatments seven years after treatment (age 11) except where virtually all aspen were eliminated (complete chemical removal). The latter treatment increased spruce size and reduced HDR. **Aspen:** Seven years after treatment, aspen height and diameter did not differ significantly between any of the treatments (341-653 cm height and 2.0-5.2 cm diameter), although the trend was for smaller aspen in the manual complete control plot than the others.

**Summary:** Results show that spruce can grow within a wide range of aspen densities at seven years of age, without an effect on its size, HDR or survival.

**Planting Study no. 2** (Kabzems et al. 2007 and Coopersmith et al. (2000)

**Species combination:** White spruce-trembling aspen

**Location:** BWBS zone; medium to rich sites; Siphon Creek and Bear Mountain; northeastern British Columbia

**Aspen manipulation treatments:** Densities of 0, 5000, and 10000 SPH aspen were created five years after aspen suckered and spruce was planted. Ten years later, some plots received a further reduction of aspen density to 1000 and 2000 SPH but only two years passed until the spruce were remeasured.

**Growth and yield results:** **White spruce:** Complete removal of aspen increased height, diameter, and stem volume of white spruce compared to the 5000 and 10000 SPH treatments at age 14-17 years, with no significant difference between the two latter treatments. Spruce volume was reduced by 50% where 1000-10,000 SPH of aspen were retained (although the 1000 and 2000 SPH density was created only 2 years before measurement). Volume of spruce and aspen combined was largest where 1000 SPH of aspen were retained. At a slightly earlier measurement at the Siphon Creek site, Coopersmith and Hall (1999) noted that excellent growth of spruce is possible under aspen canopies but 5000 SPH of aspen is too high a density for use in mixedwood prescriptions. Light levels will be too low for optimum spruce growth and whipping damage to spruce leaders will be severe as it grows up through the canopy. At this earlier measurement date, HDR of spruce was 49 in the complete removal area, 60 for the 5000 SPH aspen plot and 75 for the 10,000 SPH aspen plot. HDR differences were expressed early and changed rapidly as the vegetation developed. More time is needed before the effects of thinning to 1000 and 2000 SPH of aspen can be properly evaluated. **Aspen:** Aspen survival over the measurement period was

91-100% at Siphon Creek and 96-100% at Bear Mountain. Following thinning, diameter growth of the remaining aspen stems increased, with a trend of increasing average diameter with decreasing aspen density, although the differences between treatments were not significant at Siphon Creek. There were no post-treatment differences in aspen height across the treatments.

**Projections:** Predictions of future growth up to age 80 were made with the Mixedwood Growth Model (version MGM 2002a) using 10000 SPH of aspen, 1200 SPH of spruce, and 1200 SPH of spruce in combination with each of 1000, 2000, 5000 and 10000 stems per hectare of aspen. Future yields for spruce were predicted to be highest for the pure spruce stand but spruce volume production appeared to be relatively insensitive to a wide range of aspen densities greater than 1000 SPH. The threshold for aspen density to affect white spruce growth was suggested to be below 1000 SPH of aspen. Mixtures with moderate aspen densities were predicted to produce considerably more total volume than pure spruce stands (up to 21% more for the stand with 1000 stems per hectare of aspen). The model indicates that retaining 1000-10,000 SPH of aspen could increase total volume production but spruce merchantable volume would be only about half that of the pure spruce regime. The model predicts convergence of mixedwood stand types with time due to self-thinning of the aspen. However, stands starting with more aspen will continue to have more aspen and less spruce. In mixed stands, growth of the spruce is predicted to vary less than the aspen component although spruce growth increases with decreasing aspen density.

**Summary:** Removing aspen shifted total volume towards the spruce component.

### **Planting study no. 3** (Coopersmith et al. 2000)

**Species combination:** White spruce-trembling aspen

**Location:** BWBSmw1 variant; Bear Mountain Mixedwood Trial, Peace River, northern British Columbia

**Aspen manipulation treatments:** 0, 5000, and 10,000 SPH aspen

**Growth and yield results:** *White spruce:* Ten years after planting, white spruce in plots without aspen were significantly taller than seedlings in either the 5000 or 10,000 SPH aspen plots. The spruce had been planted under dense 2 m tall aspen suckers. There was no significant difference in spruce height between the 5000 and 10,000 SPH aspen densities. Much more hare damage occurred in the aspen plots than in the open pure spruce stand which intensified the negative effect of aspen density on seedling height. The proportion of seedlings damaged by hares was 39% in the 5000 SPH plot and 63% in the 10000 plot but only 3% where there was no aspen. Quantitative height and diameter values for the different treatments were not tabulated in the report and volume data was not included. *Aspen:* Aspen survival over the measurement period was 96-100%. Following thinning, diameter growth of the remaining stems increased with a trend of increasing average diameter with decreasing aspen density. There were no post-treatment differences in aspen height across the treatments.

### **Planting study no. 4** (Biring and Hays-Byl 2000)

**Species combination:** White spruce-trembling aspen

**Location:** SBSdw3 subzone; medium to rich site; Tillich River, British Columbia

**Aspen manipulation treatments:** Following mechanical site preparation, white spruce were planted and one year later aspen regrowth was treated with glyphosate in one area and left untreated on the other (control).

**Growth and yield results: *White spruce:*** Ten years after treatment, the 11 year-old spruce seedlings were significantly larger where there was a minimal aspen component compared to the control (188 versus 133 cm in height, and 3.7 versus 2.1 cm in diameter, respectively). HDR of the seedlings was significantly lower in the herbicided plot (53) than in the mixed control stand (63). Survival was high (84%) in both the treated and control plots but vigour was better without aspen (28% versus 57% of trees with poor vigour in the treated area and control, respectively). Both plots met the minimum stocking standard at age 10 based on 1995 free-growing (FG) stocking standards, but the control had no free-growing trees, compared to 950 FG SPH in the treated plot (even though there were 1100 aspen SPH). The control requires further treatment to meet FG requirements. ***Aspen:*** At the end of the measurement period (11 years after planting), the untreated control was a two-storied mixedwood dominated by aspen (46% cover; 20,200 SPH). Height of the tallest aspen was 8.4 m, while the spruce were about 1.3 m tall on average. The glyphosate treated plot was close to a pure single-storied conifer stand, with only 3% cover of aspen (1100 SPH; height data not available).

**Projections:** Spruce volume at rotation was predicted by MGM simulations to be 235% greater where aspen was removed than in the mixed control stand, with rotation age projected to be reduced from 100 to 70 years. However, broadleaf volume was reduced by 92% in the treated area, resulting in a lower projected total volume than in the control at rotation age. Total volume at rotation age was projected to be 539 m<sup>3</sup>/ha in the mixed control stand compared to 408 m<sup>3</sup>/ha in the predominantly conifer stand at 90 years.

**Summary:** Allowing aspen to dominate white spruce in a mixed stand is projected to increase total stand volume at rotation, but reduce conifer volume. If the objective is to have a conifer-dominated stand at rotation age, further treatment would be needed (brushing and spacing of aspen).

#### Planting study no. 5 (DeLong 2007)

**Species combination:** White spruce-trembling aspen

**Location:** SBSmk1 subzone, Nechako Plateau, 60 km northwest of Prince George, British Columbia

**Aspen manipulation treatments:** Plots were established in an untreated control and across a gradient of natural aspen competition levels that had resulted from hack and squirt one year before logging. Year five aspen densities were 2300-32,175 (none of the plots had densities between 7100 and 18,800 SPH).

**Growth and yield results: *White spruce:*** Trembling aspen density, interspecific neighbourhood competition, soil type, humus/displacement depth, moisture regime and aspect were significant factors in the regression models for white spruce size, and the models accounted for 19-28% of spruce size. The single variable explaining the most variation in white spruce seedling size was humus depth. Soil-related factors, rather than competition, were responsible for most of the height growth differences between seedlings growing under the various aspen density levels. However, most of the diameter growth differences were related to vegetation competition. Thresholds were identified to help quantify levels at which brushing may be helpful. For white spruce diameter growth, a significant threshold was identified at an aspen competition value (AC) of about 50 (equivalent to 5% cover of aspen with a mean height of

100 cm, with less than 1% cover within 100 cm of apex of the response tree measured after the third growing season). AC is calculated as  $AC = \sum(C * H) / P$  where C = percent ground cover of aspen, H = average aspen height (cm) and P = proximity (dm) of aspen tree to crop tree. Regression analysis indicated that above an aspen density threshold of 2500 SPH (measured after 5 growing seasons) optimum growth of white spruce may not be achieved.

#### **Planting study no. 6** (Man et al. 2008)

**Species combination:** White spruce-trembling aspen

**Location:** Boreal forest, White court, Alberta

**Aspen manipulation treatments:** Glyphosate treatments were applied in various ways: complete control of all vegetation; complete control of woody plants only; spot control (2 m radius) of all vegetation; spot control of woody plants only. An untreated control was left.

**Growth and yield results:** **White spruce:** Survival was good (91%) and not significantly different among the treatments. Removing aspen competition completely or in a 2 m radius around white spruce seedlings (with or without herbaceous plant treatment) had minimal effect on white spruce height growth three years after planting; height growth was about the same as where spruce was growing within a dense (>44,000 SPH) regenerating untreated aspen stand. The density of aspen in the treated areas was not reported. Removing the aspen had a strong effect on white spruce root collar diameter with best growth where the aspen was completely removed (three times greater increment than the control). HDR of white spruce was lowest for the broadcast herbicide treatment (33), higher for the spot treatments (38-46) and highest for the control (61). Spot treatments reduced exposure of spruce seedlings to summer and winter frost injury. **Aspen:** No information.

**Summary:** Spruce seedlings performed satisfactorily where enough aspen was retained to result in a mixed stand (spot treatments), but grew fastest where all aspen was removed.

#### **Planting study no. 7** (Bokalo et al. 2012)

**Species combination:** White spruce-trembling aspen

**Location:** Four locations in Alberta and Saskatchewan

**Aspen manipulation treatments:** Spruce was planted in recently logged clearcuts where aspen regeneration was already established. For the first five years aspen was controlled by clipping or with mulch mats to minimize early spruce mortality then at spruce age five aspen was spaced to 0, 200, 500, 1500 and 4000 SPH. An untreated control was left which had a density of 74,000 SPH of aspen initially but it self-thinned to 22,800 SPH aspen after 9 years.

**Growth and yield results:** **White spruce:** Spruce height was similar under all aspen densities at age 10 (5 years after treatment) (131-150 cm), but at age 20 it was significantly shorter in the control (298 cm) than the thinned plots (375-435 cm). At this time there was no significant difference in height among the 0-4000 SPH thinning treatments. At both 10 and 20 years root collar diameter decreased with increasing aspen density and the magnitude of differences increased with age. Average root collar diameter ranged from 4.51 cm in the control to 9.57 cm in the complete removal treatment. It decreased significantly with each increase in aspen density except for the 0 and 200 SPH treatments

which were similar to each other and the 200 and 500 SPH treatments which were similar to each other. Average HDR increased with increasing aspen density and this trend was apparent both at age 10 and 20. It increased significantly with each increase in aspen density except the 200 and 500 SPH treatments which were similar to each other and the 4000 PH and control treatments which were similar to each other. At age 20, HDR was 44 where aspen density was 0 SPH and 66 in the control. At age 20, average crown width of spruce did not significantly differ significantly among the 0, 200, 500 and 1500 SPH treatments but was significantly lower for the 4000 SPH treatment and lowest for the control. **Aspen:** Aspen self-thinned rapidly when the starting density was high but when initially lower it increased for 5 years before decreasing. Fifteen years after spacing aspen densities were beginning to converge. Aspen spacing had little effect on aspen height although 15 years afterward height was significantly lower in the control (1030 cm) than the spaced plots (1131-1181 cm). Aspen root collar diameter, crown width, and height to live crown declined and HDR increased with increasing density.

**Summary:** White spruce growth and HDR were not affected by low aspen densities (0-500 SPH), but started to be affected at 1500 SPH, were affected to a greater degree at 4000 SPH and performed worst at very high densities (untreated stands).

#### **Planting study no. 8 (Pitt, Mihajlovich and Proudfoot 2004)**

**Species combination:** White spruce-trembling aspen

**Location:** Twelve blocks on Alberta boreal mixedwood sites

**Aspen manipulation treatments:** Broadcast glyphosate and a portion of each block retained as untreated control.

**Growth and yield results:** **White spruce:** Plantations were assessed at age 4-22 years-old (average eight years), at an average of five years since treatment (range 1-12 years). Height and diameter growth of planted spruce responded positively to release treatments. The single release treatments resulted in a significant increase in maximum stem height of spruce (170 cm in the treated area versus 145 cm in the controls) but not average stem height (114 and 107 cm in the treated and control areas, respectively). Average spruce diameter at 15 cm above the ground was 1.5 cm on the controls compared to 1.9 cm on the treated plots. HDR and survival data was not available. **Aspen:** Untreated plots were dominated by aspen with the tallest trees just over 4 m in height and 3.8 cm stem diameter. Aspen stem densities were variable but averaged nearly 9000 SPH, giving an average stem volume approaching 30 m<sup>3</sup>/ha at age eight. The untreated plots also contained about 3000 SPH of balsam poplar, 2000 SPH of white birch, and 1000 SPH of natural lodgepole pine, natural white spruce, and the planted white spruce. Total basal area on untreated areas averaged 10.6 m<sup>2</sup>/ha; 70% of this was aspen and 88% was broadleaf. These could be considered "broadleaf stands." Treated plots had about 10% as much aspen volume as the untreated plots and less than 1000 SPH aspen, which were less than half the size of aspen in the control. Treated plots also had 2200 SPH of natural lodgepole pine and about 1000 SPH of balsam poplar and white birch. Total basal area on the treated areas averaged 4.7 m<sup>2</sup>/ha and of this 43% was white spruce and 75% was conifer. These could be considered "conifer-dominated mixedwoods." Conifer volume at age five was three times higher in treated than untreated plots (5.7 m<sup>3</sup>/ha versus 2.1 m<sup>3</sup>/ha, respectively), but total broadleaf tree volume was only 3.4 m<sup>3</sup>/ha in the treated areas compared to 31.2 m<sup>3</sup>/ha in the controls.

**Projections:** The MGM model projected that the untreated stand will stay broadleaf-dominated over a 100 year period. Total aspen volumes will peak at age 60-70 at  $350 \text{ m}^3/\text{ha}$  at which time conifer volume will be about  $100 \text{ m}^3/\text{ha}$ . After 70 years, conifer volume won't increase much and broadleaf volume will go down considerably. Conifer volume is estimated to make up only 22% of the stand basal area ( $54 \text{ m}^2/\text{ha}$ ) and density (790 SPH). Both broadleaf and conifer trees are estimated to average 41 cm in DBH at 70 years, suggesting that untreated stands may offer reasonable solid wood opportunities if broadleaf trees are marketable. Treated stands (one herbicide release treatment) are projected to stay conifer-dominated with about 20% of the stand basal area and density from broadleaf stems. Although the conifer component will likely increase in volume beyond 100 yrs, total volume is estimated to equal the projected high for the untreated stand by about age 80. At this time an average of  $360 \text{ m}^3/\text{ha}$  conifer volume and  $90 \text{ m}^3/\text{ha}$  of broadleaf volume will be available (total stand volume  $450 \text{ m}^3/\text{ha}$ ). Thus it would take at least 10 years longer for the treated stand to attain the same total volume as untreated stands, although a much higher conifer volume will be obtained. Average piece size in the conifer-dominated stands is projected to be smaller than for the mixed stands (23 cm for both conifers and broadleaf trees) which would potentially support pulp and small log markets. In the treated stands, broadleaf volume is projected to slowly increase for 100 years in the treated stands without declining. Model simulations in which all or nearly all of the broadleaf trees were removed produced virtually the same total volume as treatments that retained broadleaf stems, but conifer release amounted to trading broadleaf volume for conifer volume. Other scenarios, such as having two herbicide treatments, or including precommercial or commercial thinnings were projected to produce similar total volumes over an 80 yr rotation as the untreated or pure conifer approaches, but the percentage of volume that is conifer, density of conifers and broadleaf trees, and average piece size was projected to differ among regimes. In short, including broadleaf trees in the managed stands didn't improve total volume that could be obtained, but maximum volume was reached sooner and piece size of conifers and broadleaf trees were a lot bigger. Volume over age graphs are depicted in the paper for eight different management scenarios. They show the projected coniferous and broadleaf volume, density and DBH of conifers and broadleaf trees at different ages on the way to rotation.

#### **Planting study no. 9 (Pitt et al. 2010)**

**Species combination:** White spruce-trembling aspen

**Location:** Alberta and Ontario

**Aspen manipulation treatments:** Aspen density was manipulated with seven different herbicide treatments ranging from complete annual vegetation removal, to removal of just herbs or just woody vegetation, and removal treatments within a 2 m radius of spruce seedlings. Controls included a plot where spruce was planted but herbicide was not applied and one where nothing was done (no herbicide, no planting).

**Growth and yield results: *White spruce:*** Five year spruce survival was similar for all treatments (89%). The percentage of trees that were healthy varied from 43-83% with the highest proportion tending to be in the 2 m radius removal treatments. After five growing seasons, untended spruce were the shortest and had the smallest root collar diameter. Complete removal, woody removal only, and 2 m radius removal resulted in similar spruce sizes. There was no difference in spruce height response where

vegetation removal was done for four years rather than two years. Five years after treatment, spruce stem volume was greatest where there was complete vegetation removal, and half as much where there was no treatment. **Aspen:** Aspen cover in the controls increased linearly over time to reach just over 50% in year five although a hail storm in year three at the Alberta site markedly reduced aspen cover and curbed development rates that were exceeding those in Ontario. Natural self-thinning reduced aspen density to 59,000 SPH in year five in Alberta, or three times that of the level in Ontario. Year five codominant aspen height in Alberta ranged from 285-333 cm across the different treatments and from 315-432 across the treatments in Ontario. The tallest aspen were in the controls where no spruce was planted (pure aspen stands). Average aspen diameter ranged from 3.2 to 4.4 cm across the treatments with the smallest diameters in the control where spruce was planted. Radial treatments reduced aspen cover and density by approximately 50% and codominant aspen in these plots were 20% shorter than those in the control. Whole-plot treatments eliminated aspen.

**Summary:** These short-term results indicate that leaving a broadleaf component (i.e. the radius removal treatments) may be a successful alternative to complete broadleaf removal for growing white spruce.

#### **Planting study no. 10** (Pitt and Bell 2005)

**Species combination:** White spruce-trembling aspen

**Location:** Productive site, Fallingsnow, Ontario

**Aspen manipulation treatments:** Manual cutting (brush saw) (in which suckering doubled aspen density resulting in 78% broadleaf stocking); mechanical cutting (Sylvan) (in which suckering doubled aspen density resulting in 83% aspen stocking); aerial glyphosate (where most treated aspen were completely killed but imperfect herbicide application resulted in missed strips (16% broadleaf stocking)); aerial triclopyr (where top-kill occurred but total mortality was uncommon (66% broadleaf stocking)), and untreated control (72% broadleaf stocking).

**Growth and yield results: *White spruce:*** Seven years after treatment, survival of white spruce seedlings was 12% lower in the control than the treated plots. The dominant untended spruce were no smaller than where treatments were done but there was evidence of growth suppression in other trees. On average, spruce released by triclopyr were the largest. The control had the highest total basal area ( $5.2 \text{ m}^2/\text{ha}$ ) and volume ( $10.7 \text{ m}^3/\text{ha}$ ) at age 10, and the highest aspen basal area but the lowest conifer basal area, which comprised only 20% of the total. Broadcast glyphosate application produced conifer-dominated stands which had the lowest total basal area ( $1.7 \text{ m}^2/\text{ha}$ ) and the lowest aspen basal area. Relatively low planting densities (1350 SPH) and removal of most aspen created very open conditions that threaten overall productivity and stem quality in the glyphosate plots. Spruce basal area was similar between the two herbicided plots where it was 108% greater than in the control. Spruce basal area in the two cut plots was 67% greater than the control, but aspen was still expected to dominant the stands because cutting doubled its abundance. Stem volume followed similar trends to basal area. **Aspen:** Manual and mechanical cutting resulted in suckers that doubled aspen density. In year seven, aspen was twice as tall as the spruce in the control, aspen and spruce had similar heights to each other in the cut and triclopyr plots (but in the cut treatments aspen density was higher), and spruce was taller than the aspen in the glyphosate plot. Stands are expected to develop the following ways: Control - Future single tree release of spruce may allow it to grow well enough to develop into a stand that could support a

two-pass harvesting system. Manual or mechanical cutting - As the stands mature they will likely become broadleaf dominated. Triclopyr release - Temporary reduction of aspen growth allowed spruce to obtain near-optimal height growth without jeopardizing the ability to become a mixed stand. Glyphosate release – Much of the stand is expected to remain conifer-dominated but 23% of the stand was left untreated due to imperfect herbicide application so the block would likely not pass regeneration standards without a second treatment. The untreated areas are likely beneficial for diversity and wildlife habitat. Leaving strips untreated may be a desirable part of a prescription.

#### **Planting study no. 11** (Fleming and Smith 2011)

**Species combination:** White spruce-trembling aspen

**Location:** Ontario

**Aspen manipulation treatments:** Two types of site preparation with and without herbicide application one year later.

**Growth and yield results:** *White spruce:* Herbicide use one year after blade or barrel scarification greatly reduced broadleaf presence but did not significantly increase stand level biomass of planted white spruce over the long term (41 years), compared with no herbicide release. Barrel scarification with herbicide reduced year 41 total stand level biomass and aspen biomass and had no effect on spruce biomass compared with the barrel treatment without herbicide. Blade scarification with herbicide had no effect on total biomass or spruce biomass compared to the blade and non-herbicide plots but resulted in less aspen biomass than the blade scarification treatment without herbicide. The lack of response in spruce biomass production was a result of lower survival in the herbicided plots which was suggested to be due to increased physiological stress (e.g., frost damage, sunscald, and winter desiccation). *Aspen:* The herbicide treatments decreased year 41 broadleaf biomass by 6-10 times and density by 4-5 times compared to the non-herbicided plots. In the non-herbicided barrel scarified areas, year 41 aspen density was one half that of the year 19 aspen density (2027 versus 861 SPH). In the herbicided areas aspen density decreased by about four times over the same period (from 729 to 208 SPH). In the non-herbicided blade scarified areas, year 41 aspen density decreased by about four times from year 19 to year 41 (from 4165 to 1041 SPH). In the herbicided areas density was less than half (139 SPH) in year 41 compared to year 19 (305 SPH).

**Summary:** These results show that total stand productivity can benefit by using silviculture treatments that promote mixed stands (i.e. retain more aspen) rather than treatments such as herbicide use that results in large decreases in the broadleaf component of stands.

#### **Planting study no. 12** (Bell, Dacosta et al. 2011)

**Species combination:** White spruce-trembling aspen

**Location:** Ecosystem Project Fallingsnow and other research sites in Ontario

**Aspen manipulation treatments:** (1) Complete removal of aspen with glyphosate (0 SPH aspen, 0 SPH other broadleaf); (2) aerial application with glyphosate (1028 SPH aspen, 417 SPH other broadleaf); (3) continuous removal of aspen with brush saws (1778 SPH aspen, 1222 SPH other broadleaf); (4) brush saw (5333 SPH aspen, 1000 SPH other broadleaf); (5) mechanical cutting - Sylvan (6139 SPH aspen, 2028

SPH other broadleaf); (6) aerial triclopyr application (3028 SPH aspen, 1778 SPH other broadleaf), and (7) untreated control (5083 SPH aspen, 778 SPH other broadleaf). The numbers in parentheses are the densities of aspen and other broadleaf trees >130 cm tall in year 10. Spruce density ranged from 1278-2278 SPH in year 10 and density of other conifers was 56-806 SPH.

**Results: *White spruce:*** White spruce was grown in varying mixtures with trembling aspen and other broadleaf trees. Gross total volume of varying mixtures of white spruce and aspen were compared to untreated spruce-aspen mixedwoods ten years after aspen was cut or chemically treated (stand age 20 years). At age 20, ten years after aspen was treated, gross total volume of spruce where aspen was completely removed with glyphosate was 202% greater than on the untreated control. Where triclopyr was aerially applied, gross total volume of spruce was 127% greater than on the control. The other treatments had no significant effect on spruce gross total volume at stand age 20. Gross total aspen volume was significantly reduced by 47-100% by the treatments. Total stand gross volume at age 20 was significantly less (29-66% less) for all treatments compared to the control except aerial spray triclopyr.

***Aspen:*** Pre-treatment heights averaged 240 cm for aspen and 95 cm for spruce. Broadleaf development is not discussed in the paper. See "Aspen manipulation treatments" for densities of aspen and other broadleaf trees in year ten.

**Projections:** Yield curves (Penner et al. 2008; cited by Bell et al. 2011) were used to predict net merchantable volumes at age 60. Projections indicated that spruce net merchantable volume at age 60 would range from 127-291% greater on the treated areas than the control. Aspen net merchantable volume at 60 years was projected to be lower in all treatments than the control (23-100% lower) (lowest for the continuous removal glyphosate and continuous removal brush saw). Compared to the control, total stand net merchantable volume at age 60 was projected to be 29% lower for the two glyphosate treatment, 13% lower for continuous removal with brush saws, 7% lower for aerial spray with triclopyr, 15% higher for brush saw, and 31% higher for mechanical cutting.

#### Planting study no. 13 (Fu et al. 2007)

**Species combination:** White spruce-trembling aspen

**Location:** Ontario

**Aspen manipulation treatments:** Glyphosate; untreated control

**Growth and yield results: *White spruce:*** Fifteen years after treatment, aspen control with glyphosate increased spruce stand volume several times over the control but decreased aspen volume. The net result was no effect on total stand volume. White spruce volume did not increase with increasing site preparation intensity and was not improved by fertilization. Herbicide treatment changed the stand structure from two or more layers (broadleaf dominated layer above conifers) to a single layer of conifer crop trees with an understorey of natural shade tolerant conifers.

**Summary:** Removing aspen shifted the volume of the stand towards spruce and simplified the stand structure, changing the stand from a mixedwood to a conifer-dominated forest.

#### Planting study no. 14 (Cortini et al. 2012)

**Species combination:** White spruce-trembling aspen

**Location:** Six locations in boreal mixedwoods in Alberta and Saskatchewan. Installations were established by the Western Boreal Growth and Yield Association (WESTBOGY).

**Aspen manipulation treatments:** Two levels of white spruce density (500 and 1000 SPH) and five levels of aspen density (0, 200, 500, 1500 and 4000) plus a control were created.

**Growth and yield results:** This trial investigated the combined effect of aspen competition and climate on white spruce growth. Competition (aspen basal area), initial tree size and mean annual temperature accounted for 88% of the year to year variation in spruce volume growth. Based on the model that was used, without competition (i.e. pure spruce stands), spruce growth can increase by up to 17% when mean annual temperature goes up from 2.0 to 3.3°C, while with a high levels of aspen competition (aspen basal area 27 m<sup>2</sup>/ha) spruce growth increases by only 8% with this change in temperature. This indicates that with climate change (increased mean annual temperature) there may be reduced growth in mixtures compared with pure spruce stands. Mean annual temperature explained the largest amount of variation in spruce growth among the seven climate variables investigated.

#### **Planting study no. 15** (Harper et al. 1997)

**Species combination:** White spruce-balsam poplar

**Location:** BWBSmw subzone; medium to rich site; near Dawson Creek, British Columbia

**Balsam poplar manipulation treatments:** Balsam poplar density was reduced to 0 SPH by glyphosate and to 67 SPH by hexazinone and an untreated control. The three plots were winter-sheared prior to planting.

**Growth and yield results: *White spruce:*** Survival was good in all plots but hare damage to spruce was much higher in the control (50% of leaders clipped) compared to the hexazinone area (13% clipped) and glyphosate plot (0% clipped). Large reductions in balsam poplar density had a substantial effect on white spruce growth 12 years after establishment, even though willow, birch and Sitka alder still remained after treatment. In year 12, spruce height and diameter were clearly larger in the herbicided areas than the control (283 versus 216 cm height and 6.1 versus 3.1 cm diameter) and HDR was lower in the treated plots than the control (47 versus 59). The control had significantly lower numbers of FG spruce (< 70 FG SPH) than the herbicide treated areas (>700 FG SPH) due to the balsam poplar overstorey.

***Balsam poplar:*** Balsam poplar density was reduced to 0 SPH by glyphosate and 67 SPH by hexazinone. Density of balsam poplar in the control was 12,100 SPH in year 12.

**Projections:** Model projections derived from WinTIPSY suggest that herbicide treatment will increase spruce mean annual increment from 7.34 to 9.16-9.49 m<sup>3</sup>/ha and reduce rotation age from 66 to 53 years.

**Summary:** Including balsam poplar in spruce stands can negatively affect conifer growth, and increase the amount of hare damage, prevent achievement of free-growing, and lengthen the rotation age. However, spruce survival can still be good where balsam poplar is present.

#### **Planting study no. 16** (Jobidon 2000)

**Species combination:** White spruce-paper birch

**Location:** Boreal mixedwood forest, Quebec

**Birch manipulation treatments:** Five levels of paper birch density, defined by leaf area index (LAI): LEV-100, LEV-75, LEV-50, LEV-25, LEV-0

**Growth and yield results: *White spruce*:** Spruce survival differences were not significant until the fifth year after treatment; at that time mortality ranged from 5% at LEV-25 to 10% at LEV-100. Hare browsing damage was significantly associated with treatment by year five, with highest incidence (about 7%) where vegetation cover was complete. Five years after treatment, the largest spruce were in the open grown plots (LEV-0). Above ground biomass was almost ten times greater in the open condition compared to where there was complete vegetation cover. Each spruce growth variable followed a negative hyperbolic form of density dependence of competitive effects; the greatest growth losses were associated with the first few competitors. The greatest drop in spruce height, root collar diameter, volume and biomass was from LEV-0 to LEV-25, then growth continued to significantly decline as LAI increased. Growth losses were extreme at high levels of vegetation competition. HDR was 50 for the open grown condition and 56, 66, 69 and 75 for LEV-25, LEV-50, LEV-75 and LEV-100, respectively. HDR was significantly different in each level except LEV- 50 and LEV-75 which did not differ from each other.

***Aspen*:** In the first year of the study the site was occupied by 0.28 stems/m<sup>2</sup> of birch with a mean height of 66 cm (range 25-155 cm). By year five the control had a paper birch density of 0.93 stems/m<sup>2</sup> and a mean height of 175 cm (range 10-390 cm).

**Summary:** Competition for light indicated to be more prevalent than competition for nutrients, as revealed by the substantial increase in the HDR ratio of white spruce as vegetation cover increased. Two indicators, HDR and quantity of light received at the tree seedlings level, are suggested as a basis for managing broadleaf competition in white spruce plantations.

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