

Final contract report

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Potential impacts of including broadleaf trees in managed boreal and sub-boreal forest stands in British
Columbia: synthesis report

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Executive Summary

A literature review was undertaken to provide a comprehensive summary of the potential impacts of including broadleaf trees in managed boreal and sub-boreal stands in British Columbia. A search for literature that compared growth and yield and other values in boreal and sub-boreal mixedwoods with “pure” stands was conducted. Mixedwood stands were defined as having two or more species occurring together with no one species comprising more than 70–80% of the total basal area. The scope of the literature review was as follows:

- All forest values were considered, not just productivity/growth and yield.
- White spruce–trembling aspen and lodgepole pine–trembling aspen mixtures were the focus.
- Information on other species combinations that occur in British Columbia and northern Alberta was included where information for spruce–aspen and lodgepole pine–aspen mixtures was limited. The other species included balsam poplar, paper birch, black spruce, and jack pine.
- The Boreal White and Black Spruce (BWBS) and Sub-Boreal Spruce (SBS) biogeoclimatic zones in British Columbia were the focus, but information from other similar areas was included where local data were lacking or limited.
- Published and peer reviewed papers were the main sources of information.

This report summarizes the key findings of the literature review and identifies knowledge gaps in the topic area.

A number of findings are presented, but the information base was limited. Including broadleaf trees in conifer stands makes it difficult to meet current free-growing requirements, but growth and survival of white spruce and lodgepole pine can still be satisfactory when a moderate level of broadleaves are retained. Conifers in denser mixedwoods tend to have slower diameter growth, and less consistently, slower height growth than in pure stands, but mixtures have similar or higher total wood volumes than pure stands. Retaining broadleaves tends to shift wood volume production away from conifers and onto broadleaf trees. Limited economic analysis indicates that planting conifers without removing broadleaves results in lower long-term financial returns than removing broadleaves, and chemical treatment of broadleaves is the most cost-effective management treatment in the long term. However, the cost-effectiveness of different treatments depends on future value and demand for broadleaves compared to conifers.

Although reductions in conifer volumes can occur when stands are managed as mixtures rather than pure white spruce or lodgepole pine stands, there are a number of advantages of retaining aspen or other broadleaf trees in managed stands in the BWBS and SBS zones. Biodiversity, in terms of avian communities, ectomycorrhizae, and less consistently, vegetation, tends to be higher in mixed than pure stands. Mixed spruce–aspen stands also exploit soil resources more effectively and have higher fine root productivity than pure stands. Soil nutrient availability may be enhanced by the presence of broadleaves, although some local evidence indicates this is not always the case. Aspen canopies reduce frost damage, root disease, weevil damage, and competition from understorey vegetation but increase

the incidence of hare damage. Wood quality can be improved when there is a broadleaf component. Broadleaf trees are also important as fire breaks and for their cultural and visual values.

Despite these findings, major knowledge gaps regarding the impacts of including broadleaf trees in managed stands in the BWBS and SBS zones in British Columbia were identified:

- There are very few long-term economic analyses of managing for mixedwoods rather than pure stands.
- Growth and yield implications of managing for mixed versus pure stands are documented more frequently than influences of other values, but information is still too limited to conclusively compare the productivity of mixed versus pure stands.
- For values other than growth and yield, there is more information on pure conifer versus pure broadleaf stands and on mixed conifer–broadleaf stands than pure stands of the component species. Quantitative information from studies in British Columbia is limited, but existing data suggest that mixed stands have great importance for non-timber values.
- Information from boreal regions in other Canadian provinces is limited and is not necessarily applicable to British Columbia.
- For all values, there is more information on white spruce–aspen than lodgepole pine–aspen mixtures.

Priority needs to be given to identifying the range of ecosystem components that should be monitored in mixed versus pure stands, and to developing monitoring protocols and methodologies. Long-term monitoring (e.g., of post-free-growing stands) and data analysis for BWBS and SBS mixed stands is needed so predictions that are based on short-term data can be validated or revised and reliable operational guidelines can be produced.

1 Introduction

Boreal forests account for about one-third of the forested area in the world and 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 BWBS zone, which covers about 15% of the province (Meidinger and Pojar 1991). 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).

Forests in the BWBS zone are commonly mixed stands of conifers and broadleaf trees (“mixedwoods”); the white spruce–trembling aspen species combination is the most common. Forest stand dynamics in the BWBS zone are driven largely by frequent wildfires which generally are not hot enough to destroy the organic soil horizons and upper roots. Aspen typically suckers and sprouts vigorously following fires and after logging, and 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 for white spruce is available or the species is planted, it establishes with the aspen immediately

after disturbance. In other situations, recruitment of white spruce may occur over several decades (Lieffers, Stadt et al. 1996). 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 in only 30% full sunlight (Comeau et al. 1998). Typically, after about 70–80 years, the spruce is able to reach the height of the main canopy, and by 100–120 years, it becomes 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.

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 has had a much higher value than aspen, so the “default” silviculture strategy in the BWBS zone in British Columbia has been to promote spruce. This typically is achieved by clearcutting, followed by site preparation, herbicide application to kill aspen suckers, and planting white spruce. Using one dominant strategy such as this across the landscape, including keeping the softwood and hardwood land bases 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 in young forests, the 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 uncommonly, and in 2003, Hawkins and Maundrell stated that it was in its infancy in British Columbia. A number of possible ways to manage white spruce–trembling aspen stands as mixtures and pure stands in British Columbia and Alberta has been identified (Lieffers, MacMillan et al. 1996; University of Northern British Columbia 2002; Comeau et al. 2005), and includes successional management of two-storied mixtures, single-storey management of intimate mixtures, and “unmixing” the mix into discrete groupings of aspen and spruce (Comeau et al. 2005).

Sub-boreal forests (the SBS zone) occur farther south than the BWBS zone and occupy the vast rolling plateau that dominates central interior British Columbia. 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).

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, Douglas-fir, and less commonly, black spruce also occur.

In the SBS zone, 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, so it is often taller than lodgepole pine for at least the first 40 years of stand development. On some sites, the pine may grow at equal rates to or faster than the aspen (Newsome et al. 2004a; Comeau et al. 2006).

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.

In the past, little attention was paid to boreal mixedwood forests in British Columbia because their commercial value was lower than that of other forest types. Interest in managing stands in central and northern British Columbia as mixtures rather than pure conifer stands is greatly increasing due to (1) the availability of new wood processing technology that increases the ability to utilize broadleaf species, (2) the depletion of wood supplies from other regions, and (3) an awareness that forests should be managed in an ecologically based manner (Comeau et al. 2005). As well, there is mounting public pressure to reduce the use of herbicides to eliminate broadleaf trees.

Despite the current interest in mixedwood stand management, information on the impacts and influences of including broadleaf trees in managed stands has not been summarized. There has also been a lack of awareness about the type and amount of information available in the literature. This report had two objectives: (1) to summarize available literature on the potential impacts and influences of including broadleaf trees in managed boreal and sub-boreal stands in British Columbia, and (2) to identify key knowledge gaps related to the first objective.

Growth and yield and a range of other values were compared for mixedwoods and “pure” stands. For the purposes of this review, “mixedwoods stands” are generally 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 70–80% of the total basal area. 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. Stands that occur across the landscape may be mixed or single-species.

This report focuses on white spruce–trembling aspen mixtures in the BWBS zone and lodgepole pine–trembling aspen mixtures in the SBS zone in central and northern British Columbia. Information from boreal regions in other Canadian provinces was also included due to the scarcity of local information, but information from outside of Canada was generally not included due to time and funding constraints. Limited reference was made to other species that occur in mixedwoods in boreal and sub-boreal forests in British Columbia and northern Alberta, namely balsam poplar, paper birch, black spruce, and jack pine. Emphasis was placed on obtaining information from published and peer reviewed papers, but limited reference was also made to unpublished works.

This report compiles results from studies that 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, 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.

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

1. Astrup, A. 2005a. Review of the relationship between light availability and growth of understory 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 understory 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 understory 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. Understory 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.

2 Key Findings

2.1 Achievement of Free-growing

In British Columbia, forest companies are relieved of their legal obligations on logged areas when the net area to be reforested is deemed “free-growing.” Stands must be declared free-growing within a given period (15 years in the SBS and BWBS zones), and a minimum number of free-growing trees must be present on the site based on 3.99-m radius plots (British Columbia Ministry of Forests 2002, 2000). In order to be free-growing, a crop tree must meet spacing, species, damage, minimum height, and $\frac{3}{4}$ brush-free quadrant criteria (British Columbia Ministry of Forests 2011).

To determine if the $\frac{3}{4}$ brush-free quadrant criteria are met, a cylinder 1 m in radius is envisioned around the crop tree. If more than one quadrant of the cylinder contains a broadleaf tree that is taller than the allowable conifer:brush ratio (150% in the BWBS and SBS zones), the tree is not free-growing. If one quadrant contains a broadleaf tree that is taller than the allowable conifer:brush ratio, the tree is “potentially free-growing.” If less than a maximum number of allowable broadleaf trees are taller than the median height of the potentially free-growing trees, the tree is free-growing. The maximum number of allowable broadleaf trees in a plot is 2–5 (400–1000 SPH), depending on the ecological unit and the crop tree and broadleaf species.

There are mixedwood stocking guidelines for deciduous–coniferous mixedwoods in the BWBS in the northern interior region of British Columbia (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 refers only to grasses, herbs, shrubs, and non-commercial tree species. A healthy, well-spaced spruce in the understorey of a boreal mixedwood stand is considered to be free-growing if it meets the following criteria specified in the silviculture prescription: minimum height, 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, distance of 2.0 m between white spruce crop trees and deciduous crop trees, and height:basal diameter ratio of 70 or less. A healthy, well-spaced aspen or balsam poplar in the boreal mixedwoods is considered to be free-growing if it meets the following criteria: minimum height, 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, and distance of 2.0 m between white spruce crop trees and 1.4 m between deciduous crop trees.

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 has been the common silviculture scenario. This produces a structurally simple forest (one canopy layer) that is dominated by white spruce or other conifer species.

Some research data collected in British Columbia compare achievement of free-growing on brushed versus untreated mixed conifer–aspen stands. Brushed sites tend to meet free-growing criteria, whereas adjacent untreated stands do not (Harper et al. 1997; Biring and Hays-Byl 2000; Simard et al. 2001). Even when the untreated mixed conifer–broadleaf stands do not meet overtopping restrictions, the trees may be growing satisfactorily. Newsome’s work with lodgepole pine–aspen interactions in the Central Interior since the early 1990s (see Section 2.4.3.3 of this report), and Lieffer et al.’s (2007) work in Alberta, showed that free-to-grow status has been a poor index of future conifer performance. Newsome et al. (2012) found that lodgepole pine trees that have lower conifer:brush ratios of broadleaves than are permitted under the current free-growing guidelines can still have satisfactory growth and survival. The authors’ data are now being incorporated into revised free-growing standards for the SBPSxc subzone in the Cariboo, and work is in progress for other biogeoclimatic units, including the SBS zone.

There have been concerns about restrictive conifer:brush ratios for a long time (e.g., Davis 1998). The conifer:brush height ratio is the only competition index used to assess whether a crop tree is free-growing with respect to “non-crop” vegetation. This implies that light interception by non-crop species is the fundamental factor responsible for competition. However, although reduced light availability may reduce conifer growth rates, other limitations to conifer growth resulting from non-crop vegetation include root competition for soil moisture and nutrients, allelopathic interactions, and physical or mechanical interference with conifer crowns (Davis 1998). Other biotic and abiotic factors acting singly or in combination, including lack of soil moisture or nutrients, extreme climatic conditions, excess moisture, extremes in soil temperature, frost, pests, and wildlife and livestock interactions, can also limit crop tree growth. Different effects of non-crop vegetation on different conifer species; species, abundance, proximity, and stature of the non-crop vegetation; management treatments applied; and time further complicate the influence of the biotic and abiotic factors. Not all non-crop vegetation has the same influence, species are not additive in their competitive effects, and growth of crop trees and non-crop vegetation changes within a year and over several years (Burton 1996, cited by Davis 1998). The crop tree:brush ratio does not consider the complexity of all of these factors working together.

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. However, as other sections of this report 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, soil physical and chemical properties, biodiversity, habitat and shelter for mammals and birds, root rot and insect attack incidence, and incidence of frost damage to young white spruce seedlings.

In response to the inadequacy of the free-growing definition with respect to competition from non-crop species, Davis (1998) proposed new definitions that concentrate on crop tree performance rather than

the stature of the non-crop vegetation. The following is her proposed definition of “well-growing” crop trees for broadleaf complexes: “A stand is well-growing if it is well-established and meets the critical height:diameter ratio [HDR] for all species and/or BEC site series or, on a site specific ‘robust’ tree sample. HDR will be assessed using total height (cm) divided by diameter (cm) measured at ground level.” She defined an impeded tree as one that has not met the minimum age, height, and health standard, is not below or equal to the critical HDR, and is surrounded by more than the allowable number of broadleaf trees of equal or greater stature, within the free-growing assessment period. Her proposed changes to the free-growing standards were never implemented, and concerns about current free-growing standards still exist.

2.2 Economics

Available information on the short-term costs of managing for broadleaf–conifer mixtures rather than pure stands indicates that the least expensive regime for managing white spruce with aspen is “doing nothing.” Two-storied management for mixtures is also relatively low cost. The cost of “unmixing” mixtures into discrete patches of spruce and aspen is moderate. Regimes that require brushing and single or multiple thinning treatments to control aspen density, such as single-storied management of intimate mixtures, are the most expensive option (Comeau et al. 2005).

In the long term, chemical site preparation or chemical brushing treatments are more cost-effective than other treatments such as manual or mechanical cutting because application costs per hectare are lower and volume growth responses are better (Dampier et al. 2006; Homagain et al. 2011), or application costs are so low that they outweigh the better timber yields gained from more expensive treatments (Hawkins et al. 2006). Planting without site preparation or brushing (i.e., allowing broadleaf trees to remain in the stand naturally) results in the highest non-crop (broadleaf) gross merchantable volume but lower total gross merchantable volume than other treatments, and lower financial returns when costs and benefits are calculated over conventional rotations (Hawkins et al. 2006; Homagain et al. 2011). However, the cost-effectiveness of treatments depends on future demand and value of broadleaf trees versus conifers, which is unknown.

2.3 Wood Quality

Including broadleaf trees in managed stands can result in higher quality lodgepole pine or white spruce wood than in open conditions due to less taper (i.e., higher height:diameter ratio) (Literature Review, Sections 2.4.3.4 and 2.4.4.2). As well, lodgepole pine live crown ratio and number of branches per whorl decreases with light availability (Astrup 2005a), and branches are smaller and die sooner where lodgepole pine stands are dense (Ballard and Long 1988). According to limited published literature, average wood density and proportion of sapwood basal area in lodgepole pine stands are not strongly related to stand density (Ballard and Long 1988). Low wood density reduces the strength of wood, and the proportion of a tree’s basal area that is sapwood affects the tree’s resistance to insect and fungal attack. The presence of aspen in spruce stands is documented to reduce levels of weevil damage (Taylor et al. 1996), which reduces the incidence of forks and crooks and subsequent problems with wood

quality. Conversely, seedlings grown on sites with heavy aspen competition may be crooked or forked, which is expected to reduce wood quality (Cayford 1957), but data supporting this are lacking.

2.4 Growth and Yield

2.4.1 Overview of productivity of mixed versus single species stands

The published literature does not clearly indicate whether mixed stands have higher productivity than monocultures. Several reviews question this possibility (Kelty 1992; Kelty 2006; Knoke et al. 2008; Pretzsch 2009). In the early 1990s, Kelty (1992) thought there were enough data to indicate that the productivity of forest mixtures generally exceeds 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 enhanced 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) conducted a meta-analysis of 54 studies to determine the relationship between diversity and productivity in forest ecosystems. They found that globally, productivity, on average, was 24% higher 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 noted 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 on site quality, silviculture treatment, and proportion of the different species. 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 (Pretzsch 2009). 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).

In their review, Macdonald et al. (2010) concluded that 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, and when the mixture includes nitrogen-fixing species. The first three criteria are met for white spruce–aspen mixtures, but probably only the third criterion holds true for lodgepole pine–aspen stands. However, none of the generalizations about different productivity in mixed versus pure stands are specific to individual species combinations; therefore, they are not necessarily applicable to white

spruce–aspen or lodgepole pine–aspen mixed stands in boreal and sub-boreal regions of British Columbia.

2.4.2 White spruce–trembling aspen

2.4.2.1 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.

2.4.2.2 Projections from models

The Tree and Stand Simulator (TASS) (Harper and Polsson 2007), used in conjunction with the Table Interpolation Program for Stand Yields (TIPSY), is the most widely used source of managed stand yield information in British Columbia. It is being used to predict yields in boreal forests but currently does not allow for projections for mixed stands of conifers and broadleaves.

The Mixedwood Growth Model from Alberta is currently the only model suited to making projections of mean annual increments and volumes at rotation for mixedwoods, 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 re-measured permanent sample plots (PSPs) (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 data set, where it underestimated broadleaf density and volume. The data set as a whole overestimated increment growth in older stands, especially pure stands, probably because of age-related pathology and weather-related stand damage.

The Mixedwood Growth Model projections are fairly consistent among studies. Including broadleaf trees in managed BWBS or SBS stands is consistently projected to produce less spruce volume than in pure spruce stands (Biring and Hays-Byl 2000; Pitt, Mihajlovich et al. 2004; Comeau et al. 2005; Kabzems et al. 2007). Retaining 1000 SPH of aspen is projected to produce half the spruce volume (Comeau et al. 2005; Kabzems et al. 2007) but 20% more total volume at rotation than in pure spruce stands (Kabzems et al. 2007). Removing all or nearly all of the broadleaf trees is projected to produce virtually the same total volume as treatments that retain broadleaf stems, but conifer release amounts to trading broadleaf volume for conifer volume (Pitt, Mihajlovich et al. 2004). In another study, elimination of most of the broadleaves was projected to result in lower total volume, but this was in the SBSdw3, where the model has not been calibrated or verified (Biring and Hays-Byl 2000). Retaining high densities of aspen (up to 10,000 SPH) is projected to produce slightly less total volume than pure spruce or aspen stands, which produce the highest total yields (Comeau et al. 2005; Kabzems et al. 2007). Pure aspen stands are projected to produce the highest aspen yield (Comeau et al. 2005).

Underplanting at age 40, harvesting the aspen at age 60 with understorey protection, and making the final harvest at age 120 has been projected to result in higher total, aspen, and spruce yields (Comeau et al. 2005) than other treatment regimes. The lowest volume growth has been projected to result from splitting a block into pure aspen and pure patches, and harvesting at age 90. Planting spruce into dense aspen also resulted in low total yield at age 90.

2.4.2.3 Comparison of natural stand types

There is agreement in the limited existing literature that mature aspen stands with a spruce component have greater total productivity than pure aspen stands (Kabzems and Senyk 1967; MacPherson 2000). Total productivity is reported to be lowest in the pure spruce stands and intermediate in the pure aspen stands (Kabzems and Senyk 1967). Aspen productivity alone is documented to be greatest in areas with pure aspen (MacPherson 2000).

Overstorey aspen is documented to result in poor form and to reduce the volume by half of 55–100-year-old natural spruce growing near the aspen compared to spruce growing in small openings (Cayford 1957). The effect of aspen on spruce was reported to begin when the spruce were very young: spruce growing with aspen took significantly longer (8.7 years) than trees free of aspen (7.1 years) to reach breast height. Height growth of aspen exceeded that of free spruce for the first 30 years of stand development and exceeded that of suppressed spruce for 30–40 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 of free spruce. Another study showed that spruce height growth was not reduced “excessively” (when compared to growth in a clearcut) by being under a mature aspen stand (Lieffers, Stadt et al. 1996), but it appears that these spruce were not necessarily growing near the aspen.

2.4.2.4 Planting trials—intimate mixtures of spruce and aspen

Most published information from boreal regions, including British Columbia, has documented >85% survival of white spruce planted into clearcuts where aspen was regenerating from suckers, regardless of the degree of suckering (Literature Review, Table 3) (e.g., Biring and Hays-Byl 2000; Man et al. 2008; Pitt et al. 2010; Kabzems, Harper et al. 2011). Similar results have been documented for spruce that established with densely regenerating balsam poplar (Harper et al 1997). Survival of white spruce at sites in Ontario and Quebec improved by 5–12% where aspen or birch was partially or completely removed by herbicide or cutting, compared to an untreated control (Jobidon 2000; Pitt and Bell 2005).

There is limited published information on the vigour and condition of white spruce seedlings on new clearcuts with thinned or untreated aspen in the BWBS or SBS zone in British Columbia, but hare damage is consistently associated with plots with dense broadleaf cover (Harper et al. 1997; Coopersmith et al. 2000; Jobidon 2000). Removing aspen in 2-m radius circles around spruce seedlings reduced exposure of seedlings to frost compared to untreated areas (Man et al. 2008). In the SBS zone, better spruce seedling vigour was recorded on sites where aspen was killed by herbicide than on the untreated control area (Biring and Hays-Byl 2000).

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 et al. 2011; Bokalo et al. 2012) or not significantly different (e.g., Pitt, Mihajlovich et al. 2004; Man et al. 2008) than it was in open areas where aspen abundance was greatly reduced. There is no evidence that spruce height growth is reduced by complete or partial removal of aspen. Spruce height growth tended to be insensitive to partial removal treatments in two studies (Man et al. 2008; Kabzems, Harper et al. 2011), but Pitt et al. (2010) found that spot treatments increased height growth as much as complete aspen removal.

Most published studies documented an increase in white spruce diameter growth in response to complete removal of aspen (DeLong 2007; Kabzems et al. 2007; Pitt et al. 2010; Kabzems, Harper et al. 2011; Bokalo et al. 2012), balsam poplar (Harper et al. 1997), or birch (Jobidon 2000). Spruce diameter growth was insensitive to partial removal of aspen in two studies in the BWBS zone (Kabzems et al. 2007; Kabzems, Harper et al. 2011) but not at sites in Alberta and Saskatchewan (Bokalo et al. 2012). In the latter study, the 20-year measurement indicated that diameter tended to be smaller where aspen was denser but was not significantly different between 0 and 200 SPH aspen treatments or between 200 and 500 SPH treatments. There is no evidence that spruce diameter growth is reduced by partial or complete removal of aspen.

Several studies indicated that 5–10 years after treatment, volume of spruce where aspen was completely removed was about double that on untreated controls (e.g., Kabzems et al. 2007; Kabzems, Harper et al. 2011; Pitt et al. 2010; Bell, Dacosta et al. 2011). Partial retention of aspen, including spot treatments, resulted in volumes that were similar to those of the control (e.g., Kabzems et al. 2007; Kabzems, Harper et al. 2011) or the open areas (e.g., Pitt et al. 2010). Removing aspen tends to shift the volume of the stand towards spruce, but it does not necessarily increase total volume. No published information was found in which spruce volume was reduced by partial or complete removal of aspen.

However, total stand volume can be lower in treated areas than in mixed stands due to high aspen volume in the latter (e.g., Pitt and Bell 2005).

Height:diameter ratio (HDR) of spruce is consistently significantly lower in open areas than in areas where all aspen is left untreated, and the differences are generally large (Literature Review, Table 3). Published values of average HDR for open-grown seedlings vary from 33 to 50, compared to 61 to 79 for controls. Spot treatments sometimes have no effect on HDR (e.g., Kabzems, Harper et al. 2011); in other cases, HDR after spot treatment is intermediate between the control and complete removal treatment (Man et al. 2008). Increasing levels of thinning results in decreases in HDR (Coppersmith and Hall 1999; Jobidon 2000; Bokalo et al. 2012) but not necessarily where densities are fairly similar (e.g., retention of 200 and 500 SPH aspen has resulted in similar spruce HDRs) (Bokalo et al. 2012).

Elimination of a high proportion of aspen from a white spruce–aspen mixedwood stand shifts the stand structure from a two-storied 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 on spruce growth as complete removal of aspen (Pitt et al. 2010). Triclopyr treatment has been shown to kill only the tops of aspen, but it still results in larger spruce than do cutting treatments.

2.4.2.5 Underplanting

Three of four studies from the BWBS zone in British Columbia documented good survival of white spruce seedlings 2–10 years after underplanting in mature to old aspen stands, and similar survival in clearcut plots (Literature Review, Table 5). However, survival in Ontario has been reported to be only about 50% due to very low measured light levels (MacDonald and Thompson 2003). A canopy of aspen has consistently been reported to reduce the incidence of frost but can result in greater levels of hare damage.

In a meta-analysis of studies conducted in boreal trembling aspen–white spruce mixedwoods from northern British Columbia to Manitoba from 1950 to 2000, underplanted spruce seedlings had, on average, 7% greater survival, 24% smaller diameter, and 6% shorter height than those growing without an aspen canopy (Man 2003). Most published results from British Columbia also documented slower height and diameter growth of white spruce under an aspen canopy than in clearcuts or where aspen was thinned to 1000–2000 SPH. Man (2003) reported both positive and negative responses of height and diameter growth to underplanting, whereas in the British Columbia studies, there were no positive responses.

The difference in responses among studies may be related to the degree to which the overstorey dampened environmental extremes (Man 2003). For example, an aspen canopy reduces the incidence of frost (Literature Review, Section 2.10.1), so underplanting may produce a positive growth response in frost-prone areas but less of a benefit on sites where frost is less common. The relationship between height, diameter, or survival response and years after planting is weak, as is the relationship between these variables and overhead canopy type (mature aspen, mature mixedwood, and young aspen) (Man

2003). The poor correlations are attributed to the fact that most of the spruce plantations were less than 10 years old, and their potential performance was related to a wide range of factors that were not considered, such as stock problems, soil type, site preparation, temperature, precipitation at the time of planting, vegetation competition, and hare population levels.

2.4.2.6 Partial canopies/shelterwoods

Various published studies found no significant difference in survival of 2–4-year-old spruce planted under different sizes of shelterwood gaps (40 m versus 113 m diameter [Kabzems 2001]; 40% removal of uniform shelterwood versus strip shelterwood, narrow strips, or patch shelterwood [Groot 1999]) or within 80 × 340 m rectangular gaps versus beside them (Milakovsky et al. 2011). However, survival, as well as height, diameter, and volume growth, was better where aspen canopies were partially removed than where spruce canopies were partially removed (Gradowski et al. 2008). It is difficult to identify trends in spruce height and diameter responses to shelterwood logging due to limited availability of literature, variations in gap sizes, and short measurement periods, but growth has generally been documented to be better in shelterwoods than under intact or nearly intact canopies (Groot 1999; Man and Lieffers 1999b) (see Literature Review for details of individual studies).

2.4.2.7 Release cuttings

Release cutting refers to a treatment in which an aspen canopy is removed after seedlings are established. A meta-analysis based on studies conducted between 1950 and 2000 in boreal mixed white spruce–aspen stands located from northern British Columbia to Manitoba indicated that, on average, released spruce trees had a 4% greater survival rate than unreleased trees (Man 2003). Most of the responses were in the zero category (no difference in survival between released and unreleased trees) (475 of datasets) or negative category (32% of sub-data sets) (lower survival of unreleased than released trees). Survival data were generally not found in the literature reviewed for this document, except for one study which showed similar results as those reported in the meta-analysis: mortality of understorey spruce was higher in controls than in released stands (Yang 1989).

The meta-analysis documented an average of 61% greater height growth and 73% greater diameter growth of released trees compared to unreleased control trees (Man 2003). Strong positive responses dominated for both variables; a maximum of 12% of sub-data sets had a negative response to treatment. Height response was determined largely by initial tree height and increased slightly with number of years after release. The greatest height and diameter growth responses occurred when trees were 9–11 m tall. Height response increased with increasing residual basal area, with a maximum response of 13–15 m²/ha, while diameter response generally decreased with increasing residual basal area at release. The general trend of greater average diameter response than height response documented by Man (2003) holds true for various long-term studies from Manitoba (Literature Review, Section 2.4.3.7). Complete release of white spruce from aspen competition increased DBH increment by 15–177% over 30 years and height increment by 28–60% over 30 years compared to controls (Yang 1989).

The meta-analysis documented 32% greater volume growth of released trees compared to unreleased control trees, and strong positive responses predominated (Man 2003). Volume response followed the same trend as diameter, with a general decrease in response with increasing residual basal area at release. Long-term (30–50-year) studies in Alberta, Saskatchewan, and Manitoba reported greater volume increases following release from overstorey aspen than the averages calculated in the meta-analysis (Yang 1989, 1991). Release treatments increased tree-level spruce volume growth by 82% over 35 years compared to spruce growing in mixture with aspen (Yang 1991). In a series of trials, Yang (1989) documented increases of 29–239% in merchantable volume increment and 24–304% in total volume increment over 30 years in completely released trees versus unreleased trees.

Yang (1989) reported that partial release treatments (uniform 50% removal) resulted in total volume and merchantable volume increments over 30 years that were similar to or less than those for the controls. Twenty years after 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), total volume of white spruce in both treatments was about double that of the untreated mixedwoods (Steneker 1963; Yang 1989). Merchantable volume of white spruce in the light release treatment was about double that of the control, and merchantable volume in the heavy release treatment was almost triple that of the control. The control produced the greatest total volume (all species combined); the heavy release treatment produced the least.

Many other release studies were conducted in the 1960s and earlier in Alberta, Saskatchewan, and Manitoba, and are described in detail by Jarvis et al. (1966). They showed that all ages and sizes of spruce responded to release, but 30–40-year-old trees had the greatest potential to increase their growth rate for a given degree of release. The amount of response was directly related to the intensity of the release cutting.

2.4.2.8 Light and white spruce performance—an overview

Including broadleaf trees in managed stands affects understorey light levels that reach seedlings. This is important because competition between conifers and broadleaf trees in mixedwood stands (at least stratified stands) is primarily a result of light limitations imposed by overstorey broadleaf trees (Green 2004). Astrup (2005b) reviewed the relationship between light levels and spruce growth, based on 36 studies (20 of which were for white spruce) from various forest regions (but generally not the BWBS or SBS zones). Key findings were as follows:

- Maximum height and diameter growth of spruce occurs in full sun.
- Under aspen-dominated canopies, spruce height increment generally 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 in spruce height increment is observed at a given light level.
- 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 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 increases 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 more than conifer canopies. Astrup attributed this to differences in the composition and quality of understorey light, the leaf-off period in aspen stands, and differences in soil temperature and nutrient availability.
- A large proportion of the variation in growth rate for a given light level is due to tree size. Other sources of variation are climatic (geographic) and site conditions.

2.4.2.9 Threshold light and aspen levels for spruce performance

The published literature identified the following threshold levels of light and/or aspen required for various levels of spruce performance. These relationships are specific to the location and stand age of the study site.

- Spruce mortality is predicted to be very low in areas with up to 20 m²/ha of aspen basal area but is predicted to increase rapidly as basal area exceeds that threshold (Wright et al. 1998).
- 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).
- Survival is very poor at light levels that are less than 15% (Kobe and Coates 1997). 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. 2009, 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 m²/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 m²/ha, aspen density would have to be less than 2000 SPH when aspen diameter is 7.0 cm and less than 5000 SPH when aspen diameter is 4.4 cm (Wright et al. 1998; Comeau 2001).

- When overstorey basal area reaches 10 m²/ha in 40-year-old or younger BWBSw1 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 m²/ha or greater will result 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 would have 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.
- Low densities (up to 1000 SPH) of aspen had 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 volume growth appeared to be relatively insensitive to a wide range of aspen densities above 1000 SPH, but a relatively small amount of aspen (less than 1000 SPH) was expected to have a large effect on its production. The threshold for aspen density to affect white spruce growth was suggested to be less than 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 (measured after five growing seasons), optimum growth of white spruce may not be achieved based on data from the SBSmk1 subzone, 60 km northwest of Prince George (DeLong 2007).
- On sites in Alberta with good productivity, the competition level that resulted in substantial growth reduction in white spruce 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 diameter was 2.5 times larger than that of the spruce that were present within 2.0 m (Navratil and MacIsaac 1996).

Some studies have aimed to determine paper birch threshold levels for spruce growth, but information is limited for boreal and sub-boreal stands in British Columbia. Spruce growth is reported to be 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). Competitive interactions between spruce and birch are different on north- and south-facing aspects in the SBS zone (Green and Hawkins 2005).

2.4.3 Lodgepole pine–trembling aspen

2.4.3.1 *Measured volume of mature mixed and pure stands*

No published information on the volume of mature pure lodgepole pine stands versus mature lodgepole pine–broadleaf mixtures was found. Limited published information (one study) documented no significant differences in total basal area, total merchantable stem volume (m³/ha), or average height of jack pine in 70-year-old pure jack pine, jack pine–aspen mixtures, and jack pine–paper birch mixtures (Longpré et al. 1994). However, jack pine had significantly greater diameter growth and volume per tree when grown in mixture with paper birch than in the other stands. Stem analysis revealed that pine and

aspen grew at about the same rate, and so occupied the same canopy space. Birch grew much slower than pine, and so occupied a separate layer in the stand, which could have reduced interspecific competition for light for the pine and thereby led to an increase in its diameter growth. The study concluded that up to 5 m²/ha basal area of birch could be maintained in jack pine stands without reducing the merchantable volume of the pine. Similarly, two-storied white spruce–aspen stands had higher total volumes than pure stands of aspen, but comparisons of volumes in mixed versus pure spruce stands were not made.

2.4.3.2 Projected volume of mature mixed and pure stands

By using yield curves to make volume projections, Bell, Dacosta et al. (2011) documented a 30–76% increase in jack pine net merchantable volume by age 60 following aspen removal treatments at stand age 10. The greatest increase in pine volume was projected for both glyphosate and manual cutting treatments. The release treatments were projected to reduce aspen net merchantable volume by 75–100%. At age 60, total merchantable volume (all conifer and all broadleaf trees) in the treated stands was predicted to be within 5% of the net merchantable volume in the untreated mixed stand. This trend is similar to that for spruce (Section 2.4.2 in this report).

2.4.3.3 Juvenile lodgepole pine–trembling aspen interactions

In the reviewed studies, there was a general trend of decreasing vigour of lodgepole pine as aspen density increased above 1000 SPH (Literature Review, Table 7). The threshold for 80% survival of lodgepole pine was determined to be 7000 SPH of aspen at SBSdw1 sites in the Cariboo Chilcotin (Newsome et al. 2008; Newsome 2009) but 9000 SPH in the IDFdk3, where site productivity is lower and competitive effects are less.

At sites in British Columbia, height growth of pine in the SBS and SBPS zones was not consistently improved by reducing aspen density (Newsome et al. 2004a; 2006a). In Alberta, pine height growth did not respond to partial or complete removal of aspen (MacIsaac 1996), or when pine were planted in pots in the open compared to under an aspen–balsam poplar overstorey (Landhausser and Lieffers 2001). However, some studies indicated that above 4000–5000 SPH aspen, pine height growth was less than where there was no aspen (Newsome 1995, 2009; Newsome et al. 2008). A study from Ontario indicated that pine height at age 5 was four times taller (almost 1 m) following broadcast removal treatments than no treatment, and twice as tall as where there was no treatment following partial cut treatments. Five to 10 years after aspen was brushed in the MS, IDF, and ICH zones in the southern interior of British Columbia, there was no difference in pine height between the treated areas and untreated controls (Mather and Simard 1997a; Heineman et al. 2009). Another study in the southern interior documented a positive response of pine height growth to aspen treatment (Prasad 2002).

In the SBS and SBPS zones, diameter growth is documented to start decreasing at aspen densities of 1000–2000 SPH, although some studies indicated no effect of this level of density on diameter growth. In Ontario, pine diameter greatly increased with decreasing aspen density, but the actual density numbers were not provided. In the IDF and MS zones in the southern interior of British Columbia,

diameter growth began to decline above an average density of 1867 SPH of tall aspen (Heineman et al. 2009).

Height:diameter ratio of pine increased with increasing aspen density in three out of four studies; the ratios were consistently the lowest in the broadcast removal treatments. This trend is the same as that for spruce (Section 2.4.2).

2.4.3.4 Light and lodgepole pine performance—an overview

Astrup (2005a) reviewed the relationship between light levels and understorey lodgepole or jack pine growth based on 23 Canadian and American studies. Key points from the review are as follows:

- Under field conditions in conifer-dominated stands, the relationships between light availability and height or diameter increment of pine 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 0.1–7-m tall trees).
- Below 15% light availability, height and lateral branch growth does not increase.
- In general, height:diameter ratio is larger for understorey 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.

2.4.3.5 Competition indexes for lodgepole pine

Competition indexes that have successfully predicted lodgepole pine growth are listed in the Literature Review (Section 2.4.4.4). They are based on aspen basal area, aspen density, or the ratio of aspen diameter to pine diameter.

2.4.3.6 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. Site-specific conditions have been suggested to be significant in determining thresholds; therefore, these results should not be extrapolated directly to other sites (Harper et al. 2009; Comeau 2010; Newsome et al. 2012).

- 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 (MacIsaac 1995; 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 m²) 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, lodgepole pine vigour tended to be better where ≤ 800 aspen SPH were retained, but there were no differences in mean stand-level pine height, stem diameter, quadratic mean diameter or basal area among treatments where 0–2800 SPH of aspen were left (Newsome et al. 2006b).
- In the SBSdw1 subzone, survival of 20–24-year-old lodgepole pine declined significantly with increasing tall aspen density. The threshold for 80% survival of pine was 7000 SPH of tall aspen. 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 that were less than 23 years old (Newsome et al. 2008; Newsome 2009).
- 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 SPH of aspen were retained. Above 1000 SPH of aspen, 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 5 m²/ha of broadleaf tree basal area (lower foothills) and 9 m²/ha or 1700 SPH of aspen (upper foothills). When these levels are exceeded, diameter growth of pine was reduced by about 30%. Thresholds for pine height increment are about 15 and 20 m²/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 Alberta, 10–20% aspen cover had a positive effect on growth of 4–12-year-old lodgepole pine. Higher levels of aspen cover reduced pine growth (Navratil et al. 1990a).

2.5 Carbon Storage

Gower et al. (1997) indicated that total ecosystem carbon content (vegetation + detritus + soil) was greatest in black spruce stands, intermediate in aspen stands, and lowest in jack pine stands. In contrast, Cavard et al. (2011) found that nearly pure trembling aspen stands contained the greatest amount of above-ground carbon, black spruce stands had the least, and mixtures of conifers with aspen were intermediate. The trend could be different if there were different species proportions in the mixed stands.

2.6 Resources Required for Tree Growth

2.6.1 Light

An aspen overstorey impacts conifers by reducing light levels. Spatial distribution of aspen trees, and canopy gap size and shape influence light that reaches conifers. Aspect, slope, and canopy gaps and height together determine light levels within aspen stands. Many published studies indicate that light limitations resulting from overstorey broadleaf trees is the major force behind competition between conifers and broadleaf trees in mixedwood stands (at least stratified stands) (see Green 2004 for list of references). However, a partial decrease in light due to aspen presence does not necessarily reduce seedling growth (Wright et al. 1998). Limited shading may benefit pine in dry areas by reducing vapour pressure deficit and moisture demand. Navratil et al. (1990a) suggested that 10–20% cover of aspen had a positive effect, but data to substantiate the claim were lacking. Light limitations imposed by broadleaf trees not only impact understorey conifers trees but can affect other components of the ecosystem, such as understorey vegetation (Section 2.8.5.1 of this report). Spruce can tolerate lower light levels than can pine (Wright et al. 1998). The light levels at which white spruce and lodgepole pine seedling growth and survival are reduced are provided in Sections 2.4.2.8 and 2.4.3.4 of this report.

2.6.2 Soil moisture

Young aspen can alleviate rises in the water table and flooding following logging of wet boreal mixedwood sites through transpiration and interception of precipitation by their high leaf area (Man and Lieffers 1999b). In general, broadleaves are more moisture demanding than conifers because leaves are less able to control moisture loss than are needles. Thus, the presence of aspen can potentially improve conifer establishment on wet sites. In the BWBS zone, soil moisture decreases with increasing

density of aspen canopies (Coopersmith et al. 2000; Hawkins 2005), and soils stay drier in retention plots than in the open throughout the growing season (Coopersmith et al. 2000). However, in areas with relatively high precipitation, soil moisture is not affected by complete or spot aspen manipulation treatments (Man et al. 2008).

Snow accumulation in the boreal forest is greater under aspen stands than under jack pine because of the lack of foliage in aspen stands during winter (Pomeroy and Goodison 1997, cited by Pike et al. 2010), which could result in wetter conditions under aspen than under conifers in early spring. Published information on snow accumulation in mixedwoods compared to pure conifer or pure aspen stands is unavailable.

2.6.3 Soil temperature

Removing aspen from conifer stands can result in increased soil temperatures (Coppersmith et al. 2000; Prevost and Pothier 2003), and the increase becomes greater as more aspen is removed (Prevost and Pothier 2003). Complete removal of aspen has resulted in soil temperatures that are up to 3°C higher one year after treatment and 1.4°C higher five years after treatment compared to soil temperatures under intact mixedwood stands (Prevost and Pothier 2003). Limited research reports growing season soil temperatures are about 3°C lower under white spruce-dominated stands than under aspen-dominated stands (Fenniak 2001, cited by Gradowski et al. 2008). Cold soils result in poor root growth (Camm and Harper 1991), and cold soil temperatures in spring may significantly reduce seedling photosynthesis and growth (Filipescu and Comeau 2011).

2.6.4 Soil nutrients and soil properties

Nutrient cycling and site productivity in forest stands has traditionally been considered to be enhanced by the presence of aspen (Peterson and Peterson 1995). Important nutrient-related benefits associated with aspen presence in a stand include the following:

- 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 the ecosystem; 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 nitrogen, 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.

Most published literature from boreal regions in Canada agrees with the generalizations of Peterson and Peterson (1995) (Literature Review, Table 9); however, boreal studies from British Columbia that compare soils under white spruce and aspen are scarce and results are conflicting. In boreal regions, availability of nitrogen and other cations is usually greater beneath aspen than in white spruce stands (Literature Review, Table 9). Soil pH is usually higher under aspen than in conifer stands. The trend of higher nutrient availability under broadleaf canopies versus conifer canopies is also apparent for aspen and pine, but this species combination is less well studied than spruce–aspen.

Data that compare soils of boreal or sub-boreal mixed white spruce–aspen or mixed pine–aspen stands with pure stands of the component species are very limited, but one published study of white spruce–aspen in British Columbia reported no mixture effect (Prescott et al. 2000). Another study of lodgepole pine–birch–aspen–cottonwood reported that nutrient availability increased as the proportion of broadleaf species increased (Sanborn 2001).

When data from other conifer–broadleaf species combinations are considered, conclusions about the effects of mixtures on soils are still limited by the small number of directly applicable studies, the wide variety of observed interactions, and the difficulties in making interpretations because of differing methodologies and experimental conditions among studies (Rothe and Binkley 2001). Based on Rothe and Binkley's (2001) synthesis of 19 studies, mixed stands (not necessarily broadleaf–conifer) usually do not have different rates of litter decomposition or different pools of soil nutrients in the forest floor compared to monocultures, but either less or more decomposition has occasionally been demonstrated in the mixtures.

2.7 Root Stratification

Mixed white spruce–aspen forests may have an ecological advantage over pure white spruce stands in that below-ground competition is reduced due to spatial separations in the rooting zones of broadleaves and conifers, which allows for greater exploitation of soil resources (Kabzems and Lousier 1992; Man and Lieffers 1999a; Lawrence et al. 2012). Brassard et al. (2011) found that fine root productivity was significantly higher in mature mixed white spruce–aspen stands than in pure aspen stands, and the soil space was more fully occupied by fine roots in the mixed than in the pure stands. Data for lodgepole pine–aspen stands are lacking.

2.8 Biodiversity

2.8.1 Overview

Aspen enhances and maintains biodiversity across a spectrum of stand ages in forest stands in western Canada (Peterson and Peterson 1995) due to the following reasons:

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

The difference in biodiversity between mixed and pure aspen and pure white spruce stands is not well documented, but a rich biota has been identified in aspen mixedwood forests in Alberta, including 47 lichen species, 39 moss species, seven liverwort species, 24 fungi species, 11 horsetail, club moss, and fern species, 55 herb species, 27 shrub species, six tree species, three amphibian species, 76 bird species, and 33 mammal species (Roy et al. 1995).

2.8.2 Soil biota

Soil biota are important for biodiversity in forest ecosystems because they facilitate the processes of energy flow, nutrient cycling, and water infiltration and storage in the soil (Whitford 1996). Soil biota include microflora (bacteria, algae, fungi) and soil fauna. Cavard et al. (2011) summarized 10 international studies that compared soil fauna composition and diversity between mixed and pure stands. Information on soil biota in boreal or sub-boreal stands in British Columbia is lacking. A few studies have indicated that mixed stands or mixed litters support greater biodiversity of soil organisms than pure stands, 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 it appears that forest canopy diversity itself does not affect soil fauna diversity.

2.8.3 Ectomycorrhizal fungi

Increasing diversity of ectomycorrhizal fungi is associated with increased plant productivity and plant diversity (Kernaghan 2005). Cavard et al. (2011) summarized eight studies that examined ectomycorrhizal fungi composition and diversity in mixedwoods versus pure stands in northern forests. Although the results were generally not from stands comprised of British Columbia boreal broadleaf or conifer species, they provided evidence that mixed stand ectomycorrhizal communities are the sum of fungi types associated with each tree species, and the diversity of ectomycorrhizal fungi is positively correlated with host species diversity. Ectomycorrhizae with multiple hosts are more abundant under mixedwoods than pure stands, according to several international studies.

2.8.4 Coarse woody debris

The Literature Review summarizes the importance of coarse woody debris (CWD) to biodiversity. There are no published studies on the impacts of including broadleaf trees in managed white spruce or

lodgepole pine stands on CWD in boreal or sub-boreal forests in British Columbia. In Ontario, CWD levels were higher in mixed jack pine–aspen forest types than in pure aspen or pure jack pine types (Brassard and Chen 2008). In another Ontario study, CWD volume in conifer stands comprised of several species was greater than or equal to that in mixedwood or broadleaf stands, except in 7-year-old stands, where mixedwoods had the greatest CWD volume (Pedlar et al. 2002). Both sources indicated that the mixed and pure stands had similar proportions of CWD in the different decay states. Two studies are insufficient to draw conclusions about difference in CWD characteristics between mixed and pure forest types, and differences between studies likely reflect differences in tree species between sites, including the presence of spruce budworm hosts. Decay rates of logs were higher for aspen than for white spruce and jack pine in Minnesota (Alban and Pastor 1993).

2.8.5 Understorey vegetation

2.8.5.1 Overstorey-understorey relationships

Overstorey composition and structure influences understorey vegetation through modifications of light, water, soil and air temperature, and soil nutrients (Roy et al. 1995; Barbier et al. 2008). However, management practices, forest age, forest density, site characteristics, and presence or lack of a subcanopy also play a part in determining understorey characteristics.

Stand-level understorey vegetation species richness in boreal mixed conifer–aspen stands is either greater than in pure conifer or pure aspen stands or is intermediate between the two stand types (Literature Review, Table 10). Specific indicator species for mixed stands have not been identified. Species diversity tends to be higher in broadleaf stands than in conifer or mixed stands, but there are cases where mixed stands have the highest diversity (Cavard et al. 2011). The proportions of species in the overstorey influence vascular plant diversity, but effects vary among studies. Broadleaf stands tend to have vascular plant species in the understorey, conifer stands are associated more with bryophytes in the understorey, and understorey communities under mixedwoods are intermediate between pure conifer and pure broadleaf stands (Hart and Chen 2006).

2.8.5.2 Impacts of removing aspen on understorey vegetation

An aspen overstorey can suppress understorey vegetation (Literature Review, Table 11). Most published studies (six out of eight) documented an increase or shift in species composition 2–12 years after the removal or reduction of overstorey aspen in white spruce stands; two reported minimal change. There are no reports of decreases in understorey vegetation cover following removal treatments targeted at aspen. *Calamagrostis canadensis* cover generally increases following aspen removal. Increases in the overall categories of herbs, graminoids, or shrubs are occasionally reported. Data are too limited to separate out differences in vegetation response to varying levels of aspen reduction. Information on the effects of aspen removal on understorey vegetation in lodgepole pine stands is lacking.

2.8.6 Birds

Avian richness appears to be greater in aspen–conifer mixedwoods than in pure stands because bird species that use either pure aspen or pure conifer habitats are often both present (Schieck and Song 2006). Stand-level avian diversity is generally higher in boreal aspen–conifer mixedwoods than in pure conifer stands (Literature Review, Table 12), especially jack pine stands (Kirk and Hobson 2001). Abundance or frequency of occurrence of some bird species is greater in mixed stands than in pure stands, and evidence from some regions suggests that a few species are mixed-stand specialists. Up to 30–50% more individual birds have been found in mixedwoods than in coniferous or broadleaf stands (Hobson and Bayne 2000; Machtans and Latour 2003), likely because increased floristic and structural diversity in mixedwoods creates more habitat niches, such as nesting sites and foraging areas (Hobson and Bayne 2000). Old boreal mixedwoods have greater species richness than young stands, which have greater richness than mature stands (Roy et al. 1995). No studies of avian communities in mixedwoods compared to pure conifer stands in British Columbia were found; the information documented here is from Alberta, Saskatchewan, Quebec, and the Northwest Territories.

2.8.7 *Mammals*

Comparisons of mammal use of mixed aspen–spruce or mixed aspen–lodgepole pine stands versus pure conifer stands in boreal or sub-boreal forests are lacking in the published literature.

2.9 *Forest Damage*

2.9.1 *Frost*

Cold temperatures and frost risk are important issues in boreal climates where the growing season is short and freezing conditions can occur at any time of the year (Filipescu and Comeau 2011). Minimum air temperatures can be colder in the open than under aspen canopies (Groot and Carlson 1996; Filipescu and Comeau 2011). Frost damage to white spruce seedlings in boreal mixedwoods has consistently been reported to be lower under aspen canopies than in open areas on sites such as low-lying basins where there is potential for frost (Literature Review, Table 13). Although the literature consistently reports an increase in frost incidence with decreasing canopy cover or size of canopy opening, frost incidence has been similar at aspen densities of 500 and 1500 SPH (Filipescu and Comeau 2011). Unless canopy openings are very small (<9–18-m wide strips) or distances from edges into openings are short (less than one tree length for juvenile aspen stands), the incidence of frost will not be as low as under aspen cover (Groot and Carlson 1996; Voicu and Comeau 2006). On areas such as topographic rises where the risk of frost is lowered by wind and air mixing, the incidence of frost has been similar across a range of aspen densities (Filipescu and Comeau 2011).

2.9.2 *Insects*

Including broadleaf trees in white spruce stands in British Columbia can reduce attack by leader weevils (Taylor et al. 1996; Nykoluk and Hawkins 2001). Published studies from eastern Canada and Minnesota have documented a reduction in spruce budworm damage when broadleaf trees are included in stands (MacLean 1980; Su et al. 1996). Defoliation due to spruce budworm is strongly linearly related to the

proportion of broadleaf trees in conifer stands; a broadleaf component of at least 40% will substantially reduce losses (Su et al. 1996).

A meta-analysis of boreal and northern temperate studies confirmed the positive effect of mixing tree species on resistance to insects (Griess and Knoke 2011), although none of the studies included conifer–broadleaf combinations found in boreal and sub-boreal forests in British Columbia. Another review of studies in boreal forests did not support the results of Griess and Knoke’s (2011) meta-analysis: it concluded that experimental data from published studies provided no overall support for the hypothesis that diversifying forest stands can prevent pest outbreaks and epidemics, although benefits are observed in some cases (Koricheva et al. 2006).

2.9.3 Diseases

Several studies have shown that juvenile conifer mortality rates due to root rot increase as the density of broadleaf trees is reduced (Woods 1994, cited by Baleschta 2005; Gerlach et al. 1997; Simard et al. 2001; Baleschta et al. 2005). Most of this work was conducted in Douglas-fir–paper birch stands, and less commonly lodgepole pine–aspen stands, in southern interior British Columbia. No published information for boreal or sub-boreal white spruce–broadleaf mixtures in British Columbia was found. Rust incidence on pine may indirectly be reduced by broadleaf competition through a reduction of crown area and branches.

2.9.4 Animal damage

In the BWBS zone, levels of hare damage are consistently higher under mixed broadleaf–conifer or pure broadleaf canopies (50–63% of seedlings damaged) than in open areas where broadleaves have been removed (e.g., clearcuts) (0–13% damaged) (Literature Review, Table 14). Limited information from the SBS zone shows that this trend also applies to voles: 50-cm radius removal treatments and untreated controls had higher levels of damage than did 100-cm radius treatments or clearcuts (Newsome et al. 2004a), which suggests that voles prefer broadleaf cover.

2.9.5 Physical damage

Lodgepole pine and white spruce are susceptible to whipping damage from aspen (Lees 1966; Newsome 1997; Newsome et al. 2008), but the frequency or severity of this type of damage has not been quantified in published reports, except for data on the combined frequency of whipping and other damage. One published study suggested that whipping abrasion to lodgepole pine branches by “tall” aspen (taller than the pine) increases with increasing density of tall aspen (Newsome et al. 2008), but data were not provided.

A meta-analysis based on boreal and northern temperate biomes suggested that mixing tree species has a positive effect on resistance to windthrow, but only seven studies were included in the analysis, and all studies investigated European tree species. Windthrow incidence in mixed white spruce–aspen or mixed lodgepole pine–aspen stands versus pure conifer or pure aspen stands has been documented only when

it is combined with other reasons for mortality (see discussion of results from Solarik et al. [2012] in the Literature Review, Section 2.10.5).

2.10 Invasive Plants

Published information on the impacts on invasive plants of retaining aspen in conifer stands is lacking. The Literature Review, Section 2.11 provides a brief overview of unpublished results.

2.11 Fire Hazard

Limited published information has indicated that aspen stands are half as flammable as conifer stands, and therefore can serve as fire breaks (Fechner and Barrows 1976). However, aspen's effectiveness as a fire break is reduced under severe weather conditions or when fuel loads are high. Unpublished information indicates that mixed stands also provide benefits, but clumping is better because it creates breaks in the canopy, which can slow fire spread in crowns (Misener 2009). Flammability of conifer stands in Quebec is reduced when aspen and paper birch are mixed in the stands because there is less small woody material, fewer conifer pieces, and less aerated organic matter (Hely et al. 2000a). Flammability is also lower in pure broadleaf stands than in mixedwoods in Quebec (Hely et al. 2000a).

2.12 Cultural Values

Information on the cultural use of pure conifer or pure broadleaf stands versus mixtures of the two is lacking. However, information on historic and cultural values of individual broadleaf species has been documented, especially with regards to First Nations peoples (Literature Review, Section 2.13, Table 15).

2.13 Visual Values

Published information on the visual values of pure conifer versus mixed conifer–broadleaf or pure broadleaf forests is lacking.

3 Knowledge Gaps

Overall, quantitative information on the impacts of including broadleaf trees in managed stands in the BWBS and SBS zones in British Columbia is scarce. (Table 1). In general:

- Growth and yield implications of managing for mixed versus pure stands are documented more frequently than influences of other values.
- For values other than growth and yield, there is more information on pure conifer versus pure broadleaf stands than on mixed conifer–broadleaf stands versus pure stands of the component species.
- For all values, information on lodgepole pine–trembling aspen mixtures is more limited than that on white spruce–aspen mixtures.

Information from boreal regions in other Canadian provinces is also limited and is not necessarily applicable to British Columbia because study sites may differ in site factors, such as climate and soils, and tree species composition. Stand age, stand structure, tree density, and experimental approaches also differ among studies, which makes comparisons difficult and extrapolations to other conditions inappropriate in many situations. More site- and region-specific information is needed.

Further development of models to predict future growth and yield and other values in boreal and sub-boreal mixedwood forests is critically needed. This is essential for making sound management decisions. The growth and yield models calibrated for boreal forests in western Canada are TASS/TIPSY (currently for single species only, but including trembling aspen) and the Mixedwood Growth Model (calibrated for boreal mixedwood stands). There currently are no models calibrated for the SBS zone. Models need to predict not just growth and yield but also ecosystem responses to forest management treatments and scenarios.

The possibilities for innovative management of white spruce–trembling aspen mixtures are well described (e.g., Lieffers, MacMillan et al. 1996; University of Northern British Columbia 2002; Comeau et al. 2005) and serve as a good starting point for innovative operational management. However, in general, the long-term impacts of these regimes on growth and yield, site/soil productivity, forest health, biodiversity, wood quality, economics, and other values are not known. Priority needs to be placed on increasing our understanding of the potential outcomes of the tending and management practices that have been identified for creating or perpetuating mixed stands. The range of ecosystem components that should be monitored for forestry purposes needs to be identified, and monitoring protocols and methodologies need to be developed. These types of innovative systems have not been developed for lodgepole pine–aspen mixtures, probably because management choices are limited because both species are shade-intolerant.

Long-term monitoring and analysis of data for BWBS and SBS mixed stands is needed so that predictions that are based on shorter term data and produce reliable operational guidelines can be validated or revised. Long-term data are important in British Columbia because rotations are long and stand development following canopy closure may be quite different than early on. Long-term data can be obtained from reporting on data already collected, measurements of existing installations, and putting in new installations to fill knowledge gaps.

Because of public pressure to reduce broadcast herbicide use, alternative vegetation management treatments need to be tested to determine if they are effective in terms of growth and yield, environmental, economic, and social outcomes. Issues that have been raised with regards to herbicide use are the possible effects on natural succession patterns, long-term species diversity, ecosystem stability, and degradation of wildlife habitat and cultural values (Harper and Kabzems 2003), all of which are largely unknown. New or revised treatment regimes are also needed to respond to changes in government requirements and policies (e.g., requirements for retention of CWD). There is also pressure from the forest industry to reduce all costs, including those associated with brushing and planting. Knowledge about the long-term consequences of changing practices, policies, or standards is lacking.

Specific knowledge gaps are as follows:

Economics

- Long-term economic analysis of alternative silviculture treatments for boreal and sub-boreal mixedwoods is critically needed. Of 1256 scientific publications that were directly related to vegetation management (as of 2002), only 18 (1.4%) included an economic analysis of forestry vegetation management treatment (Thompson and Pitt 2003, cited by Homagain et al. 2011), and only three focused on boreal tree species.
- Analyses should be conducted for a range of conditions (e.g., varying interest rates, rotation ages).
- The range of up-front (short-term) costs of conventional silviculture treatments (e.g., planting) have been documented (e.g., Comeau et al. 2005), but further summaries of past cost records would allow more site-specific and treatment-specific costs to be made available. It would be useful to complement costs derived from operational experience with data from controlled research trials that compare a range of less conventional treatments (e.g., brushing with various levels of retention).

Wood quality

- The effects of various densities of aspen or other broadleaf trees on wood quality have not been documented in the literature.

Growth and yield

- The short-term effects on conifers and vegetation of chemical and manual brushing to control broadleaf competition are well documented (e.g., Harper et al. 1997, Biring et al. 1999) ; therefore, this is not a critical knowledge gap.
- Long-term quantitative data on growth and yield of mixed versus pure stands are needed to add to and verify the limited amount of existing local data. Monitoring of, and long-term research on, post-free-growing stands is needed. Tree productivity data are needed for both white spruce and lodgepole pine, and for a range of species proportions, stand densities, stand structures (e.g., canopy stratification), climatic areas, and sites. Priorities for data collection need to be set because there are too many combinations to study all situations.
- Several long-term (30–50 year) studies on white spruce volume responses to removing aspen overstories were conducted in the 1960s and earlier in Alberta, Saskatchewan, and Manitoba (release treatments), but no such long-term studies exist for British Columbia and none provide data on underplanting, planting into partial cuts/shelterwoods, or thinning of conifer–aspen mixtures where the two species are established concurrently.
- Underplanting has frequently been identified in the literature (e.g., Comeau et al. 2009) as a good treatment option for growing white spruce–aspen mixtures, but because understorey spruce performance has not been good in all cases, further trials in a range of conditions,

including varying aspen basal area/densities, would help identify situations where underplanting can be expected to be successful.

- Data on white spruce responses to planting in shelterwoods are very limited for British Columbia (one study) and elsewhere in Canada (one study in each of Alberta, Saskatchewan, and Ontario). Further study of responses of natural and planted spruce to shelterwood cuts would help quantify the effectiveness of this system.
- Quantitative data for lodgepole pine–aspen mixtures in the SBS have been collected to determine if existing free-to-grow standards make biological sense (i.e., whether free-to-grow trees have better growth than non-free-to-grow trees), but these types of data are lacking for spruce in both the SBS and BWBS zones.
- In the SBSdw subzone, short-term data indicate that a density of 1000 aspen per hectare will allow for acceptable lodgepole pine performance, but the long-term effects of this density of aspen on the timber supply is unknown.

Inventory data

- Existing growth and yield information for tree species and species mixtures in the BWBS is inadequate (UNBC's 2002 report to Dave Harrison, Canadian Forest Products).
- Repeated measurement of existing long-term boreal and sub-boreal mixedwood Permanent Sample Plots should be a priority.
- There is a need to determine which mixedwood stand types and ecosystem units are under-represented in Permanent Sample Plots, and these gaps need to be filled.

Natural disturbance, succession, and stand dynamics

- Information on how stands in the BWBS and SBS evolve after being declared free-to-grow is critically need.
- The development of conifer–aspen mixedwoods from establishment to harvest and the effect of broadleaf density on development need to be tracked.
- The way successional pathways differ between natural mixedwood and managed stands needs to be studied.

Natural regeneration

- Few studies have examined the interactions of natural spruce seedlings with broadleaf trees.

Competitive interactions in mixedwoods

- Much research has focused on the role of light in competitive interactions between aspen and conifers, but less work has been done on the contributions of soil moisture and temperature.
- Relationships between conifer growth and interspecific competition have been published (see Literature Review), but they are specific to the site (e.g., elevation, aspect, slope), study location

(climate), and stand age. The influence of stand age, climatic and site conditions, and year-to-year variations on competitive interactions is not well known.

- Long-term additive and replacement series studies are necessary to describe mixed species competition and facilitation traits.

Carbon storage

- Information on how carbon storage differs between stand types is needed.

Soils

- Greater understanding of soil processes (e.g., litter decomposition, nutrient cycling, nutrient sequestration, and forest floor development with succession) in boreal and sub-boreal forest mixedwoods compared to pure stands is needed.
- Studies on the effects of mixtures on nutrient cycling and availability are needed in British Columbia because statements that growing conifers with aspen produces nutritional benefits are not supported by data from British Columbia.
- Continued monitoring the Long Term Soil Productivity Study is needed.

Biodiversity, in general

- Available information suggests that biodiversity is linked to forest composition, age, and habitat features, but there is a significant knowledge gap regarding the short- and long-term impacts on biodiversity of changing the composition of mixedwood stands in the BWBS and SBS, including converting them to pure stands. Biodiversity in managed pure stands should be compared to that in mixedwoods for a range of species compositions and ages.

Birds

- Bird communities differ among old mixed spruce–aspen, spruce, and aspen stands (e.g., Schieck and Song’s 2006 meta-analysis), but no studies were found that compared avian communities in mixed conifer–broadleaf stands with those in pure stands in the BWBS or SBS zones in British Columbia.
- The pattern and relative amount of each type of boreal forest required for long-term maintenance of birds in managed landscapes is unknown and requires further research. Information on how to remedy negative effects of habitat loss and fragmentation at the landscape scale is needed.
- Studies that focus on bird communities rather than single species are needed.

Mammals

- Published literature provides general information on the benefits that aspen provides to mammals (e.g., Peterson and Peterson 1995), but no studies were found that compared

mammal use of aspen–conifer stands to pure conifer or pure aspen stands in boreal or sub-boreal forests.

Understorey vegetation

- Vegetation under mixed conifer–aspen canopies is not well studied in boreal and sub-boreal regions of British Columbia, even though it influences overstorey succession, nutrient cycling, and long-term productivity, and provides food and habitat for faunal communities (Hart and Chen 2008; Chavez and Macdonald 2012). Comparisons of vegetation communities under mixed stands versus aspen–conifer stands have been made in Alberta, Ontario, and Quebec but not British Columbia.
- Research is needed to better understand the relationship between overstorey and understorey vegetation. There currently is not enough information to draw conclusions about the effect of any particular overstorey tree species on the understorey vegetation.
- Quantitative evaluation of the factors that control understorey vegetation abundance, diversity, and composition in boreal and sub-boreal forests in British Columbia is lacking.
- More information on competition from understorey vegetation in mixedwoods is needed, and the understorey needs to be incorporated into mixedwood models.

Roots/mycorrhizae

- Little research has been conducted on the prevalence and mechanisms of beneficial below-ground interactions in mixed stands (Kelty 2006).
- Mycorrhizal connections between root systems of paper birch and Douglas-fir facilitate the transfer of water, nutrients, and carbon between the two tree species (Simard et al. 1997), but it is not known if this is true for aspen and white spruce or lodgepole pine.
- Mixed spruce–aspen stands have spatially stratified root systems (Lawrence et al. 2012), but it is not known if this improves nutrient utilization and productivity in these stands.

Hydrology

- Effects of broadleaf trees on hydrology have been studied, but information on the effects of mixed versus pure stands on hydrology in British Columbia is not available.

Forest health

- Attack levels from forest pests such as white pine weevil decrease as the cover of broadleaf overstories increase (Taylor and Cozens 1994), but the optimum level of broadleaf cover at which pest attack is reduced and conifer growth is not limited due to competition is not known.
- Long-term studies involving experimental manipulations rather than just observations of natural forests are needed to test the effects of forest diversification on pests and pathogens.

- Effects of tree species diversity on forest pests need to be examined over a large scale rather than just within a few hundred square metres.
- Formal studies on physical damage to conifers caused by aspen are lacking.
- Trends regarding the influence of the overstorey on hare and frost damage levels are known.

Cultural values

- Information on the cultural importance of mixed stands in boreal and sub-boreal British Columbia needs to be compiled. Formal information is not available in the literature, but information could be derived from interviews with First Nations and other groups.

4 Summary

This report provides a summary of a comprehensive literature review on the potential impacts and influences of including broadleaf trees in managed boreal and sub-boreal stands in British Columbia. Growth and yield and a range of other values were compared for mixedwoods and “pure” stands. The report focuses on white spruce–trembling aspen and lodgepole pine–trembling aspen mixtures in the BWBS and SBS zones in central and northern British Columbia, but information from boreal regions in other Canadian provinces was also included due to the scarcity of local information.

Key findings of this review are as follows:

- Including broadleaf trees in conifer stands makes it difficult to meet current free-growing requirements.
- Chemical treatments are more cost-effective in the long-term than other aspen removal treatments. Planting without removing broadleaves results in lower long-term financial returns than removing broadleaves. However, cost-effectiveness of different treatments depends on future value and demand for broadleaves compared to conifers, which is largely unknown.
- Including broadleaf trees in conifer stands can increase conifer wood quality.
- The Mixedwood Growth Model consistently projects reduced spruce volume at rotation when broadleaves are included in stands. Including broadleaves in conifer stands amounts to trading some of the conifer volume for broadleaf volume, and results in similar or higher total volume than in pure stands.
- Mature aspen stands with a spruce component have greater total productivity than mature pure aspen stands.
- Removing aspen from even-aged spruce–aspen mixtures usually results in increased diameter growth and decreased height:diameter ratio of spruce but does not consistently benefit height growth. The volume of spruce 5–10 years after complete aspen removal tends to be double that in untreated controls.
- Underplanted spruce tend to have reduced diameter and height growth compared to spruce grown in the open.

- Survival of underplanted white spruce tends to be good provided aspen canopies are not too dense. Survival of spruce planted into regenerating aspen tends to be good.
- Completely removing an established aspen canopy tends to result in substantially increased height, diameter, and volume growth of white spruce. Growth responses are lower when aspen is partially removed.
- Height growth of lodgepole pine in the SBS zone is not consistently improved by reducing aspen density, but some studies show height growth is reduced when aspen density is greater than 4000–5000 SPH.
- Some studies conducted in the SBS zone have shown that diameter growth of juvenile lodgepole pine starts to decrease at aspen densities of 1000–2000 SPH, but in other studies this density of aspen had no effect on diameter growth.
- Thresholds for conifer performance are specific to the site and stand age.
- Nutrient availability is generally assumed to be higher under broadleaf than white spruce or lodgepole pine canopies, but some evidence from the BWBS zone has shown that this is not always true.
- Mixed spruce–aspen stands exploit soil resources more effectively and have higher fine root productivity and more diverse ectomycorrhizal fungi than do pure stands.
- Broadleaf stand types usually have the highest species diversity, but sometimes mixed stands have the highest diversity. Species that are specific to mixed stands have not been identified, but species composition of mixed stands tends to include species found in both pure broadleaf and pure conifer stands of broadleaf and conifer stands. Removal of aspen canopies tends to increase or cause a shift in species composition of the understorey vegetation.
- Avian species diversity appears to be greater in aspen–conifer mixedwoods than in pure stands. A few species are mixed-stand specialists.
- The presence of an aspen canopy can reduce frost damage and weevil attack levels but can lead to increased hare damage. A broadleaf component in stands can reduce the incidence of root disease.
- Aspen stands are less flammable than conifer stands and can serve as firebreaks.
- Broadleaf trees are important for their cultural and visual values.

A range of potential strategies for mixedwood management has been identified for British Columbia, but overall there is insufficient information to predict their outcomes. Many information gaps exist, particularly for non-timber forest values, and especially for lodgepole pine–trembling aspen mixtures. Local information (i.e., from central and northern British Columbia) was limited, and information from other Canadian provinces was insufficient to fill those information gaps. The relevance of non-local studies to the situation in British Columbia was often questionable (e.g., due to different climatic, soil, and other site factors).

The knowledge gaps that were identified based on the literature review provide direction for future research in British Columbia. Quantitative information is needed to verify or refute opinions that are not based on scientific evidence or that are based on very limited evidence. For example, it is generally assumed that broadleaf trees enhance nutrient availability, but evidence from British Columbia indicates

that this is not necessarily true. Further study is needed to address this subject. As well, opinions appear to be circulating about whether mixed stands are more productive than pure stands, and although the findings of this review suggest that they may be in some cases, additional data are required to clarify the findings. Another important topic that is not well addressed in the literature is the impact on biodiversity of eliminating or reducing broadleaf presence.

In summary, retaining broadleaf trees (especially aspen) in managed BWBS and SBS stands in northern and central British Columbia has both advantages and disadvantages. Broadleaf competition tends to reduce conifer volume but not at low densities (e.g., <1000 SPH). Resource managers need to consider whether some reduction in conifer volume is tolerable, and whether there is a future market for broadleaf timber. Including broadleaf trees in managed stands is important for retaining non-timber values, but further investigation into this type of management is needed.

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