Cumulative Impact of Biotic and Abiotic Damage Agents on Lodgepole Pine Tree Form and Stand Structure in Southern British Columbia

Discussion Paper

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Abstract

Not all pests kill trees or compromise final tree form; however, the cumulative effect of one or more damage agents over time can significantly limit final expectations at harvest, severely reducing or compromising wood quality and timber supply expectations going forward. This study highlights the effects of damage agents on young lodgepole pine in southern British Columbia during the formative years of stand development. Over 4,300 trees were monitored for up to three decades with over 40 damage agents recorded, causing significant repercussions on stocking, health, and form of potential crop trees. By the final assessment, density of potential crop trees had declined dramatically, with 84% affected by one or more pests, and 63% of natural ingress dead. Most natural ingress was severely suppressed; thus, it is unlikely to fill in stand gaps caused by mortality and damage agents affecting larger potential crop trees. Lodgepole pine terminal weevil and western gall rust were the predominant damage agents influencing form and quality of potential crop trees. Lodgepole pine terminal weevil attacked up to 73% of pine and over 24% suffered multiple attacks. Results from this study emphasize the need for more short- and long-term monitoring of young stands to inform the development of forest policy and promote healthy, resilient new forests.

KEYWORDS: lodgepole pine, damage agents, lodgepole pine terminal weevil, western gall rust, Southern British Columbia

Introduction

Forested land in British Columbia covers an area of just over 60 million hectares (BC MOF 2003). Lodgepole pine is the most ubiquitous tree species found throughout the interior of the province, and the dominant species in most dry, cold forests in British Columbia and much of western North America, forming pure successional stands or co-dominant mixtures (Klinka et al. 2000). In the last few decades, mortality of mature and young trees has increased dramatically (Kurz et al. 2008, Maclauchlan et al. 2015, Westfall & Ebata 2017, Maclauchlan & Buxton 2019, Fettig et al. 2021, Robbins et al. 2021) because of many damage agents affecting lodgepole pine throughout its rotation. The dominant natural disturbance agents of mature lodgepole pine are mountain pine beetle, *Dendroctonus ponderosae* Hopk. (Coleoptera: Curculionidae; Scolytinae) (IBM) (Safranyik & Carroll 2006,

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Amoroso et al. 2013, Westfall & Ebata 2017, Negrón & Cain 2019) and stand replacing fires (Lotan et al. 1985, Klutsch et al. 2011, Kulakowski et al. 2012). The catastrophic effects of recent fire and IBM outbreaks alone account for approximately 1.75 million hectares of forest that are in a denuded or severely damaged state (Hughes 2020). British Columbia has recently experienced three devastating drought events occurring in 2017, 2018, and 2021 that has further affected forests, particularly young stands in the southern interior of British Columbia (Maclauchlan & Buxton 2019, Brooks 2020). Many young managed stands are dominated by lodgepole pine (Woods & Coates 2013) due to the accelerated harvesting brought on by the IBM outbreak and more than 1 million hectares are single species plantations. These young stands represent British Columbia's future forests and are critically important for economic and community stability, carbon sequestration, habitat and cultural values, and ecological functioning.

Numerous insects, diseases, animals, and abiotic pests affect young lodgepole pine stands in the southern interior of British Columbia. These damage agents, in combination with changing climate (e.g., drought) can influence stand establishment and productivity, with respect to timber volume and quality. Their occurrence and impact will vary across the land base, resulting in some mortality or significant decreases in yield. Moreover, a single damage agent may not result in mortality, but the cumulative effects of these agents may significantly affect productivity expectations at a stand or landscape level over time.

There are well-established assessment and monitoring programs in British Columbia that collect information on the health of young stands, with the most notable being the Free Growing Survey (BC MOF 2008, BC MFLNRORD 2020) and Young Stand Monitoring (YSM) (BC FLNR 2013). The Free Growing Survey is legally required under the Forest and Range Practices Act (FRPA) and its regulations (Government of BC 2002), and is usually conducted as early as possible in the development of the stand (e.g., 8–10 years) (BC MFLNRORD 2020). However, Free Growing Surveys only provide point-in-time data from very young stands and do not provide meaningful information on the development and health of stands through to mid-development stage. Young Stand Monitoring plots were initially located in high-risk areas where inventories are compromised due to the impact of mountain pine beetle and where young stand growth rates are critical to mid-term timber supply. These plots track the performance of young stands, including forest health (50 years and younger), across the province. Long-term data from YSM plots will provide valuable insight on the performance and health of these stands but will require many years of monitoring.

Other studies that have investigated the incidence of damage agents in young lodgepole pine stands in British Columbia (Heineman et al. 2010, Mather et al. 2010, Woods 2011, Woods et al. 2011, 2017, Woods & Coates 2013) found that hard pine rusts, foliar disease, and lodgepole pine terminal weevil were typically the most dominant pests. However, few studies have explored the cumulative effect of damage agents on trees over time. A long-term study looking at incidence and impact (Maclauchlan & Brooks 2020) recorded 25 damage agents over a 30-year period with only 24% of trees remaining pest-free. More importantly, the study showed that two or more damage agents per tree caused tree form to decline (Maclauchlan & Brooks 2020). Currently, there is little information on the effect of individual or multiple damage agents on trees and stands over the early- to mid-development period. With compounding pressures from changing climatic conditions plus the ever-increasing importance of maintaining healthy and productive young forests, the cumulative effects of abiotic and biotic factors on young stands must be more clearly documented and understood.

This study summarizes the results of monitoring insect, disease, animal, and abiotic damage on individual trees within 14 plots in two biogeoclimatic zones in the southern portion of the Thompson Okanagan Region of British Columbia for up to three decades, and describes and interprets their cumulative effect on tree development over time. This broader analysis expands on the detailed analysis of pest impact reported in the case study by Maclauchlan and Brooks (2020).

Methods

A network of permanent sample plots was established in the late 1980s through the 1990s in young lodgepole pine stands that had been harvested and regenerated following the 1970s IBM outbreak. These plots were established in two biogeoclimatic zones in south central British Columbia to investigate the incidence and impact of lodgepole pine terminal weevil attack and other damage agents on individual trees over time. One of these original plots, not included in this report, was summarized in Maclauchlan and Brooks (2020) as a case study to lay the foundation for the analysis and interpretation of this plot network. Six of the 14 plots included within this study were originally established as part of a Ph.D. research project (Maclauchlan 1992). The original plots were restored, and additional plots were established and monitored as part of this ongoing research (Table 1, Figure 1). Plots are located in the Interior Douglas-fir dry, cool variant 1 (IDFdk1), Interior Douglas-fir dry, cool variant 2 (IDFdk2), Montane Spruce dry, mild variant 1 (MSdm1) and Montane Spruce dry, mild variant 2 (MSdm2) biogeoclimatic zones (BEC) (Lloyd et al. 1990, Meidinger & Pojar 1991; MacKillop et al. 2021, Ryan et al. 2021) (Table 1).

Table 1. List of plots with biogeoclimatic zone (BEC), year of first assessment after establishment, plot size (hectares), and location (latitude, longitude)

Plots	BEC	First assessment	Plot size (hectares)	Latitude	Longitude
1. Dardanelles	IDFdk1	2015	0.0625	50.3636	-120.134
2. Ketchan	IDFdk2	1990	0.1	49.7772	-120.567
3. Ketchan-pruned	IDFdk2	2000	0.25	49.7700	-120.569
4. Ketchan-9	IDFdk2	1991	0.05	49.7696	-120.569
5. Missezula Lake	IDFdk2	1996	0.16	49.7624	-120.528
6. 200 Road	MSdm1	1991	0.035	49.3082	-119.384
7. Ellis Creek	MSdm1	1988	0.25	49.4939	-119.345
8. Hydraulic Lake	MSdm1	1998	0.25	49.7830	-119.162
9. Beblow Road	MSdm1	1990	0.25	49.4076	-119.339
10. Dave's Creek	MSdm1	1991	0.25	49.9205	-119.243
11. Placer Creek	MSdm2	1997	0.25	49.1767	-120.503
12. Dillard Creek-1	MSdm2	1988	0.16	49.7791	-120.407
13. Dillard Creek-10	MSdm2	1996	0.16	49.7597	-120.402
14. Dillard Creek-11	MSdm2	1996	0.0375	49.7653	-120.434

Notes: BEC, biogeoclimatic ecosystem classification; IDFdk1, Interior Douglas-fir dry, cool variant 1; IDFdk2, Interior Douglas-fir dry, cool variant 2; Lat., latitude; Long. longitude; MSdm1, Montane Spruce dry, mild variant 1; MSdm2, Montane Spruce dry, mild variant 2.

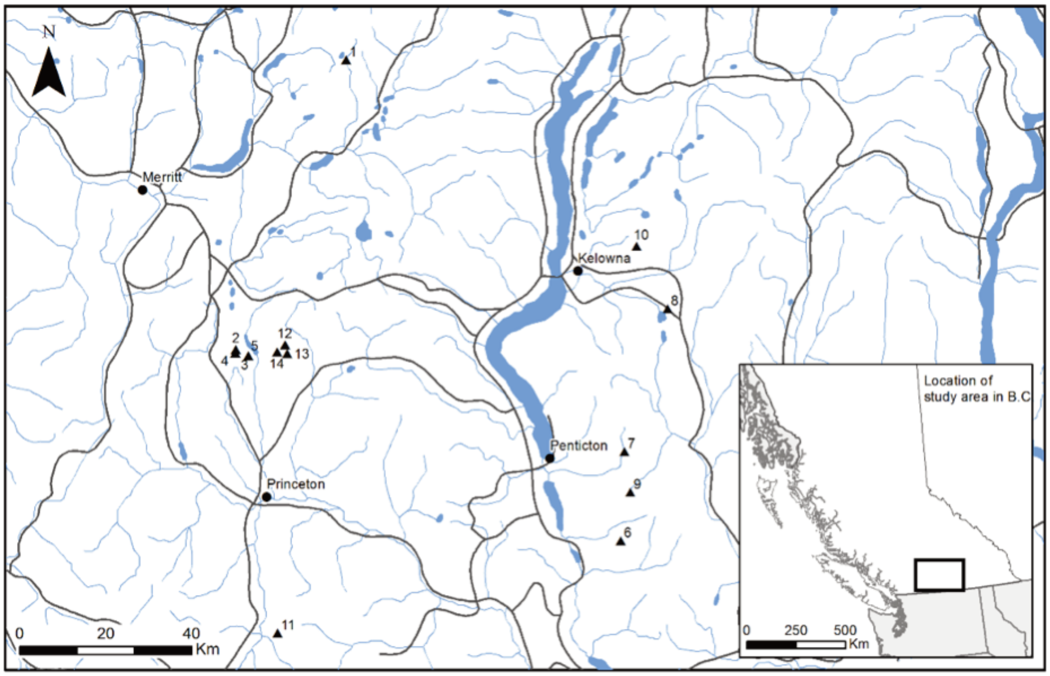


Figure 1. Location of 14 plots in southern British Columbia. The inset shows the location of the study area.

The original plots were established in young lodgepole pine stands representing a range of stem densities or stand tending treatments such as spacing and pruning. Plot 6 was operationally spaced following plot establishment reducing the number of trees in the plot, and trees in plots 2 and 4 were killed by IBM and harvested prior to the final 2020 assessment. All trees in each plot were assessed every 5 to 10 years for the duration of the study. The monitoring period ranged from 16–32 years, except for plot 1, which was established in 2015. Plots were assessed 3 to 8 times. Trees greater than 1.3 m in height were tagged with a unique number, assigned a trees status (live, dead, down), and examined for all above- and below-ground damage from biotic and abiotic agents such as lodgepole pine terminal weevil, comandra blister rust, *Cronartium comandrae* Peck, western gall rust, *Cronartium harknessii* (J.P. Moore) E. Meinecke), Armillaria root disease, *Armillaria ostoyae* (Romagnesi), drought, suppression (minimal height growth and small stem size compared to main plot trees), animal damage, and other factors (BC MOF 2001, BC MSRM 2005). Diameter at breast height (DBH) of every tree was recorded at each assessment and a random subsample of tree heights was taken. Additional measurements and observations recorded in most assessment years included: year of lodgepole pine terminal weevil attack; height to each new weevil attack (measured from the base of the affected leader); and defect caused by weevil attack. In later assessments, tree crowns were large, and we could no longer accurately determine if there were new weevil attacks or the year of attack. However, all past attacks were visually evaluated at each assessment and assigned a defect category for that assessment year. This enabled us to determine if defects caused by weevil attacks remained unchanged from the first record of attack or increased or decreased in severity over time as the tree developed. Four categories of stem defect were used to describe each attack by lodgepole pine terminal weevil (crease, crook, fork, staghead) (Maher 1981, Alfaro 1989, Maclauchlan & Borden 1996, Maclauchlan & Brooks 2020).

The final plot assessment was conducted in 2020. At this time, we visually evaluated tree form and rated the tree as having good, moderate, or poor form (Maclauchlan & Brooks 2020). We measured the height of the lowest occurring (first) stem gall caused by western gall rust. For trees with multiple stem galls, only the height to the lowest stem gall was measured because the lower bole is the most valuable portion of the tree at harvest. We tested the hypothesis that trees with better form would have fewer recorded pests by comparing our ocular estimate of tree form to the incidence of recorded pests affecting each tree.

Other summary statistics included damage agents affecting trees; percentage of trees and stems per hectare (sph) affected by damage agents; stems per hectare (and % stems) live and dead lodgepole pine; average DBH (cm) and height (m); defect caused by weevil attack over time; and tree form at final assessment.

For some analyses, trees were assigned to a silviculture layer (BC MOF 1992) based on DBH and height to illustrate stand development and structure over time:

Layer 1 = mature layer (> 12.5 cm DBH and over 1.3 m height)
Layer 2 = pole layer (7.5 to 12.49 cm DBH and over 1.3 m height)
Layer 3 = sapling layer (0 to 7.49 cm and over 1.3 m height)
Layer 4 = regeneration (less than 1.3 m height)

Frequency tables were compiled to examine the total number of pests recorded on each tree, by layer and tree form, and then compared using a polyserial correlation (Chi square analysis, $P < 0.05$). The frequency of pests per tree at the first and final assessments in the IDFdk and MSdm were compared (Chi square analysis, $P < 0.05$). A correlation analysis was conducted of the total number of weevil attacks per tree vs. final tree form (Chi square analysis, $P < 0.05$).

Results

At the first assessment, lodgepole pine density ranged from 631 sph to 6,171 sph (Table 2). The majority were layer 2 (range: 1–53%) and layer 3 (range: 41–98%) trees. At final assessment, the majority were layer 1 (17–74%) trees, with 5–37% in layer 2, and 5–69% in layer 3. Final live layer 1 lodgepole pine density ranged from 168 sph to 1,344 sph, with layer 2 trees ranging from 29 sph to 1,330 sph. Natural pine ingress (layer 3) varied among plots, ranging from zero to 1,480 sph (Table 2). Most plots saw a decline in density over time. Average height and diameter of pine increased with decreasing density.

Table 2. Density of lodgepole pine (Pl) and other species in 14 plots at the first assessment and density of lodgepole pine, by layer, at the final assessment. Average age (years), diameter at breast height (DBH) (cm), and height (m) (average ± Standard Error) is shown for layer 1 lodgepole pine at final assessment.

Plot name & number	Stems per hectare live trees					Layer 1 Pl at final assessment		
	First assessment		Pl at final plot assessment					
	Pl	Other	Layer 1	Layer 2	Layer 3	Age	DBH	Ht.
1. Dardanelles	1,616	16	1,152	272	80	36	16.7 ± 0.3	12.6 ± 0.2
2. Ketchan[a]	3,770	0	960	1,330	1,130	30	15.0 ± 0.2	12.3 ± 0.1
3. Ketchan-pruned[b]	1,120	36	944	108	984	42	17.4 ± 0.2	15.0 ± 0.2
4. Ketchan-9[a]	3,200	20	980	420	1,480	30	15.0 ± 0.2	11.7 ± 0.2
5. Missezula Lake	631	6	394	44	81	41	18.3 ± 0.4	17.2 ± 1.5
6. 200 Road[c]	6,171	143	771	29	0	43	20.3 ± 0.6	15.1 ± 0.3

Table 2 (contunued).

Plot name & number	Stems per hectare live trees					Layer 1 Pl at final assessment		
	First assessment		Pl at final plot assessment					
	Pl	Other	Layer 1	Layer 2	Layer 3	Age	DBH	Ht.
7. Ellis Creek	1,880	24	748	92	36	45	16.6 ± 0.2	15.2 ± 0.5
8. Hydraulic Lake	1,244	28	776	340	24	38	15.8 ± 0.2	12.8 ± 0.2
9. Beblow Road[b]	1,180	20	868	232	56	45	15.9 ± 0.1	12.6 ± 0.2
10. Dave's Creek	1,304	296	796	124	96	42	19.5 ± 0.3	16.4 ± 0.5
11. Placer Creek	840	92	168	132	176	36	15.6 ± 0.4	15.5 ± 0.4
12. Dillard Creek 1[b]	2,550	0	1,344	125	150	42	17.6 ± 0.2	13.3 ± 0.2
13. Dillard Creek 10[b]	1,368	44	281	150	313	42	18.1 ± 0.5	15.3 ± 0.3
14. Dillard Creek 11[b]	3,013	160	827	293	373	42	18.1 ± 0.6	13.9 ± 0.7

Notes: DBH, diameter at breast height; Ht., height; Pl, lodgepole pine. [a] Final assessment 2007. [b] Natural ingress included when > 1.3 meters height. [c] Many trees were cut (spaced) after plot establishment

Forty-two damage agents, most affecting lodgepole pine, were recorded in the 14 plots, with western gall rust and lodgepole pine terminal weevil recorded in all plots (Table 3). Some damage agents affected all species (e.g., abiotic damage) or only affected other tree species (e.g., spruce broom rust on spruce). Other prevalent pests included squirrel damage (13 plots), Atropellis canker *Atropellis piniphila*, (Weir) Lohman & Cash (12 plots), northern pitch twig moth *Petrova albicapitana* (Busck) (12 plots), and pine needle cast *Lophodermella concolor* (Dearn) (11 plots). Pests causing mortality or having significant growth implications included comandra blister rust (9 plots), stalactiform blister rust *Cronartium coleosporioides* Art. (6 plots), Armillaria root disease (6 plots), mountain pine beetle (6 plots), lodgepole pine dwarf mistletoe *Arceuthobium americanum* Nutt. Ex Engelm (4 plots), and Warren root collar weevil *Hylobius warreni* Wood (1 plot). Secondary bark beetles (9 plots) and Yosemite bark weevil *Pissodes schwarzi* Hopk. (4 plots) also caused tree mortality; however, they usually occurred in combination with other pests such as comandra blister rust, mountain pine beetle, or drought. Numerous plots had trees with dead or broken tops, forks, or basal sweeps, which were not attributed to a specific pest or climatic event and were therefore categorized as abiotic damage. Suppression due to the impact of surrounding vegetation or neighboring trees affected much natural pine ingress. However, most observed stem damage or mortality was attributed to a specific insect, disease, or damaging agent.

Lodgepole pine terminal weevil affected between 20% and 73% of pine and many trees had multiple attacks. Forty percent or more pine were affected by lodgepole pine terminal weevil in plots within the IDFdk1, IDFdk2, and MSdm1, and 26% were affected in the MSdm2 (Table 3). Comandra blister rust was very site-specific, occurring most commonly in plots located in the MSdm1 and ranging from zero infections to 50% pine infected. Stalactiform blister rust had a similar distribution but was present at lower levels. Atropellis canker was present at similar levels in the IDFdk2, MSdm1, and MSdm2 (Table 3) and was recorded in 86% of sites, ranging from zero infections to 56% pine infected. Northern pitch twig moth occurred in 86% of sites across all ecosystems, but generally at low levels and did not cause mortality. Every plot had trees with suppression due to vegetation (Table 3). Most of these trees were natural ingress on the site, had minimal live crowns and small diameters, and were unlikely to become dominant or future crop trees. Up to 33% of pine was classified as suppressed on some sites.

Table 3. Percentage lodgepole pine in four ecosystems affected by major damage agents over the duration of each plot.

Damaging agent	Across all sites (%)			By biogeoclimatic zone (% Pl)			
	Percentage of sites with pest	Average of affected pine	Range of occurrence on affected sites	IDFdk1 (*n* = 101)	IDFdk2 (*n* = 1,328)	MSdm1 (*n* = 1,519)	MSdm2 (*n* = 1,210)
Squirrel damage	93	6.5	1–23	20.8	3.9	10.3	3.4
Lophodermella needle cast	79	10.0	1–41	0	0.8	4.3	27.9
Lodgepole pine dwarf mistletoe	29	1.6	1–12	0	4.8	0.1	0
Armillaria root disease	50	0.8	1–4	2.0	0.1	1.6	0.1
Atropellis canker	86	9.3	1–56	0	10.5	9.0	9.2
Comandra blister rust	64	6.8	1–50	0	1.4	16.8	0.1
Western gall rust*	100	20.8	1–65	5.0	21.7	7.7	37.3
Stalactiform blister rust	43	1.0	1–17	0	0.1	2.6	0.1
Secondary beetles	64	1.6	1–6	0	2.6	1.6	0.6
Mountain pine beetle	43	0.9	1–14	0	2.5	0.3	0.1
Northern pitch twig moth	86	5.1	1–18	6.9	2.0	10.7	1.6
Lodgepole pine terminal weevil	100	38.2	20–73	45.5	38.4	46.7	26.4
Broken top (unidentified reason)	86	2.9	1–7	1.0	1.4	4.7	2.4
Fork (unidentified reason)	86	8.5	1–27	3.0	4.8	10.1	11.1
Suppression due to vegetation	100	12.2	1–33	4.0	15.7	7.4	15.1

Notes: IDFdk1, Interior Douglas-fir dry, cool variant 1; IDFdk2, Interior Douglas-fir dry, cool variant 2; MSdm1, Montane Spruce dry, mild variant 1; MSdm2, Montane Spruce dry, mild variant 2; Pl, lodgepole pine.*Stem infections only.

Biotic and abiotic agents affected trees over the entire duration of this study. Some damage agents had negligible impact, such as browsing on lateral branches by deer or moose, whereas others caused severe and ongoing damage, such as multiple attacks by lodgepole pine terminal weevil or infections by western gall rust and comandra blister rust. Pests such as pine needle cast affected almost all trees in a stand during an outbreak, but were present at only one point in time, lasting a few years and having minimal growth impact on most trees.

The cumulative number of pests per tree was summarized by BEC subzone and compared at two different assessment times (Table 4): early in plot establishment and at the final assessment. The proportion of pine having no pests at the early assessment in the IDFdk and MSdm ecosystems was similar, with less than 20% having two or more pests per tree (Table 4). By the final assessment, the percentage of pest-free pine in these ecosystems had declined significantly, even though the total number of pest-free trees in the IDFdk had increased due to inclusion of natural ingress. Up to 9% of pine in all plots had been impacted by four or more pests (Table 4).

Table 4. Percent lodgepole pine (number of pine in brackets) (all plots) having zero pests to multiple pests per tree at the early and final assessments in the IDFdk and MSdm.

BEC and sample time	% lodgepole pine					X^2 Test Statistic	*p*-value
	No pests	1 pest	2 pests	3 pests	≥4 pests		
IDFdk							
Early	38.9%	42.1%	16.3%	2.3%	0.4%		
	(403)	(436)	(169)	(24)	(4)	154	< 0.001
Final	29.6%	35.1%	16.6%	10.8%	7.9%		
	(427)	(507)	(240)	(156)	(114)		
MSdm							
Early	41.8%	43.6%	12.5%	1.9%	0.1%		
	(1036)	(1082)	(310)	(48)	(3)	693	< 0.001
Final	24.8%	29.9%	22.6%	13.7%	9.0%		
	(678)	(817)	(617)	(376)	(246)		

Notes: BEC, biogeoclimatic ecosystem classification; IDFdk, Interior Douglas-fir dry, cool; MSdm, Montane Spruce dry, mild

Table 5 shows the percent of live, dead, and down (and missing) lodgepole pine at the final assessment by layer in the four BEC variants in this study. Layer 3 trees in the MSdm2 sustained the highest mortality (dead or down). Mortality occurred over the duration of the study and clearly demonstrated that most deaths occurred when trees were small (Table 5). At the final assessment, 35% of layer 1 and 2 pine were still alive and 11% of layer 3 trees (Table 5).

Table 5. The percent of lodgepole pine live, dead, or down and total number of lodgepole pine in four biogeoclimatic zones (BEC) by layer at final assessment.

BEC & layer	Tree status (% Pl in each BEC)			Number of trees
	Live	Dead	Down	
IDFdk1				
Layer 1	71.3	0.0	0.0	73
Layer 2	16.8	1.0	0.0	18
Layer 3	5.0	2.0	1.0	10
IDFdk2				
Layer 1	38.4	0.7	0.1	355
Layer 2	6.1	0.2	0.3	60
Layer 3	36.8	12.4	0.9	491

Table 5 (continued)

BEC & layer	Tree status (% Pl in each BEC)			Number of trees
	Live	Dead	Down	
MSdm1				
Layer 1	56.7	2.8	0.1	888
Layer 2	13.6	4.1	1.6	293
Layer 3*	3.6	11.4	2.2	257
MSdm2				
Layer 1	27.7	0.6	1.1	357
Layer 2	7.3	1.6	7.0	197
Layer 3	11.0	15.1	25.2	647

Notes: BEC, biogeoclimatic ecosystem classification; IDFdk1, Interior Douglas-fir dry, cool variant 1; IDFdk2, Interior Douglas-fir dry, cool variant 2; MSdm1, Montane Spruce dry, mild variant 1; MSdm2, Montane Spruce dry, mild variant 2; Pl, lodgepole pine.*Most ingress in plot 9 were not assessed in 2020 due to high numbers.

In the IDFdk2, only 19% and 15% of layer 1 and 2 pines, respectively, were pest-free by the final assessment (Table 6). Twenty-two percent of live layer 1 pine and 86% of dead or down layer 1 pine had three or more pests and over half of layer 3 trees had at least one pest recorded. In the MSdm1, only 13% of layer 1 pine were pest-free and 53% of layer 1 pine had two or more pests per tree (Table 6). In the MSdm2, over half of live layer 1 lodgepole pine had three or more damage agents affecting them, but not causing mortality.

Table 6. Number of pests per tree (% lodgepole pine) by layer and biogeoclimatic zone. This table shows the % of pine with zero pests, 1, 2, and 3 or more pests per tree over the duration of the study.

BEC-layer	No. pests per tree							
	Live pine (%)				Dead/down pine (%)			
	0	1	2	≥3	0	1	2	≥3
IDFdk1								
Layer 1	24	56	17	4	0	0	0	0
Layer 2	47	35	12	6	0	0	0	100
Layer 3	20	60	20	0	67	0	0	33
IDFdk2								
Layer 1	19	40	19	22	0	14	0	86
Layer 2	15	40	20	25	40	0	20	40
Layer 3	50	29	9	13	24	53	15	8
MSdm1								
Layer 1	13	33	25	28	5	8	11	76
Layer 2	27	41	18	14	1	11	22	66
Layer 3	21	38	19	21	5	56	24	15
MSdm2								
Layer 1	0	13	31	51	5	20	50	25
Layer 2	30	32	23	16	8	42	41	10
Layer 3	11	32	37	20	39	24	22	16

Notes: BEC, biogeoclimatic ecosystem classification; IDFdk1, Interior Douglas-fir dry, cool variant 1; IDFdk2, Interior Douglas-fir dry, cool variant 2; MSdm1, Montane Spruce dry, mild variant 1; MSdm2, Montane Spruce dry, mild variant 2.

Atropellis appeared in plots as trees matured (Figure 2). By the final assessment, incidence had increased significantly in the IDFdk2, MSdm1, and MSdm2.

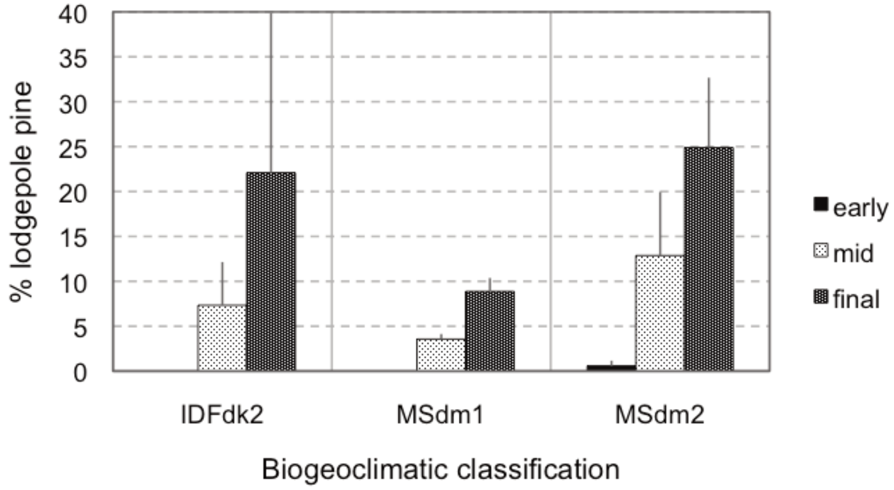


Figure 2. Average % lodgepole pine infected with Atropellis in early, mid-, and final-assessment times (± Standard Error) in the IDFdk2, MSdm1, and MSdm2. No Atropellis was recorded in the IDFdk1 (plot 1).

The prevalence of western gall rust was second only to lodgepole pine terminal weevil in this study. Most western gall rust infections (stem and branch) occurred early in stand development, increasing minimally from first to final assessment, except in the MSdm2 where all infections increased by almost 18%. The average percent of trees with stem galls increased from 40% to 58% from the early to final assessments, respectively. The median height of the first (lowest) stem gall on most trees was at or just below 2 m (Figure 3) and the average height of the first stem gall ranged from 2 m to 4.4 m.

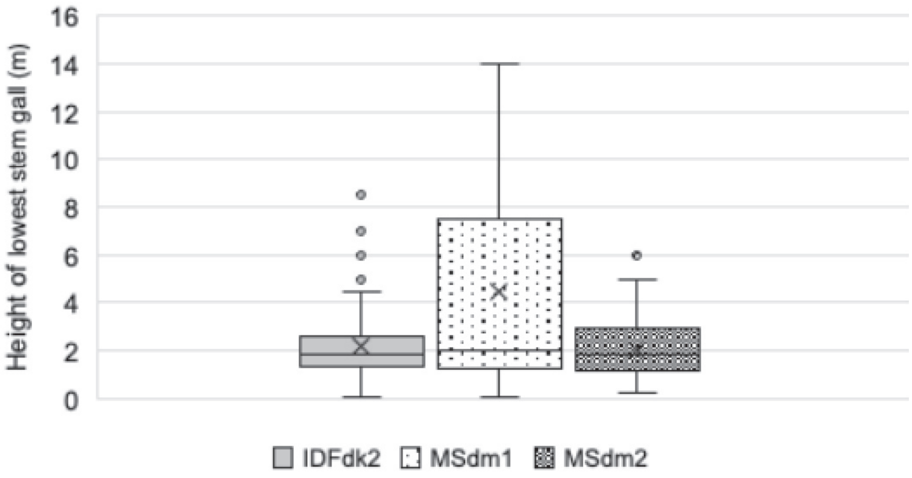


Figure 3. Box plot showing mean (X), median, and range of lowest occurring western gall rust stem galls on trees in the IDFdk2, MSdm1, and MSdm2.

The lodgepole pine terminal weevil was the most prevalent pest in this study, recorded in all 14 plots, affecting an average of 38% of pine (Table 3), with a maximum of 73% pine affected in the MSdm1. Figure 4 depicts the number of attacks per hectare over time in each plot. Attacks increased as stands developed. During the later years of stand development, the number of attacks declined. However, with canopy closure, new attacks may be difficult to see from the ground and thus we may be underestimating the actual number of attacks that are occurring (Maclauchlan 1992). In some years, over 350 attacks per hectare were recorded (Figure 4).

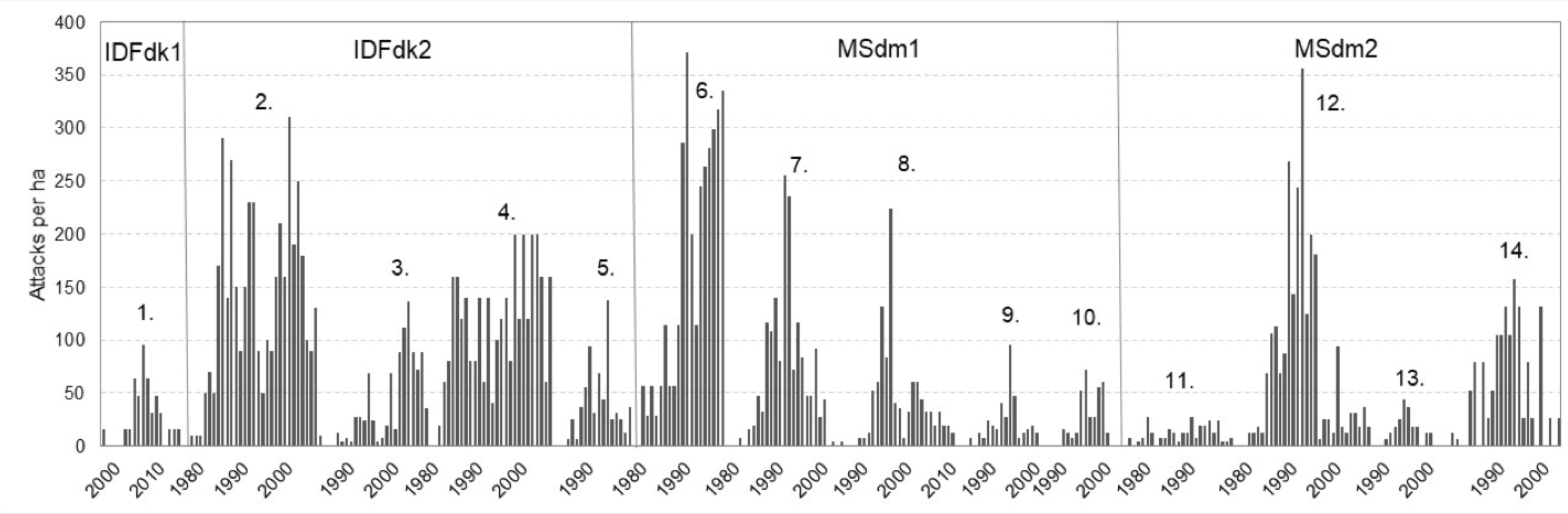


Figure 4. Frequency of lodgepole pine terminal weevil attack over time in 14 plots grouped by biogeoclimatic classification. The plot number is labelled above each time series of attacks.

Over the course of this study, individual trees sustained multiple attacks by the lodgepole pine terminal weevil (Figure 5). Some trees had up to eight attacks. By the final assessment, significantly more lodgepole pine had one to four or more attacks per tree than at the first assessment (P < 0.01, t-test) (Figure 5). On average, over all plots, 53% of pine had one or more weevil attacks.

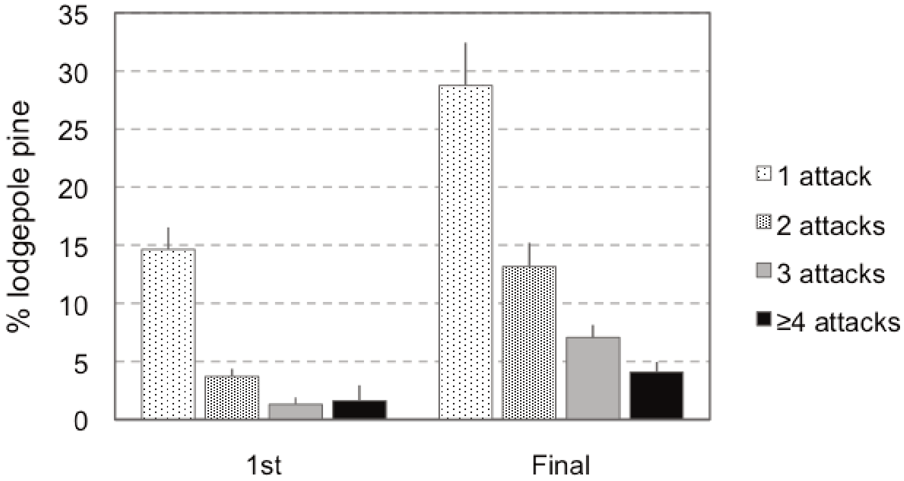


Figure 5. Comparison of the average % lodgepole pine (Average ± Standard Error) with one to four or more attacks per tree by the lodgepole pine terminal weevil at the first and final assessment.

As the number of pests per tree increased, there was a higher likelihood of trees (all layers) acquiring moderate or poor form (X^2 test; *p*-value < 0.001) (Figure 6). Very few layer 1 lodgepole pine with good form were pest-free (11.9%), 18% had one pest, and 25% had two or more pests (Figure 6) illustrating that not all pests negatively influence tree growth and form. Fewer layer 2 and 3 trees had good form as the number of pests per tree increased, most likely because the cumulative effect of pests on smaller trees is greater. Assessing the form of layer 3 trees was difficult because most trees were suppressed.

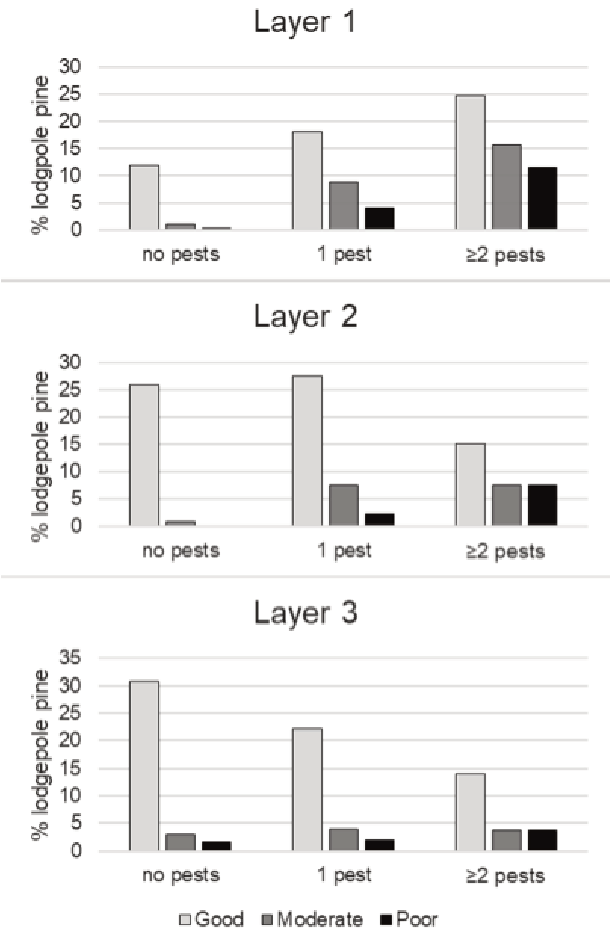


Figure 6. Comparison of the number of pests per tree, by layer, having good, moderate, or poor form.

Lodgepole pine terminal weevil attack began early in stand development with most attacks occurring when trees were 2 m to just less than 8 m in height (Figure 7). There was little variation in the height of attack and resultant defects among BECs. The majority of crooks, forks, and stagheads developed from attacks at 4 m to just over 7 m (Figure 7), thus causing a major stem defect to the most valuable portion of the tree (first log)

(Alfaro and Omule 1990, Jozsa and Middleton 1994, Weyerhaeuser Company Limited, pers. comm.).

The dominant influences on layer 1 and 2 tree form were defects caused by lodgepole pine terminal weevil attack and western gall rust stem galls. Other damage agents including squirrel feeding, Atropellis infection, and abiotic damage also strongly influenced final tree form. At the first assessment, most attacks in the IDFdk and MSdm were classified as a crease, at 37% and 32%, respectively. By the final assessment, crooks and forks dominated in the IDFdk, at 47% and 26%, respectively. Only 5% of defects were classified as stagheads (multiple tops). The final assessment in the MSdm recorded that most defects were still classified as a crease (42%), while crooks and forks made up 32% and 23% of defects, respectively, and only 3% of the defects were stagheads (Figure 8). Very few defects increased in severity, the most common being a crease turning into a crook.

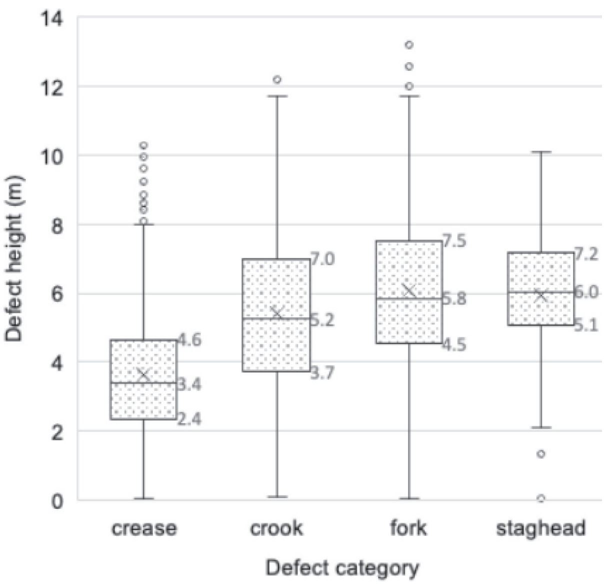


Figure 7. Comparison of defect category at final assessment and height (meters) on tree where weevil attack occurred. Box plots show mean (X), and values of the first quartile, median and third quartile of all defect heights for each defect category.

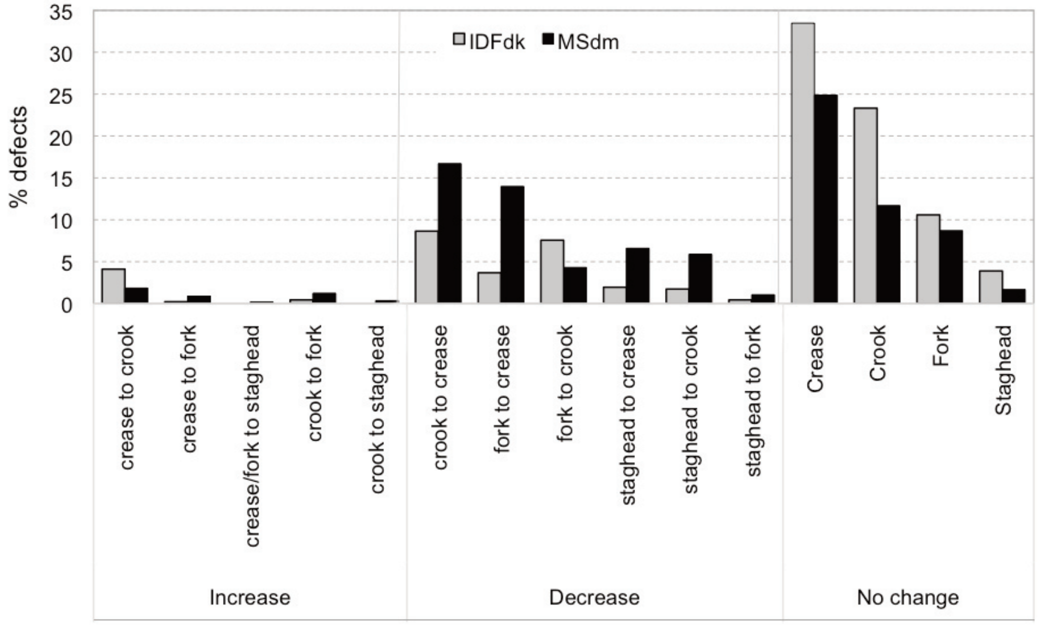


Figure 8. Change in defect severity from the first to the final assessment in the Interior Douglas-fir (IDFdk) and Montane Spruce (MSdm) ecosystems.

Tree form worsened with increasing numbers of weevil attacks per tree (X^2 [$N = 2{,}673$] = 198.8769, p-value < 0.00001) (Figure 9). Just under half of pine having moderate or poor form had no weevil attacks. Conversely, very few pines with good form had three or more attacks compared to trees with poor form. Trees with only one weevil attack had an equal likelihood of having good, moderate, or poor form (Figure 9).

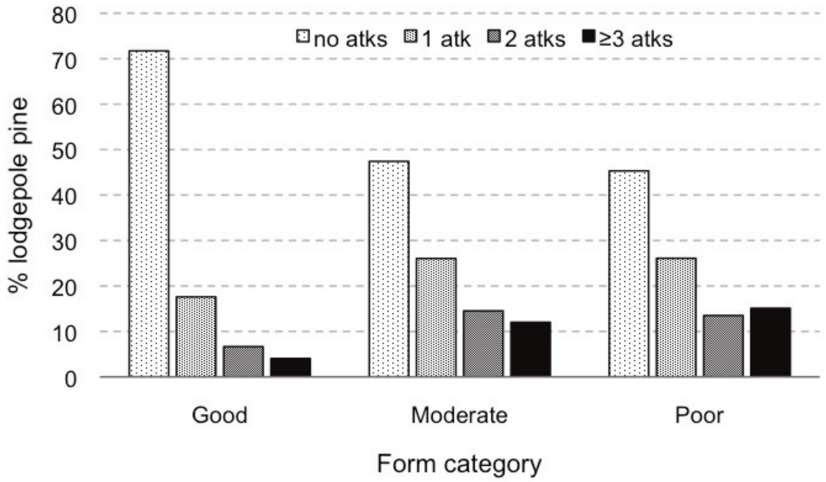


Figure 9. Percent of lodgepole pine with zero, 1, 2, or 3 or more attacks per tree within each form category.

Discussion

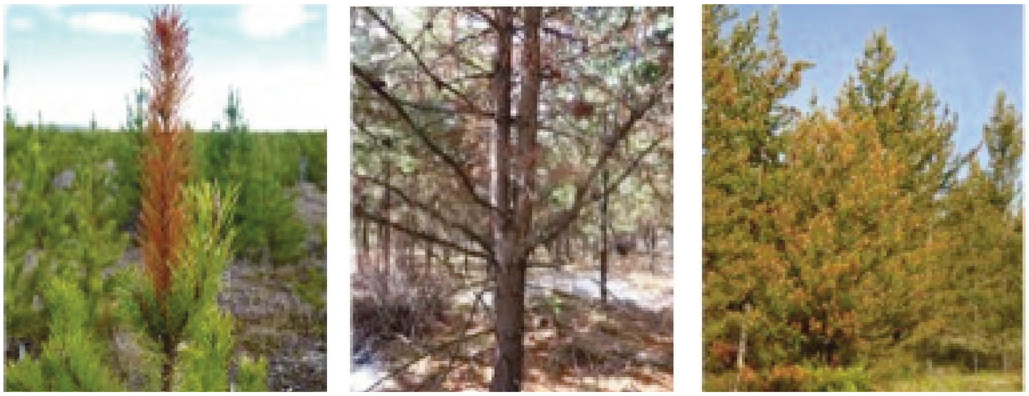
We clearly show that not all damage agents kill trees or compromise final tree form, but the cumulative effect of one or more damage agents over the life of a tree may significantly limit the final expectations of that tree or stand at harvest. Only a few damage agents cause significant mortality to lodgepole pine, most notably IBM (Safranyik & Carroll 2006, Negrón & Cain 2019, Bentz et al. 2021), and top-kill or serious stem deformation, such as western gall rust and other hard pine rusts. When these damage agents are present, consequences can be devastating, as evidenced by the loss of two plots to IBM during the 2000s outbreak in British Columbia (Safranyik & Carroll 2006, Westfall & Ebata 2017). Climate conditions are no longer predictable; therefore, events that were documented in the past IBM outbreak whereby thousands of hectares of young pine were killed (Maclauchlan 2006, 2008) may re-occur during the next IBM outbreak cycle, with even greater repercussions. The impacts of climate change on trees (young and old), landscapes, insects, and diseases are accelerating (Woods et al. 2000, Allen 2009, Pojar 2010, Woods et al. 2010, 2017, Ramsfield et al. 2016, Maclauchlan & Buxton 2019, Maclauchlan & Brooks 2020). We anticipate that they will become more pronounced and damaging as we experience unseasonable or extreme weather events (Woods 2011, Woods et al. 2005, 2017, van Mantgem et al. 2009, Heineman et al. 2010, Haughian et al. 2012), whether by new pest occurrences or existing site-resident pests, until these stands reach their harvest age. Bentz et al. (2021) recommend creating stand- and landscape-level resilience to beetle outbreaks by promoting appropriate silviculture treatments and timed regeneration of desired species to mitigate climate-induced disruption.

Young lodgepole pine are impacted by a wide range of biotic and abiotic damage agents from early to mid-stage development (Figure 10) (BC FLNRORD 2020), which has significant repercussions on the stocking, health, performance, and final form of potential crop trees. The occurrence of one or multiple pests can affect tree outcome in several ways (Heineman et al. 2010, Mather et al. 2010, Woods & Coates 2013, Alfaro & Fuentealba 2016, Woods et al. 2017, Maclauchlan & Brooks 2020, MacKenzie & Mahony 2021), from survival (mortality) to final tree form. Many trees with poor form may be rejected at harvest time or will have noticeable reductions in usable volume due to stem deformities. Some pests have a wide distribution throughout British Columbia; therefore, general inferences can be made as to how these damage factors may affect trees and stands beyond the scale of this study. During the 20–30 years of monitoring, over 40 damage agents were recorded, affecting primarily lodgepole pine—more than were documented in other studies (Humphreys & Van Sickle 1992, Heineman et al. 2010, Mather et al. 2010, Woods et al. 2017, Maclauchlan & Brooks 2020). Past surveys conducted in young pine stands (Humphreys & Van Sickle 1992) found many of the same pests that were documented in our study, but at a lower frequency, further emphasizing that pest incidence increases as trees develop, and is likely influenced by changing climatic and stand conditions, which are becoming more favorable to many damage agents (Maclauchlan & Buxton 2019).

Western gall rust gall

Stalactiform infection

Atropellis canker



Lodgepole pine terminal weevil current attack

Fork caused by lodgepole pine terminal weevil attack

Pine needle cast

Dead, down layer 3 lodgepole pine

Figure 10. Damage agents impacting young lodgepole pine.

Impacts to tree health and decline in tree form over two to three decades of monitoring were most often caused by combinations of sublethal pest damage. The most common compounding damage factors were western gall rust and lodgepole pine terminal weevil (Heineman et al. 2010, Mather et al. 2010, Alfaro & Fuentealba 2016) occurring in all the study sites, and northern pitch twig moth occurring on almost all the sites. Larvae of the northern pitch twig moth feed on new and old growth of stems and branches of young trees, often causing deformity or breakage by wind and snow, and occasionally girdling the entire stem, leading to top-kill or mortality (Alfaro & Fuentealba 2016).

Many other insect, disease, and abiotic damage agents inflicted site-specific or individual tree damage that compromised long-term performance and merchantability of trees. Severe or prolonged outbreaks of pine needle cast may reduce growth and overall tree performance, particularly when combined with other pests or extreme climate events (e.g., drought). It rarely causes tree mortality (Worrall et al. 2012, Burleigh et al. 2014) but disproportionately affects suppressed understory trees. Even-aged management and lower stand density can reduce disease severity (Worrall et al. 2012), but is always a tradeoff, with other pests such as lodgepole terminal weevil thriving in more open-grown stands (Maclauchlan & Borden 1996, Maclauchlan & Brooks 2020) and causing more damage at low stand densities. This highlights the need to set targeted goals at regeneration, and to identify the risks and tradeoffs due to pests, climate, and other values.

Atropellis canker and stalactiform blister rust became more prevalent as the stands aged. Western gall rust and comandra blister rust infections occurred during early-stage development (Reich et al. 2015). The majority of first stem infections by western gall rust occurred at or below 2 m, emphasizing the need to continually refine and implement hazard rating indices (Sattler et al. 2019) in British Columbia and to promote more proactive reforestation techniques, such as density manipulation, mixed species planting, and the development and use of resistant lodgepole pine. Squirrel feeding was often present on trees infected by hard pine stem rusts (Sullivan & Sullivan 1982, Burleigh et al. 2014), which aggravated rust damage by causing top-kill and deformities on the main bole. Mortality of suppressed natural ingress usually could be attributed to a single causal agent or pest complex.

Repeated leader destruction by the lodgepole terminal weevil leads to stem deformities, similar to the damage caused by Sitka spruce weevil attack on spruce (Alfaro 1989). Deformed stems reduce a tree's value and limit the options for end use. Lodgepole pine terminal weevil has a very plastic life history (Cameron & Stark 1989, Maclauchlan & Brooks 2000, 2020), requiring one to three years to complete its development from egg to adult, depending upon the ecosystem where it is found. As trees and stands develop, the influence of terminal weevil attack on stem form and quality changes, increasing the likelihood that an attack will result in a major defect (Maclauchlan & Brooks 2020). Tree form worsened with increasing number of attacks per tree and most crooks, forks, and stagheads occurred below 8 m within the most valuable portion of the tree (Alfaro & Omule 1989, Jozsa & Middleton 1994, Maclauchlan & Brooks 2020, Weyerhaeuser Company Limited, pers. comm.). Our final assessment occurred when the study sites were considered mid-stage in stand development and half of defects caused by weevil attack had resulted in a serious defect (Maclauchlan & Brooks 2020). As the growing season in pine stands becomes longer with accelerating climate change, we can expect to see a higher proportion of weevils having a shorter life cycle, thereby increasing the amount of potential damage to trees.

Tree density naturally declines as stands age, but the dramatic decline of potential crop trees in this study coupled with most remaining live trees being impacted by some damage agent, may limit both quality and volume expectations for these stands. We can-not depend on natural ingress to fill in stand gaps caused by the numerous mortality and damage agents affecting layer 1 and 2 trees. There is a high probability that the remaining live layer 1 pine will suffer additional mortality or sublethal damage from pests prior to reaching harvest age. This long-term analysis of how pests affect the growth, performance, and survival of trees over time leads us to question if young lodgepole pine stands will meet British Columbia's future forest management expectations. Only a few insects, diseases, or other damage agents cause mortality, but we have shown that the cumulative effect of multiple damage agents over the development of a tree greatly increases the likelihood of mortality, negatively alters final tree form, and decreases the quality of a tree. In conclusion, we offer the following recommendations:

- Extensively and intensively monitor insects, diseases, and other damage agents at all stages of stand development and their climatic and ecological drivers.
- Align harvest and reforestation practices to address the threat of biotic and abiotic damage agents (Heineman et al. 2010, Mather et al. 2010, Haughian et al. 2012, Woods et al. 2017).
- Evaluate and quantify the range, incidence, and severity of damage agents affecting young forests in the context of future expectations.
- Regenerate with mixtures of ecologically suitable species at higher initial stem densities as a possible mitigation tactic against sustained climate change (Hennon et al. 2021, Mackenzie & Mahony 2021).
- Conduct more short- and long-term monitoring of young stands to inform the development of forest policy, to provide input to models used to guide British Columbia's forest management and to promote healthy, resilient new forests.

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