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Evidence against planting lodgepole pine monocultures in the cedar–hemlock forests of southeastern British Columbia

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Single-species planting of lodgepole pine (*Pinus contorta* var. *latifolia*) following clear-cut logging or wildfire has been common throughout interior British Columbia, Canada, but health problems with the species have been documented as it grows beyond the juvenile stage. We examined damage and stocking in twenty-seven 15- to 30-year-old lodgepole pine plantations that were previously declared free growing in the highly productive cedar–hemlock forests in southeastern British Columbia, where lodgepole pine is absent from many primary forests. In order to be free growing, stands must meet minimum tree density, height, damage and brush competition criteria as legislated by the Provincial government. Overall, 44 per cent of lodgepole pine trees had unacceptable damage (causing them to be rejected as crop trees), and as a direct result, one-third of the plantations were no longer defined as free growing because there were insufficient crop trees remaining. Natural regeneration of other tree species partially compensated for the unhealthy pine. Logistic regression and odds ratio analysis associated increasing risk of damage from western gall rust with increasing soil moisture, more northerly aspects and mechanical site preparation, and decreasing risk with pre-commercial thinning treatment. Risk of damage from snow and ice was associated with increasing mean annual precipitation, decreasing longitude and broadcast burning. Risk of bear damage was associated with increasing soil moisture, pre-commercial thinning treatment and broadcast burning. Based on our results, we recommend that single-species planting of lodgepole pine be curtailed in the Interior Cedar–Hemlock zone in southeastern British Columbia.

Introduction

There is a long history of introducing tree species from areas where they are native to other areas in the world, driven by economic, aesthetic, scientific and other reasons. Lodgepole pine is one of several North American tree species that has been planted outside of its native range, including New Zealand and parts of Europe such as Sweden (Gundale *et al.*, 2014). In Sweden, lodgepole pine has been planted on a large scale since the 1970s to meet a predicted shortage of harvestable softwood (Engelmark *et al.*, 2001). It is a desirable species because it can produce 36 per cent greater total volume growth than the native Scots pine (*Pinus sylvestris* L.), regardless of site index (Elfving *et al.*, 2011). The success of lodgepole pine in Sweden has been associated with a more favourable soil biotic community than in native Canada (Gundale *et al.*, 2014). However, it is well known that transferring species to areas outside of their natural range can also have potentially serious consequences. For example, the introduction of lodgepole pine to New Zealand has resulted in prolific unwanted natural regeneration, which is a threat to indigenous flora and fauna as well as visual and landscape values, and it is now largely considered a weed species and seldom planted (Ledgard, 2001). In Sweden, introduced lodgepole pine has also spread outside of areas where it was initially planted (Engelmark *et al.*, 2001). Pests and pathogens from the introduced lodgepole pine could potentially spread to native tree species such as Scots pine, which have not co-evolved with these exotic pests.

While lodgepole pine has been introduced to countries far from its natural range, it has also been transferred outside its productive range within British Columbia, Canada. This includes areas where it is not prevalent naturally in primary forests, such as the cedar–hemlock forests in the interior of the province. In the Interior Cedar–Hemlock (ICH) zone in the Kootenay–Boundary Forest Region in southeastern British Columbia, lodgepole pine was absent or a minor pre-harvest species on 53 per cent of sites where it was planted in the last 15–30 years (British Columbia Ministry of Forests, Lands and Natural Resource Operations, 2011). Western redcedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) dominate late successional ICH forests, and mixtures of interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), western white pine (*Pinus monticola* Douglas ex D. Don), western larch (*Larix occidentalis* Nutt.) and lodgepole pine are the major species in early successional ICH forests. The ICH zone contains the most productive forests in interior British Columbia (Meidinger and Pojar, 1991). To take advantage of the high potential timber yields in the ICH zone, it is important to regenerate sites with tree species that will be healthy and productive until they reach maturity. Lodgepole pine is among the fastest growing species in the ICH zone for the first 10 to 30 years, which has contributed to its use as a preferred regeneration species in this zone, but by age 80, it has lower yield than almost all other natural associated species (Vyse *et al.*, 2013). The long-term health of stands is largely unknown because they are not usually monitored after they reach 'free growing', the point where licensees are relieved from the reforestation obligations set by the provincial government. A free-growing stand is comprised of trees of preferred or acceptable species that are ecologically suited to the site and meet established criteria for health, height, density, spacing and overtopping vegetation (British Columbia Ministry of Forests, 2000) (see Table 1 for definitions of terms). Once a stand reaches this important administrative milestone, which is usually at age 7–20 years, the stand is assumed to remain healthy and productive until the next harvest. There is mounting evidence, however, that in British Columbia lodgepole pine plantation health beyond the free-growing assessment age is often poor (Heineman *et al.*, 2010). Poor pine health has been documented across six biogeoclimatic zones in southern interior British Columbia, but health concerns were highest in the ICH zone where 70 per cent of lodgepole pine stands previously declared free growing no longer met this requirement by age 15–30 (Mather *et al.*, 2010). Two-thirds of the lodgepole pine in the plantations studied was damaged, and 93 per cent of this damage was 'unacceptable' (preventing free growing, that is, causing the tree to be rejected as a potential crop tree).

The health of lodgepole pine plantations may decline even further as climate change progresses (Dale *et al.*, 2001). Climate change is likely to have a profound and long-term impact on forest ecosystems in British Columbia and may provoke losses of other goods and services that sustain communities and the provincial economy. Changes in precipitation and temperature can affect forests by altering the frequency, intensity, duration, extent and timing of fire, drought, insect and pathogen outbreaks, windstorms, landslides, ice storms or hurricanes (Dale *et al.*, 2001). Forests dominated by a single species such as lodgepole pine are expected to be particularly susceptible to catastrophic losses, as was seen with the recent mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic in interior British Columbia (Kurz *et al.*, 2008). The current widespread distribution of lodgepole pine in western North America is predicted to be dramatically altered under a changing climate, with other species progressively favoured and lodgepole pine potentially disappearing from much of its current range by 2070 (Coops and Waring, 2010). Other important conifer species in British Columbia are also expected to significantly decrease in frequency and/or lose a large portion of their suitable

Table 1 Glossary of terms

Term	Meaning
Silviculture prescription (SP)[a]	A silviculture prescription outlines the required management objectives, standards and timelines that the owner of an opening must achieve, including reaching a free-growing stand.
Target stocking standard (TSS)[b]	Target stocking is the number of well-spaced preferred and acceptable trees per hectare that will, under normal circumstances, produce an optimum free-growing crop. On circum-mesic sites, TSS in the ICH zone has averaged 1200 stems ha^{-1}, although planting density is often higher (up to 1600 stems ha^{-1}). The TSS is 50 to 70% higher than the MSS. Significant volume reductions are projected if stands are managed to minimum rather than target stocking standards.
Minimum stocking standard (MSS)[b]	Minimum stocking standard is the lowest number of acceptable well-spaced stems per hectare required to consider an area satisfactorily stocked at the free-growing stage.
Well-spaced[b]	Well-spaced trees are healthy trees of preferred or acceptable species that are at least the minimum horizontal inter-tree distance from other well-spaced trees. The inter-tree distance is specified in the silviculture prescription and is usually 2 m.
Free growing[b]	A free-growing tree must be well-spaced, free from damage as defined in the free-growing damage criteria, the required minimum height specified in the SP or in the 'Establishment to Free Growing Guidebook', and free from unacceptable brush and broadleaf tree competition as described in the *Establishment to Free Growing Guidebook*.
Preferred and acceptable species[b]	Preferred and acceptable species are those species that are ecologically suited to the site. Preferred species are those that best meet the management objectives for a site and will produce the greatest volume of high-quality saw logs over the rotation. Acceptable species may occur as a component of mixed stands but are not considered to be the target species for a site.
Unacceptable damage	Unacceptable damage is the term we use in this article to refer to damage that prevents a tree from being well-spaced and free growing.
Monoculture plantation	Monoculture plantations is the term we use when a single species is planted on a site. Natural regeneration may also occur, so that the resulting stands are not 'monoculture stands'.
Monoculture stand	Monoculture stands are stands in which ≥80% of the trees on the site are comprised of one species.

[a]British Columbia Ministry of Forests 2002.
[b]British Columbia Ministry of Forests 2000.

habitat, including subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), white spruce (*Picea glauca* (Moench) Voss), Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) and black spruce (*Picea mariana* (Mill.) B.S.P.) (Hamann and Wang, 2006).

Our study investigated the current state of monoculture lodgepole pine plantations, and logistic regression and odds ratios were used to associate certain factors with risk of damage to lodgepole pine. In this article, ‘monoculture lodgepole pine plantations’ are defined as those where lodgepole pine was the only species planted; however, these stands may include other naturally occurring species. We define ‘monoculture forests’ as stands comprised of ≥80 per cent one tree species, which may or may not be of natural origin. The overall objective was to investigate stocking and damage incidence in 15- to 30-year-old lodgepole pine plantations that were previously declared free growing. The study area was the ICH forests of the Columbia Basin in southeastern British Columbia, Canada. Previous studies of lodgepole pine health in this area are lacking. Six questions were posed: (1) Are lodgepole pine plantations that were previously declared free growing continuing to meet stocking and free-growing requirements past the juvenile stage (at age 15–30 years)? (2) How much and what species of natural regeneration occurs in these plantations and to what degree is it contributing to free-growing success? (3) What are the biotic and abiotic causes of damage leading to reductions in stocking, and what are their extent and incidence levels? (4) Are certain climatic, site or stand factors or silviculture treatments associated with increased risk of damage to lodgepole pine from the most prevalent damaging agents? (5) How can management practices be adjusted to address increased risk of damage associated with these factors? (6) Given climate change predictions, is damage from the major agents likely to worsen over time?

Methods

Study area

A total of 27 plantations were sampled throughout the ICH zone in the Columbia Basin in southeastern British Columbia, between 49° 04′ N and 51° 53′ N latitude and 114° 58′ W and 118° 05′ W longitude. The Columbia Basin drains the Columbia River and covers 671 000 square kilometres, making it the sixth largest river basin in North America. About 15 per cent of the Basin lies within Canada (Columbia Basin Trust, 2008). In British Columbia, it extends from the Canada–US boundary north to the Kinbasket Reservoir, and from the British Columbia–Alberta border to just west of the Upper and Lower Arrow Reservoirs. It is located within the Kootenay–Boundary Forest Region. Within the Basin, the ICH zone occupies valley bottom to mid-slope positions (400–1550 m), below the Engelmann spruce-subalpine fir (ESSF) zone. The ICH zone has an interior, continental climate with warm dry summers and cool wet winters and is among the wettest zones in the interior of British Columbia (Meidinger and Pojar, 1991). Long-term mean annual precipitation (MAP) averages 640–1128 mm y^{-1}, and mean summer precipitation (MSP) averages 211–385 mm y^{-1}. It is the most productive forested zone in interior British Columbia (mean annual increment up to 30 m^3 ha^{-1} y^{-1}) and has the highest natural tree species diversity of that region (site richness up to 15 species ha^{-1}) (Simard and Vyse, 1992). In the wetter parts of the ICH zone in the Columbia Basin, wildfires have been infrequent and large areas are dominated by climax stands, comprised of western redcedar and western hemlock throughout, and with hybrid Engelmann-white spruce and subalpine fir also common at higher elevations and where cold air drainage occurs. In drier ICH subzones in the Columbia Basin, wildfires have been more frequent, resulting in seral stands that include lodgepole pine, western larch, interior Douglas-fir, western white pine, trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.) and black cottonwood (*Populus balsamifera* ssp. *trichocarpa* (T. & G.) Brayshaw). Seven ICH subzones occur in the Columbia Basin, with the most widespread the ICHmw (Moist Warm), where the greatest number of the sample sites were located (17 of 27). Sampling was also conducted in the ICHmk (Moist Cool), ICHdm (Dry Mild) and ICHdw (Dry Warm) subzones. Plantations were not assessed in the ICHwk (Wet Cool) or ICHvk (Very Wet Cool) subzones because accessible surviving plantations of the appropriate age could not be found, nor in the ICHxw (Very Dry Warm) subzone because of its limited occurrence in the Columbia Basin, and British Columbia as a whole. Elevation of the sites ranged from 680 to 1550 m, and the absolute soil moisture regime varied from moderately dry to fresh, which was classified using methods described in British Columbia Ministry of Forests and Range and British Columbia Ministry of Environment (2010). Slope positions were lower, mid and upper, aspect was variable and slope gradient ranged from 0 to 60 per cent. Characteristics of the study sites are summarized in Table 2.

Site selection

Twenty-seven sites were randomly selected from the population of 1386 plantations in the British Columbia government RESULTS database of silviculture activities (British Columbia Ministry of Forests, Lands and Natural Resource Operations, 2011). The population sites: (1) were located in the ICH zone in the Columbia Basin, (2) were planted with lodgepole pine between 1981 and 1996 (15–30 years prior to field sampling), (3) had no other species except lodgepole pine planted and (4) met provincial standards for free growing prior to 2011.

Sampling from across the geographic range of the Columbia Basin was stratified, with sites randomly selected in three site preparation categories (no site preparation, broadcast burn and mechanical site preparation) and three stand tending categories (no stand tending, pre-commercial thinning and weeding). Broadcast burning is the controlled application of fire across a cut block to reduce slash (logging debris such as branches) and/or vegetation density. Mechanical site preparation involves the use of heavy equipment to physically alter slash, forest floor and mineral soil layers by a variety of methods, including scalping (exposing patches of mineral soil), disc trenching (creating continuous or intermittent furrows), mixing (chopping together vegetation, forest floor and mineral soil) and mounding (creating raised planting spots). Pre-commercial thinning involves mechanically cutting trees out of juvenile stands, usually with chainsaws, to reduce tree density and competition between trees in a stand, usually with the objective of concentrating growth on fewer high-quality trees. Weeding involves removing or reducing abundance of vegetation or broadleaf trees that are competing with crop trees. The weeded sites in our study were treated by manual cutting rather than herbicide application.

We sought to randomly sample nine sites in each site preparation category and nine sites in each stand tending category. This was not possible, however, due to insufficient numbers of accessible sites with the required treatment history. Instead, seven burned, eight mechanically prepared and 12 sites with no site preparation were randomly sampled ($n = 27$). For standing tending, seven of these were weeded, five pre-commercially thinned and 15 were not treated ($n = 27$). Although some sites had both site preparation and stand tending treatments applied, these two treatment categories were evaluated as individual effects.

Field sampling

All field sampling was conducted in July and August, 2011. At each site, six 50 m^2 ($r = 3.99$ m) plots were systematically established at 50-m intervals along a randomly located transect. Site series, elevation, slope gradient, aspect, slope position and absolute soil moisture regime (i.e. based on a conversion from a relative to absolute scale for sites in the

Table 2 Summary of site, climatic and tree species characteristics of the study sites by biogeoclimatic subzone

Variable description	Biogeoclimatic subzone			
	ICHmw	ICHmk	ICHdw	ICHdm
Number of sites	17	2	3	5
Climatic region	Moist	Moist	Dry	Dry
Temperature class	Warm	Cool	Warm	Mild
Climate description[a]	Hot moist summers Very mild winters with light snowfall	Warm wet summers Cool winters with moderate snowfall	Very hot moist summers Very mild winters with light snowfall	Hot dry summers Cool winters with light snowfall
Mean annual temperature (°C)[b]	3.7	3.6	5.1	3.7
Mean warmest monthly temperature (MWMT) (°C)[b]	15.0	15.1	16.3	15.4
Mean coldest monthly temperature (MCMT) (°C)[b]	−7.7	−7.8	−5.9	−8.1
MAP (mm)[b]	914	841	747	860
MSP (mm)[b]	330	333	264	277
Precipitation as snow (PAS) (mm)[b]	374	334	260	386
Total number of frost-free days (NFFD) (days)[b]	163	159	180	161
Number of continuous frost-free days (FFP) (days)[b]	92	86	108	89
Elevation (m)	680–1492	1099–1240	913–1188	1053–1590
Slope (%)	0–60	35–60	5–50	5–40
Forest characteristics[a]	Moderate-to-recurrent fire return periods have led to a mosaic of seral and climax stands.	Extensively disturbed by wildfire so climax stands are rare. Seral stands dominated by Pl are common.	Fire origin stands of Fd and Lw very common. Many stands originated around 1900 from fires set by mines. Few climax or old growth stands exist.	Mixed stands of Lw, Pl, Hw, Cw, Sxw and Bl are most common. Broadleaf trees are uncommon.
Climax tree species[a]	Hw[c], Cw	Cw, Sxw, Bl	Cw, Hw	Cw, Hw (Sxw, Fd, Lw)
Seral tree species[a]	Fd, Lw, Sxw, Bl, (Hw, Cw)	Pl, Fd, Lw	Fd, Lw, Pw, Ep	Cw, Hw, Fd, Bl, Lw, Pl

[a]General subzone characteristics from Braumandl and Curran (1992) and Braumandl and Dykstra (2005).
[b]Determined from Climate BC for the period 1971–2000 (Wang *et al*., 2006) based on latitude and longitude recorded at individual sites.
[c]Tree species codes (in alphabetical order): Bl (subalpine fir, *Abies lasiocarpa*), Cw (western redcedar, *Thuja plicata*), Ep (paper birch, *Betula papyrifera*), Fd (Douglas-fir, *Pseudotsuga menziesii*), Hw (western hemlock, *Tsuga heterophylla*), Lw (western larch, *Larix occidentalis*), Pl (lodgepole pine, *Pinus contorta*) and Sxw (hybrid spruce, *Picea engelmannii x glauca*). Less common species are in parentheses.

Kootenay–Boundary Forest Region) were recorded at each plot using methods described by British Columbia Ministry of Forests (British Columbia Ministry of Forests and Range and British Columbia Ministry of Environment, 2010). Aspect was recorded in degrees and later converted to the continuous variable, northness (cosine (aspect × 3.14159/180)). Soil moisture regime was based on site characteristics (presence of indicator species in the understory vegetation, slope position, slope gradient, aspect and soil texture) and was converted to a categorical scale of 2 (very dry) to 6 (very moist). Within each plot, total, well-spaced and free-growing conifer densities were recorded based on provincial standards (British Columbia Ministry of Forests, 2000) and site-specific silviculture prescriptions. Densities of broadleaf trees (trembling aspen, paper birch and black cottonwood) were also recorded. Planted lodgepole pine were distinguished from naturally regenerated lodgepole pine based on their regular spacing and difference in size. All other tree species were counted as naturally regenerated. All trees were assigned to a height class (<2, 2–4 and >4 m) and diameter at breast height (1.3 m from the base) (DBH) was recorded for all well-spaced trees of >1.3 m tall. Well-spaced trees are healthy trees of preferred or acceptable species that are at least the minimum horizontal inter-tree distance (usually 2 m) from other well-spaced trees. If they meet minimum height requirements and are not impeded by vegetation competition, they are also free growing. Symptomatic presence of all disease, insect, animal and abiotic damage were recorded for all trees according to Henigman *et al*. (2001). Damage was classified as 'unacceptable' (failing to meet the health standards defined by the British Columbia provincial free-growing guidelines) or 'acceptable' (not serious enough to disqualify the tree from being classified as free growing). Standards for acceptable and unacceptable damage are found in the 'Establishment to Free Growing Guidebook' (British Columbia Ministry of Forests, 2000) and include the following: unacceptable galls caused by western gall rust (*Endocronartium harknessii* (J.P. Moore) Y. Hirat) are those found on the main stem or on branches within 5 cm of the main stem. Bear damage is unacceptable when scars from bark peeling encompass greater than one-third of the tree's circumference. Criteria for unacceptable snow and ice damage depend upon the type of damage (e.g. broken stems, forks, bends). Foliar diseases are unacceptable when ≥80 per cent of the crown is affected.

All instances of white pine blister rust are unacceptable and western white pine was not a preferred or acceptable species on any of our study sites. Broadleaf trees are also not considered crop species in the Columbia Basin.

Analysis

Summary statistics describing damage incidence (acceptable and unacceptable), total, well-spaced and free-growing densities, and height and DBH of lodgepole pine and other species were produced. Logistic regression analysis and odds ratios were used to determine whether the incidence of damage on lodgepole pine from the three most commonly observed agents (western gall rust, snow and ice, and bears) were associated with climatic, location, silvicultural treatment, or site or stand factors. The general form of the model was:

$$P(Y) = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k)/(1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k))$$

where $P(Y)$ is the probability of incidence of a damaging agent. β_0 is the intercept, $\beta_1, \ldots, \beta_k$ are estimated coefficients and $x_1, \ldots, x_k$ are independent climatic, location, silvicultural treatment, or site or stand variables. Three regressions were used, one each for western gall rust, snow and ice, and bears.

Logistic regression analysis was done using SAS PROC LOGISTIC (SAS Institute, Inc. 2002–2003). A total of 162 plots were used in the analysis. The events/trials syntax of PROC LOGISTIC was used where the events were equal to the number of trees in a plot affected by a given agent, and trials were equal to the total number of trees in the plot. Latitude, longitude, elevation, northness, slope gradient, stand and climatic variables were continuous predictive factors, soil moisture and slope position were categorical and the silviculture factors were binary (coded by plot as 'yes' or 'no').

For each of the three common damaging agents, a stepwise regression model was fitted with predictive factors allowed to enter or leave the model automatically using relative probability Wald $\chi^2 \leq 0.05$ as the default criteria for inclusion. The order in which individual factors were accepted into the model reflects their relative probability χ^2 value and therefore their relative importance in the model. For each factor included in the final model, odds of the agent occurring (i.e. the probability of an event divided by the probability of non-event) were calculated and an odds ratio (the multiplicative factor by which risk changed when the independent variable increased by one unit) was determined. Due to the logarithmic nature of odds ratios, a change in 'x' units of the predictive factor corresponded to a change in risk of the damaging agent equivalent to the odds ratio raised to the power 'x'. Odds ratios above 1 indicated increased risk and those below 1 indicated decreased probability. The validity of the final models was assessed using the Hosmer–Lemeshow (H-L) statistic (Hosmer and Lemeshow 1980), which indicates the extent to which the model provides better fit than a null model with no predictors. A non-significant H-L statistic ($P = 0.05$) provides evidence the model adequately fits the data.

Results

Total stocking

Total conifer stocking averaged 4629 stems ha^{-1} across all subzones and tended to be highest in the ICHmw, then the ICHdm and ICHdw and much lower in the ICHmk subzone, where most of the trees on the sites were lodgepole pine (Table 3). Lodgepole pine density (planted plus natural) averaged 1599 stems ha^{-1} across all sites and trends by subzone followed that of total conifer density but the variation among subzones was not as great (range 1267–1743 stem ha^{-1}).

Free-growing and well-spaced stocking

All plantations had met minimum free-growing requirements prior to 2011 (i.e. ≥700 free-growing stems ha^{-1} as defined by the British Columbia Ministry of Forests (2000)), but at age 15–30 years, one-third had <700 free-growing stems ha^{-1} and very few met the target free-growing density of 1200 stems ha^{-1} (Table 4). Forty-eight per cent of sites were within 100 stems ha^{-1} of the minimum required free-growing density. Performance was best where other tree species were abundant and total stocking was high. Free-growing stands averaged 3977 total stems ha^{-1} and stands that were not free growing averaged 1141 total stems ha^{-1} (data not shown).

Species composition and diversity

Fifteen per cent of our stands were comprised of ≥80 per cent lodgepole pine, and 19 per cent had free-growing stocking comprised of ≥80 per cent lodgepole pine (Figure 1). Natural regeneration of species other than lodgepole pine averaged 65 per cent of the total stocking (Table 3) but varied considerably among sites. The ICHmk subzone had the lowest density of non-lodgepole pine trees (average 450 stems ha^{-1} or 26 per cent of the total stocking) and the ICHmw subzone the highest (average 3837 stems ha^{-1} or 69 per cent of the total stocking). An average one-quarter of the natural regeneration (1153 stems ha^{-1}) in the lodgepole pine plantations was western redcedar or western hemlock. The other dominant conifer species were Douglas-fir, western larch, western white pine, hybrid spruce and subalpine fir. Density of broadleaf trees (black cottonwood, paper birch and trembling aspen) was variable and averaged 175 stems ha^{-1} across the 27 plantations. Excluding one ICHmw site and one ICHmk site that each had >1000 broadleaf stems ha^{-1} reduced the average broadleaf density to <50 stems ha^{-1}.

Planted lodgepole pine was larger in height and diameter than natural pine or the other species (data not shown). Fifty-seven per cent of lodgepole pine (including naturals) were in the tallest (>4 m) height class, whereas only 16 per cent of the other conifer species were >4 m tall and 59 per cent were <2 m tall. However, western larch, western white pine and to a lesser degree Douglas-fir tended to be taller than the climax species. Twenty-five per cent of broadleaf trees were >4 m tall and 26 per cent were <2 m tall. The average DBH of well-spaced lodgepole pine was 9.4 cm, which is greater than any of the other species (Douglas-fir 7.0 cm; western larch, western red cedar and subalpine fir 6.3 cm; western hemlock 5.1 cm and hybrid spruce 4.6 cm).

Damage

Overall, damage levels to lodgepole pine were high (66 per cent of trees had damage and 44 per cent had unacceptable damage) whereas non-lodgepole pine species tended to be healthier (39 per cent of trees had damage and 12 per cent had unacceptable damage) (Table 5). Lodgepole pine suffered damage from a total of 18 agents across all sites surveyed. Unacceptable damage was the major factor contributing to reduced free-growing and well-spaced stocking levels in the plantations. The three most

Table 3 Total, well-spaced (WS) and free-growing (FG) stocking of conifer tree species at the study sites averaged by biogeoclimatic subzone

Tree species	Stocking (stems ha^{-1}) and proportion of stocking comprised of each species														
	ICHmw (moist warm)			ICHmk (moist cool)			ICHdw (dry warm)			ICHdm (dry mild)			All sites		
	Total	WS	FG	Total	WS	FG	Total	WS	FG	Total	WS	FG	Total	WS	FG
All conifers															
Stocking	5580	1086	962	1717	567	516	2845	844	712	3697	820	713	4629	972	855
%	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Lodgepole pine															
Stocking	1743	439	414	1267	500	483	1289	400	389	1427	307	300	1599	415	395
%	31	40	43	74	88	94	45	47	55	39	37	42	35	43	46
Non-lodgepole pine															
Stocking	3837	647	548	450	67	33	1556	444	323	2200	513	413	3030	557	460
%	69	60	57	26	12	6	55	53	45	61	63	58	65	57	54
Western redcedar															
Stocking	900	108	86	317	0	0	600	89	67	27	13	13	622	80	64
%	16	10	9	18	0	0	21	11	9	1	2	2	14	8	7
Western hemlock															
Stocking	806	108	76	0	0	0	0	0	0	27	20	20	513	72	52
%	14	10	8	0	0	0	0	0	0	1	2	3	11	7	6
Douglas-fir															
Stocking	815	202	184	33	33	0	568	157	67	473	127	93	660	171	141
%	15	19	19	2	6	0	18	19	9	13	15	13	14	18	16
Western larch															
Stocking	180	33	33	33	33	33	333	189	189	1281	273	247	390	95	90
%	3	3	3	2	6	6	12	22	27	35	33	35	8	10	11
Western white pine															
Stocking	231	0	0	0	0	0	22	0	0	0	0	0	148	0	0
%	4	0	0	0	0	0	0	0	0	0	0	0	3	0	0
Hybrid spruce															
Stocking	573	137	120	0	0	0	0	0	0	240	60	33	405	97	82
%	10	13	12	0	0	0	0	0	0	7	7	5	9	10	10
Subalpine fir															
Stocking	329	55	47	67	0	0	11	0	0	167	20	7	244	38	31
%	6	5	5	4	0	0	1	0	0	5	2	1	5	4	4
Grand fir															
Stocking	4	4	2	0	0	0	22	11	0	7	0	0	6	4	1
%	<1	<1	<1	0	0	0	1	1	0	<1	0	0	<1	<1	<1
All broadleaves															
Stocking	434			350			56			20			175		
%	100			100			100			100			100		
Paper birch															
Stocking	359			0			56			0			99		
%	83			0			100			0			57		
Trembling aspen															
Stocking	71			100			0			7			53		
%	16			29			0			35			30		
Black cottonwood															
Stocking	4			250			0			13			23		
%	1			71			0			65			13		

common damaging agents on lodgepole pine were western gall rust, snow and ice, and bears, and because of their prevalence and severity, they are the focus of this paper.

Western gall rust occurred on 97 per cent of sites and affected 39 per cent of lodgepole pine on average (Table 5) (range 3–89 per cent of lodgepole pine infected on individual sites). Seventy per cent of the occurrences were serious enough to reject the tree as free growing.

Snow and ice damage to lodgepole pine occurred on 82 per cent of sites and affected an average of 7 per cent of the pine. The

Table 4 Percentage of sites meeting minimum and target well-spaced and free-growing densities

Subzone	No. of sites	Sites meeting criteria (%)					
		Target well-spaced	Minimum well-spaced	>800 well-spaced stems ha^{-1}[a]	Target free-growing	Minimum free-growing	>800 free-growing stems ha^{-1}[a]
ICHmw	17	41.7	94.1	76.4	13.3	82.3	71.6
ICHdm	5	20.0	80.0	20.0	0	60.0	20.0
ICHdw	3	0	100.0	66.7	0	33.3	0
ICHmk	2	0	0	0	0	0	0
All	27	22.2	85.2	44.4	7.4	66.7	48.2

[a]Sites with <800 well-spaced or free-growing stems ha^{-1} are within 100 stems ha^{-1} of the minimum requirement.

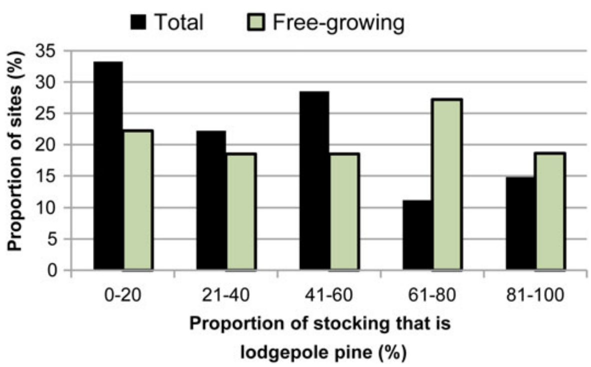

Figure 1 Proportion of assessed plantations comprised of 0–20, 21–40, 41–60, 61–80 and 81–100 per cent of lodgepole pine according to (a) total number of trees present and (b) number of free-growing trees.

maximum proportion of lodgepole pine trees damaged by snow and ice was 74 per cent on an individual site, and 15 per cent of sites had >25 per cent lodgepole pine damaged. Effects of snow and ice included bends, basal sweep, leans, severely distorted form, forks, crooks, broken stems and trees pushed right over. That snow and ice were the cause of these defects was based on visual evidence, local experience and historic snow loads. Broken stems within the live crown and bends in the bole were prevalent but mortality due to breakage below the live crown or uprooting was uncommon. Overall, the percentage of trees with any type of snow and ice damage was similar for lodgepole pine and most other species, but with lodgepole pine, 60 per cent of the damage was unacceptable, whereas the percentage of unacceptable incidences ranged from 0 per cent for western white pine to 28–36 per cent for subalpine fir and hybrid spruce, and 43–47 per cent for western red cedar, western hemlock and Douglas-fir. Western larch was the only species with as much unacceptable snow and ice damage as lodgepole pine (63 per cent of the damage on western larch was unacceptable).

Bear damage, involving stripping bark off the lower portion of tree trunks, occurred on 78 per cent of sites and affected an average of 6 per cent of lodgepole pine. Bears damaged at least 15 per cent of lodgepole pine trees on one-third of the sites and in one plantation 52 per cent of the lodgepole pine were affected. Three-quarters of occurrences of bear damage were serious enough to reject trees as free growing. Damage was most common on larger diameter, dominant trees (10–20 cm in diameter; data not shown) and almost exclusively on lodgepole pine, although 2 per cent of western white pine and 0.3 per cent of western larch were also affected. No damage was seen on Douglas-fir, western redcedar, western hemlock, hybrid spruce, subalpine fir or broadleaf trees. Damage tended to be clustered, even in relatively uniform plantations.

Other types of damage were less prevalent than western gall rust, snow and ice, or bears, but important on some sites. Atropellis canker (*Atropellis piniphila* (Weir) (Lohman & Cash)) infected up to 19 per cent of pine on an individual site, and all incidences caused trees to be unacceptable as crop trees. Lodgepole pine terminal weevil (*Pissodes terminalis* Hopping) and sequoia pitch moth (*Synanthedon sequoia* Hy. Edw.) were the major insect pests, with up to 21–27 per cent of trees affected on a single site, respectively. However, each type of insect damage was present on only about 10 per cent of sites. Twenty-two per cent of terminal weevil damage was unacceptable; sequoia pitch moth damage was never considered unacceptable. The incidence of pine terminal weevil damage is probably higher than we report because the reason for many forks and crooks could not be determined. Lodgepole pine suffered foliar diseases at about one-third of the plantations but damage was never unacceptable. In almost all affected plantations, <10 per cent of trees were diseased, and on most trees, <5 per cent of needles were affected. Root disease symptoms were seldom seen, except on one site where 23 per cent of pine suffered from Armillaria root disease (*Armillaria solidipes* Peck). Ungulate browsing affected 16 per cent of lodgepole pine in one plantation, but dominant (crop) trees were too tall for their leaders to be recently browsed, and few trees of any size had extensive clipping of laterals. Damage from silviculture treatments was present in 10 per cent of plantations and was rare on canopy layer trees. In the most extreme case, 26 per cent of the understorey trees were damaged by pre-commercial thinning and pruning. Some trees that were not targeted for removal were partially cut, and others were damaged by falling trees and branches, resulting in wounds, crooks, forks and severe bends. Damage from conifer and broadleaf tree competition occurred on ~5 per cent of all trees and was less prevalent on lodgepole pine than other species. The main effects were abrasion, forks, crooks and bends.

The major damaging agents on the natural regeneration were white pine blister rust (*Cronartium ribicola* J.C. Fisch.) and foliar diseases on western larch, including larch needle blight (*Hypodermella laricis* (Tub.)). Seventy-three per cent of western white pine

Table 5 List of all damaging agents recorded on lodgepole pine and other species and their frequency of occurrence

Damaging agent	Lodgepole pine			All other species		
	Proportion of sites	Proportion of trees damaged	Proportion of trees with unacceptable damage	Proportion of sites	Proportion of trees damaged	Proportion of trees with unacceptable damage
Diseases						
Western gall rust	97.3	39.0	31.7	0.0	0.0	0.0
Atropellis canker	37.0	1.3	1.3	0.0	0.0	0.0
White pine blister rust	0.0	0.0	0.0	37.0	2.6	2.6
Armillaria root disease	11.1	0.7	0.7	11.1	0.2	0.2
Foliage diseases	29.6	2.2	0.0	55.6	8.3	0.2
Insects						
Lodgepole pine terminal weevil	11.1	0.7	0.2	0.0	0.0	0.0
Spruce terminal weevil	0.0	0.0	0.0	7.4	0.0	0.0
Sequoia pitch moth	7.4	0.7	0.0	0.0	0.0	0.0
Cooley spruce gall adelgid	0.0	0.0	0.0	55.6	7.0	0.0
Animal damage						
Bear	77.8	5.9	4.4	11.1	0.4	0.1
Moose and deer	48.1	4.2	1.8	18.5	0.9	0.3
Hare	11.1	0.2	0.1	18.5	0.4	0.2
Squirrel	3.7	0.1	0.0	0.0	0.0	0.0
Unknown	29.6	0.8	0.1	11.1	0.4	0.2
Abiotic						
Snow and ice	81.5	7.4	4.5	55.6	7.7	3.3
Frost	3.7	0.1	0.1	3.7	0.1	0.0
Drought	3.7	0.1	0.0	7.4	0.1	0.1
Vegetation						
Trees (including broadleaves)	33.3	4.3	2.7	70.4	4.6	1.5
Shrubs	25.9	0.8	0.5	33.3	0.9	0.2
Treatment damage						
Pre-commercial thinning	11.1	0.8	0.2	14.8	2.8	1.2
Other						
Falling trees/rolling logs	33.3	0.8	0.2	44.4	1.0	0.7

trees were infected by blister rust (not including trees already dead). However, white pine averaged only 3 per cent of total stocking, was never a major stand component and occurred only in the ICHmw subzone. Foliar diseases affected two-thirds of the western larch, and on average, 21 per cent of needles were dead on the affected trees, but only 2 per cent of larch had unacceptable damage.

Predictors of damage

All three logistic regression models appear to fit the data as evidenced by *P*-values greater than $\alpha = 0.05$ in the Hosmer and Lemeshow Goodness-of-Fit test (Table 6). Our logistic regression model predicted increased risk of western gall infection with increased soil moisture, more northerly aspects and mechanical site preparation (Table 7). Pre-commercially thinned stands were associated with lower risk of the disease than un-thinned ones. Our model predicted an increase in snow and ice damage risk moving from

Table 6 Results of Hosmer and Lemeshow goodness-of-fit test for the three logistic regression models

Damaging agent	Hosmer and Lemeshow goodness-of-fit test		
	χ^2	DF	Prob. > χ^2
Western gall rust	11.19	8	0.19
Snow and ice	8.82	8	0.36
Bear damage	14.06	8	0.08

Table 7 Summary of odds ratios (logarithmic scale) and probability of $>\chi^2$ for the mean, for factors predicting the presence of damaging agents

Factor types	Factor	Units	Western gall rust		Snow and ice		Bear damage	
			Odds ratio	$P>\chi^2$	Odds ratio	$P>\chi^2$	Odds ratio	$P>\chi^2$
Climatic	MWMT	1°C						
	MCMT	1°C						
	TD	1°C						
	MAP	1 mm			**1.01**	<0.0001		
	AH:M	1 unit						
	SH:M	1 unit						
	DD < 0	1 degree-day						
	DD > 5	1 degree-day						
	NFFD	1 day						
	PAS	1 mm						
Location	Elevation	1 m						
	Latitude	1°						
	Longitude	1°			***0.51***	0.0012		
Site	Soil moisture	1 unit	**1.81**	<0.0001			**2.32**	0.0019
	Slope gradient	1%						
	Slope position	lower *vs* mid						
	Northness	1 unit	**9.48**	<0.0001				
Stand	Stand age	1 year						
	Pine density	200 stems ha^{-1}					***0.83***	0.0019
Treatment	Broadcast burn	Yes *vs* No			**2.32**	0.0012	**2.43**	<0.0001
	Mechanical site preparation	Yes *vs* No	**2.01**	<0.0001				
	Pre-commercial thinning	Yes *vs* No	***0.46***	0.0132			**3.63**	0.0200
	Weeding	Yes *vs* No						

Bold values indicate an odds ratio of >1, thus predicting an increase in the damaging agent with an increase in the climatic, location or site factor or with the application of a silviculture treatment. Bold italic values indicate an odds ratio of <1, thus predicting a decrease in the damaging agent with an increase in the factor. White cells indicate no effect as predicted by logistic regression. An increase of 'x' units of the predictor factor corresponds with a change in risk of the damaging agent equivalent to the odds ratio raised to the power of 'x'.
MWMT, mean warmest monthly temperature; MCMT, mean coldest monthly temperature; TD, continentality; MAP, mean annual precipitation; AH: M, annual heat: moisture index; SH: M, summer heat: moisture index; DD $<$ 0, no. of degree-days $<$0°C; DD $>$ 5, no. of degree-days $>$5°C; NFFD, no. of frost-free days; PAS, precipitation as snow.

west to east. Risk of snow and ice damage was also associated with increasing MAP and broadcast burning. Our model indicated a strong association between bear damage and pre-commercial thinning treatments as well as declining pine density. An increased risk of bear damage was also associated with increased soil moisture and broadcast burning.

Discussion

Six questions were posed at the onset of this study. The first was whether lodgepole pine plantations that were declared free growing are still meeting this criteria at age 15–30 years. We found that 30 per cent of them now fail as free growing, but this failure rate is much lower than the 70 per cent rate found by Mather *et al.*, (2010) in a study using the same methods as ours, which was conducted in other parts of southern interior British Columbia. In the northern interior of the Province, 18 per cent of stands (not limited to ICH lodgepole pine plantations) that had been declared free growing no longer met this requirement when they were re-surveyed 5 years later (Woods and Bergerud, 2008). In our study and Mather *et al.* (2010), about half of the plantations had free-growing and well-spaced stocking levels of ≤100 stems ha^{-1} above the minimum requirement of 700 stems ha^{-1}. The Forest Practices Board (2003) considered stands in this category to be at high risk of not achieving their full productivity potential, which is of particular significance in the ICH zone because of its high growth potential and contribution to timber supply in British Columbia.

Our second question addressed stocking and species composition of natural regeneration in the lodgepole pine plantations and the degree to which it is contributing to stocking. The amount and species composition of natural regeneration was highly variable among sites, but overall it made a substantial contribution to stocking. In our study, free-growing performance was best where other tree species were abundant, emphasizing the benefits of natural seeding to forest regeneration. Lower free-growing success in Mather *et al.* (2010) may in part have been due to lower densities of natural regeneration (1748 total non-pine stems ha^{-1} *vs* 3030 in our study). A diversity of naturally regenerating species prevented many of our stands from being monocultures (i.e. ≥80 per cent of stocking comprised of one species), but we found a much higher proportion of monoculture stands than the overall ICH average reported for the southern interior of British Columbia. The provincial government reports that only 2 per cent of free-growing southern interior ICH stands are lodgepole pine monocultures and that lodgepole pine monocultures are decreasing with harvesting (from 5 per cent pre-harvest to 2 per cent post-harvest) (British Columbia Ministry of Forests and Range, 2008). However, Stevenson *et al*. (2011) report that the abundance of stands dominated by lodgepole pine in the ICH zone has increased over time, from 4 per cent of stands selected for harvest to 10 per cent of regenerated stands (note that such comparisons should be interpreted cautiously due to differences in sampling strategies and populations). An increasing trend towards single-species stands is likely to continue because the area of monocultures (all species and all biogeoclimatic zones combined) at the point of free-growing assessment has increased by 9 per cent since licensees and British Columbia Timber Sales assumed the primary silvicultural obligation for reforestation in 1987 (British Columbia Ministry of Forests and Range, 2008).

An average one-quarter of the natural regeneration in our lodgepole pine plantations was western redcedar or western hemlock and although the trend has been to reforest with seral species such as lodgepole pine, western redcedar has recently been gaining acceptance as a planted species in the ICH zone (Stevenson *et al*., 2011). Thus, climax species are still maintaining a presence in second growth ICH stands; however, their early growth is slower than that of the seral species. This resulted in an average of only 13 per cent (116 stems ha^{-1}) of the free-growing stocking being comprised of western redcedar and western hemlock. During pre-commercial thinning operations, even the largest cedar and hemlock trees are frequently removed, so the presence of these two species post-thinning is often limited to very small trees that escape cutting and may not reach merchantable size when the seral species mature.

The third question we asked regarded the type, extent and incidence of damage in 15- to 30-year-old lodgepole pine plantations. Damage levels were high on lodgepole pine whereas natural regeneration, with the exception of western white pine, tended to be healthier. The prevalent foliar diseases on larch are generally associated with only minor growth reductions (Henigman *et al*., 2001). Total damage levels were comparable with those found by Heineman *et al*. (2010) in the ICH zone elsewhere in southern interior British Columbia, but they found a higher proportion of pine with unacceptable damage (61 per cent *vs* 44 per cent). Vyse *et al*. (2013) found that mountain pine beetle was the most important damaging agent in 20- to 26- year-old ICH lodgepole pine-planting trials. Their study was based on a small sample of plantations not located in the Columbia Basin. Regardless, the high levels of damage found in our study and these others show that single-species planting of lodgepole pine in the ICH zone is a questionable regeneration strategy unless considerable losses are accepted and planned for. Damaged planted lodgepole pine takes up valuable growing space in young stands and expected quality reductions, as well as growth and mortality losses, suggest that other species should be used to a greater degree.

That we found very high levels of western gall rust incidence is not surprising since others have found similar results elsewhere, and western gall rust is the most common stem rust of lodgepole pine in Canada (van der Kamp and Tait, 1990). Twenty-seven per cent of lodgepole pine were affected in the ICH zone across the southern interior of British Columbia (Mather *et al*., 2010), 49 per cent in northern British Columbia (van der Kamp *et al*., 1995), >20 per cent of trees on one-third of sites in northern interior British Columbia (Woods and Bergerud, 2008), 43 per cent in west-central Alberta (Blenis and Duncan, 1997) and 67 per cent in trials of 53 provenances from British Columbia, Alberta and the Yukon (Wu *et al*., 1996). As with our results, infection rates varied considerably among sites and exceeded 85 per cent of trees on some sites. Western gall rust has long been recognized to cause significant losses in young lodgepole pine stands (Ziller, 1974; Hiratsuka and Powell, 1976). Both stem and near-stem galls result in similar outcomes for the tree (Wolken, 2008). They can result in growth losses, poor tree form, reduced wood quality, restricted end-product use and stem breakage and can ultimately cause mortality or prevent trees from reaching merchantable size (Gross, 1983; Blenis *et al*., 1988). These are much more serious than more distal branch galls, which have little impact on the host tree, although they are an important source of spores that spread the disease and, if very abundant, may reduce photosynthesis (Gross, 1983). The magnitude of losses due to western gall rust is not well documented, but reductions in volume of 7 per cent by rotation age have been estimated for central British Columbia (Woods *et al*., 2000). A higher volume loss (15 per cent over a 20-year period) was reported for stands in Alberta (Bella and Navratil, 1988). In one of the few published studies of mortality rates due to western gall rust, Wolken (2008) projected that 57–62 per cent of stem-galled trees would not survive to age 80, which translates to ~15 per cent of the lodgepole pine on our sites. However, mortality depends on the degree of gall encirclement of the stem and is highest when galls encircle >79 per cent of the stem (Wolken, 2008).

We found that snow and ice was an important damage cause in many juvenile Columbia Basin lodgepole pine plantations. Other published data on snow and ice damage to lodgepole pine from interior British Columbia are limited. However, Heineman *et al*. (2010) reported high levels of snow and ice damage in some lodgepole pine plantations, but these were mainly >1600 m in elevation (ESSF zone). Broken stems within the live crown, which we frequently observed, result in loss of dominance and a reduction in growth rate. Although trees may recover satisfactorily, timber loss still results due to crooks, forks or multiple leaders. Bends or sweep in the lower part of the stem can be caused not only from snow accumulations on the tree, but also from lateral movement of the snowpack and result in reduced height growth and sometimes compression failure on the concave or downhill side of the stem. An indirect effect of snow damage is increased susceptibility to fungal or insect attacks such as root rot and pine weevils (Nykanen *et al*., 1997). In our study, lodgepole pine stood out as having the most severe snow and ice damage of all species except western larch, indicating low suitability of lodgepole pine for regeneration in areas where high levels of snow damage have previously been observed. European studies indicate that spruce and subalpine fir withstand snow damage better than pine. This is probably because they have a narrower crown, creating less surface area for snow accumulation and concentrating snow closer to the stem, thereby keeping the stem more stable (Nykanen *et al*., 1997). It is unknown whether snow and ice damage on our sites occurred during single storms or prolonged snow loading, but stresses and defects result from both situations. In Europe, extensive snow and ice damage to thousands of hectares of forest has sometimes occurred (Nykanen *et al.,* 1997), but this has not been the case in the Columbia Basin.

Bears were an important damaging agent, affecting 78 per cent of our sites, in congruence with reports elsewhere. A single bear is capable of stripping bark from 50 to 70 trees per day (Schmidt and Gourley, 1992) or destroying 10 to 15 per cent of a forest stand each year (Ziegltrum, 1994). In some areas, injury levels have affected up to 87 per cent of trees (Sullivan, 1993), which exceeds what we observed. Heineman *et al*. (2010) observed infrequent bear damage in juvenile lodgepole pine plantations across southern interior British Columbia, although it occurred more often in the ICH zone than other areas. Damage from bears can be detrimental to the health and economic value of a stand because complete girdling kills the trees and partial girdling leads to a reduction in tree growth rate during the recovery period, especially if wounds encompass >50 per cent of a tree's circumference (Nelson, 1989). The wounds also become entry points for decay fungi. Timber yield may be seriously affected by bear damage, with estimates of a 13–17 per cent reduction in yield at rotation age (Brodie *et al.,* 1979; Mason and Adams, 1989), although Lowell *et al*. (2010) reported a smaller impact (6 per cent lower log cubic volume recovery). Lumber from bear-wounded trees is sometimes degraded due to distortion, borer tunnels and decay (Childs and Worthington, 1955). Lowell *et al*. (2010) reported that bear-damaged trees yielded 23 per cent of the highest grade of lumber compared with 35 per cent for undamaged trees. The impacts of bear damage are made worse by the tendency for animals to select the most vigorous trees, especially in thinned stands where each tree comprises more of total stand volume. Species other than lodgepole pine were probably undamaged on our sites due to denser branches on the lower bole, which bears avoid (Maser, 1967). In other locations in western North America, lodgepole pine has also been a preferred species (Mason and Adams, 1989; Barnes and Engeman, 1995). Our finding that dominant, vigorous trees were preferentially attacked has been reported elsewhere (Maser, 1967; Fersterer, 2000). Most affected trees were 10–20 cm in diameter, agreeing with Mason and Adams (1989). Juvenile trees (age 10–45 years) are usually preferentially attacked, based on seven studies in the northwestern US (Fersterer, 2000), indicating that our stands were of a highly susceptible age. The patchy nature of damage that we observed in our stands agrees with observations from other areas (Childs and Worthington, 1955; Schmidt and Gourley, 1992).

Our fourth question was whether climatic, site or stand factors, or silviculture treatments are associated with increased risk of damage to lodgepole pine from western gall rust, snow and ice, or bears. Our model predicted increased risk of western gall rust damage on moister sites and northerly aspects which supports other studies showing that moister, cooler sites favour production, release, germination and infection by western gall rust fungi (Chang and Blenis, 1986; Chang *et al.,* 1989; Adams, 1997). Risk of damage from western gall rust was greater in unthinned than thinned stands perhaps because stand criteria for thinning included low infection rates and/or damaged trees were preferentially removed. However, other studies have found higher western gall rust incidence in more open stands than denser ones (Hills *et al.,* 1994). Pre-commercial thinning could favour rust incidence by changing microclimate, crown structure and inoculum levels, which may affect spore dispersal and change the rate of infection (Bella, 1985; van der Kamp and Spence, 1987). The larger, more vigorous trees in thinned stands may be more favourable hosts than smaller trees due to more surface area for spore deposition (van der Kamp and Spence, 1987). Mechanical site preparation was also associated with increased risk of western gall rust but we are unable to explain this result. Although we found that risk of western gall rust was associated with certain factors, van der Kamp (1994) concluded that it is not possible to predict at the time of stand establishment which lodgepole pine stands will suffer significant damage from the disease. He emphasized instead the concept of 'wave years' when conditions are just right for infection, which may occur locally only once every 10 years. Some stands may never experience a wave year while in a susceptible state, whereas others may experience several of these years. The logistic regression model predicted an increase in snow and ice damage risk moving from west to east, which may be related to higher precipitation levels in the east caused by orographic lift over the mountain ranges. That the model predicted a greater risk of snow and ice damage with increased MAP is likely due to greater snow loads where the amount of winter precipitation is higher. The prediction of higher risk of snow and ice damage on burned *vs* unburned sites may be explained by the fact that burning reduces slash density, which could increase snow movement. Higher risk of bear damage was associated with increased soil moisture, which aligns with the preference of bears for moist areas where plants are more succulent and nutritious (Herrero, 1985). Fersterer (2000) also reported that bears peel more trees on moist sites than dry ones. Our model indicated a strong association between bear damage and pre-commercial thinning treatments as well as declining pine density, which agrees with others who have found that bears cause more damage in open stands. Mason and Adams (1989) found that bear damage was 5–7 times higher in thinned than untreated stands, and Childs and Worthington (1955) found it was 3–4 times higher in understocked compared with well-stocked stands. Bears prefer tree canopies sparse enough to let sunlight reach the forest floor (Van Tighem, 1999), accessibility to tree boles is better in open stands and thinning results in increased carbohydrate levels (Kimball *et al.,* 1998). Bear damage was associated with broadcast burning possibly because of improved access following slash reduction.

The fifth question we posed was how management practices can be adjusted to reduce the risk of damage from western gall rust, snow and ice, and bears. Our results suggest management practices favour mixed stands rather than monocultures of lodgepole pine. Silviculture treatments and harvesting operations are logistically simpler when management is done for single-species stands, but plantation health may be reduced in stands dominated by one species because most forest pests are species-specific and tree diversity spreads the risk of damage (Woods *et al.,* 2000; Jactel *et al.,* 2009; Gamfeldt *et al.*, 2013). The recent mountain pine beetle and Dothistroma needle blight outbreaks in British Columbia are examples where catastrophic losses occurred in pine-dominated stands and such epidemics are expected to increase with climate change (Sturrock *et al*., 2011). Given that virtually all ICH sites in the Columbia Basin are ecologically suited to species besides lodgepole pine (British Columbia Ministry of Forests, 2000), it would not be difficult to scale back planting of pine in favour of more complex mixtures emulating natural stand composition. This can be achieved by planting a variety of species and/or implementing silviculture systems that favour diverse natural regeneration. Both pest and long-term productivity concerns with lodgepole pine have been identified by others as reasons to curtail the use of lodgepole pine (Vyse *et al.*, 2013) and the Chief Forester of British Columbia recently made recommendations that support a reduction in the prolific use of this species (Snetsinger, 2011).

Results from ours and other studies suggest that pre-commercial thinning that favours lodgepole pine should be avoided in regions where bear damage levels are historically high, especially on moist sites. Our results indicate that up to half of the lodgepole stems in thinned plantations can be damaged by bears. Unlike other studies, we provide no evidence of increased risk of western gall rust in thinned stands. Broadcast burning was associated with increased risk of snow and ice and bear damage, and mechanical site preparation was associated with increased risk of western gall rust. However, the choice to utilize these site preparation treatments must consider many other factors such as their impact on plantable spots as well as natural regeneration.

Our final question was whether damage to lodgepole pine will increase given climate change predictions. Our study took place across a relatively small geographic area, explaining why we found few associations between risk of lodgepole pine damage and climatic factors. However, climate change has already contributed to two recent major insect and disease epidemics in lodgepole pine forests in British Columbia: the mountain pine beetle and Dothistroma needle blight (Woods *et al.*, 2010). The warming climate predicted for the Columbia Basin in particular is expected to result in increased insect outbreaks, through increased diversity and activity of insects and through increased drought stress and weather-related damage of forests. Further damage to lodgepole pine plantations by sequoia pitch moth, lodgepole pine terminal weevil and mountain pine beetle can be expected. Snow damage may become more common because of the likelihood of more snow events at temperatures near freezing, which is when snow best adheres to tree crowns (Nykanen *et al.*, 1997). The possibility of increased use of trees for food by bears (i.e. increased damage due to stripping of bark) exists if food acquisition becomes more difficult due to either drought in the feeding season or earlier emergence from hibernation, when plants are still undeveloped. The wetter climate predicted for the Columbia Basin, particularly when combined with warmer temperatures, should favour pathogen populations as well, with increasing frequency of wave years for stem rusts such as western gall rust, and increasing risk of foliar diseases such as Dothistroma needle blight (Sturrock *et al.*, 2011). Summer drought stress will place lodgepole pine at more risk of Armillaria root disease, Atropellis canker and lodgepole pine dwarf mistletoe (*Arceuthobium americanum* Nutt. Ex Engelemann) as well as alien invasive pests (Sturrock *et al.*, 2011). The compromised condition of lodgepole pine plantations in the Columbia Basin today places them at greater risk for future insect and pathogen damage than healthier plantations that have been regenerated to a more locally suitable and diverse mix of tree species. Pest complexes, where multiple insects and diseases co-exist in a single plantation, have the potential to build in these lodgepole pine plantations, potentially leading to decline of planted lodgepole pine forests in this area in the future.

Conclusions and recommendations

Single-species planting of lodgepole pine is common in the ICH zone in southern interior British Columbia, which is the most productive and tree-species diverse biogeoclimatic zone in this region. Our results suggest that the majority of ICH lodgepole pine plantations in British Columbia's Columbia Basin will suffer reduced potential stand productivity because damaged pine is taking up valuable growing space that could be occupied by other species with fewer problems. Stresses imposed by changes in climate towards conditions that lodgepole pine is not adapted to, or moving lodgepole pine away from its native range, are likely to increase plantation losses. Our analysis found few associations between damage to pine and climatic conditions, but the study area was fairly small. Site conditions, such as increasing moisture, were associated with increased western gall rust and bear damage. We found associations between silviculture treatments and damage. In particular, pre-commercial thinning can increase incidence of damage to lodgepole pine from bears, and broadcast burning was associated with increased snow and ice damage and bear damage. In the ICH zone, we found that natural regeneration was diverse and plentiful on many sites and partially compensated for poor lodgepole pine performance. Based on our findings, we recommend that single-species planting of lodgepole pine in the ICH zone be curtailed and that, where possible, pre-commercial thinning operations in existing lodgepole pine stands favour a diversity of species. Mitigating damage as climate changes in the Columbia Basin should involve a combination of natural and artificial reforestation with a rich mix of locally adapted and migrated tree species that together comprise a resilient and stress-tolerant forest. Management of these stands should involve monitoring, modelling, risk assessments and planning following a complex adaptive systems approach (Woods *et al.*, 2010; Sturrock *et al.*, 2011; Filotas *et al.*, 2013).

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Conflict of interest statement

None declared.

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