Quantifying Yellow-Cedar Decline Impacts in Young-Growth: Preliminary Results from Five Stands on Zarembo, Kupreanof & Wrangell Islands

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Summary

In 2018, 41 plots (0.26 ac, circular) were installed in five young-growth stands that had been harvested between 1973 and 1984 on Zarembo, Kupreanof and Wrangell Islands. Each stand had abundant yellow-cedar young-growth trees. The five stands were targeted for intensive monitoring because they had the highest detected levels of yellow-cedar mortality and crown discoloration associated with yellow-cedar decline. The primary objectives of plot installation were to quantify impacts to yellow-cedar at the stand level and to facilitate long-term monitoring. All stands were pre-commercially thinned to prioritize retention of yellow-cedar above other species. Random plot locations were selected within the matrix of yellow-cedar habitat in the stands, which was based on tree spacing and crown color from low-altitude imagery. Data was collected on 1,402 yellow-cedar crop trees. Overall levels of yellow-cedar mortality were low (2% of yellow-cedar overall, 0-8% per stand), but 30% of yellow-cedar trees had crown discoloration symptoms greater than typical of healthy trees (≥20% red, yellow or brown discoloration). Eight times as many yellow-cedar trees were dead compared to all other tree species combined. Signs of *Phloeosinus* bark beetle attack were common on yellow-cedar trees, but attacked trees without crown symptoms may survive. The lowest proportion of plots affected by decline were found in the stand in which decline was most recently detected. More extensive decline in stands in which the problem has occurred for longer is consistent with the progressive pattern of decline observed in old-growth, and the pattern of decline intensification we have observed in the young-growth stands on Zarembo Island that have been monitored since 2013. Cursory plot-level analysis suggests that decline was more common on gentler slopes, but also occurred on steep slopes (up to 56%) with shallow soils. Decline was also relatively more common on SW, W and SE aspects, but these were also the most common aspects in the evaluated stands. Yellow-cedar decline, which we detected in 27 of 41 plots, is having considerable impact to yellow-cedar in these affected stands and mortality is expected to increase as symptomatic live yellow-cedars continue to lose vigor. Detailed mapping of hydrology and soil depth, key risk factors for yellow-cedar decline, would provide valuable insight into decline patterns in these stands, with possible applications for predicting decline risk in other young-growth stands.

Introduction

In summer 2018, plots were installed to quantify decline impacts in five young-growth stands confirmed to have yellow-cedar crop trees affected by yellow-cedar decline. Three of the stands were located on central-western Zarembo Island, one stand on the Tonka road system of Kupreanof Island, and one stand on Wrangell Island. The Wrangell Island stand was detected midway through the field season and appears to have become affected by decline within the last year or two. The primary objective of plot installation was to assess the percentage of trees and percentage of yellow-cedar affected by decline. Individual trees were not tagged, but plot centers were marked with 1-inch diameter PVC pipes so that plots can be revisited for change in tree health and further evaluation of site factors. Tree diameters were measured to allow for impact assessments based on basal area.

Until recently, yellow-cedar decline was considered a problem limited to old-growth forests. Yellow-cedar decline is caused by freezing injury to shallow fine roots of yellow-cedar in the absence of insulating snowpack. Yellow-cedar roots do not go into true winter dormancy, which makes this species uniquely vulnerable to freezing injury following periods of warm weather that activate its tissues in early-spring. In young-growth stands, yellow-cedar trees were thought to be protected from freezing injury by having greater rooting depth on relatively more productive sites harvested and then managed for timber.

In 2013, Forest Health Protection investigated the cause of yellow-cedar crop tree mortality on Zarembo Island with Wrangell Ranger District silviculture staff and determined that the cause was yellow-cedar decline (Fig. 1). We observed necrotic lesions moving up from coarse roots and secondary agents commonly associated with yellow-cedar decline in old-growth (*Phloeosinus* bark beetles and Armillaria root disease caused by *Armillaria* spp.). Decline was most common in poorly-drained portions of stands and yellow-cedar was the only species affected. Forest Health Protection has since prioritized monitoring of yellow-cedar young-growth to better understand the extent and severity of the problem, and to determine key risk factors and management alternatives to mitigate impacts. As of 2018, there are 338 young-growth stands known to contain yellow-cedar in our yellow-cedar young-growth database. Decline has been detected in 33 stands (Fig. 2), but in most cases damage is not currently severe. Affected stands are 28-45 years old, and most were thinned between 2004 and 2012. Moderate to severe levels of decline have only been found in ten stands. The severity levels are not well-defined because this is our first effort to quantify decline at the stand level, but generally relate to the number and distribution of affected trees. In most cases, decline has been initially detected in stands 5-7 years after thinning, at which point the phenomenon has likely been occurring for several years. In old-growth stands, decline is often progressive with an apparent spreading pattern; as trees die, the loss of tree crown facilitates greater soil temperature fluctuation, which increases the risk of root freezing injury to adjacent cedars.

Figure 1. Young-growth yellow-cedar decline on Zarembo Island at the stand- and tree-level.

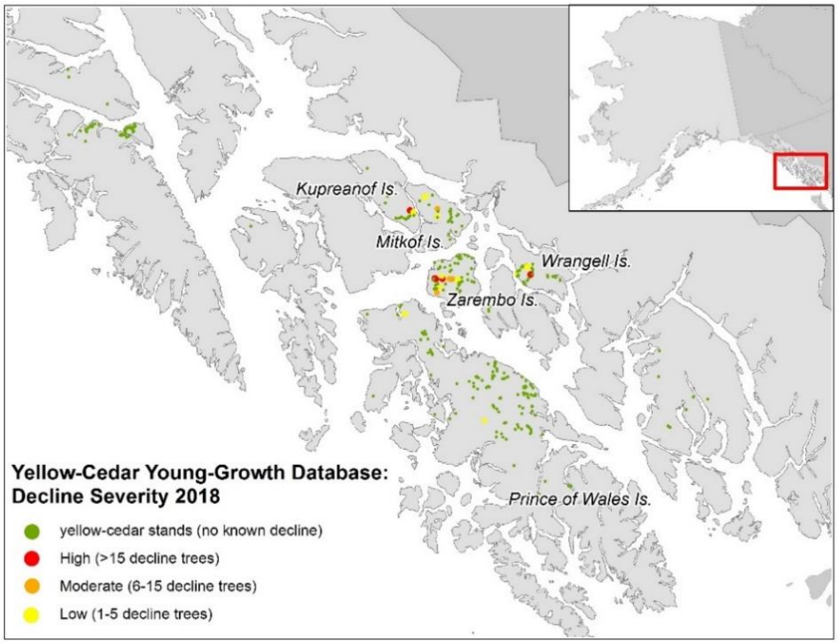

Figure 2. Managed young-growth stands on the Tongass National Forest known to contain yellow-cedar (338 stands) with the severity of yellow-cedar decline detected in individual stands as of 2018.

Methods

GIS tools and low-altitude imagery were used to partition stands into likely vs. unlikely yellow-cedar habitat based on crown color and tree-spacing (Fig. 3). Yellow-cedar is most abundant in less productive parts of stands (corresponding to shallower and wetter soils), which can be identified in the imagery by greater spacing between trees (i.e., lack of crown closure following precommercial thinning). Random plot locations were then selected in areas identified as suitable yellow-cedar habitat (Random Point Tool in ArcMap 10.3.1). The number of plots installed per management unit was based on the area of yellow-cedar habitat in the stand, with the goal of sampling at least 4% of the area to adequately characterize cedar habitat within the stand with 60-ft radius (0.26 ac) circular plots (Table 1). Areas of known or suspected damage were not specifically targeted by the survey because of our desire to understand impacts at the stand-level, not only in affected parts of the stands. Plots were only shifted slightly to avoid overlap with stand boundaries or roads; all established plots contained yellow-cedar.

Data was collected on all trees greater than 3 inches diameter at breast height; the goal was to assess crop trees only, but trees released by thinning may have also been included. Tree species, diameter, live/dead status, decay class for snags, and apparent insect or pathogen damage were recorded for all species. Measurements aimed to assess yellow-cedar health included crown color (the percentage of the tree crown that was green, light green, yellow, red and brown; total percentage summed to 100%), crown fullness (the percent of crown volume occupied by the tree crown relative to a healthy, vigorous tree), and crown dieback (the percent of crown volume that was defoliated that would normally be foliated in a healthy tree; excludes normal lower branch dieback). Crown discoloration of up to 15% can be normal for a healthy yellow-cedar tree with senescing older foliage in the interior crown. Evidence of *Phloeosinus* bark beetle attack and Armillaria infection were noted on yellow-cedar trees whenever observed. These agents are frequently encountered on yellow-cedar trees stressed by yellow-cedar decline and are considered secondary to abiotic damage from root-freezing injury. Aggressive excavation of live trees was discouraged because associated damage may affect long-term tree survival; this inherently limited our ability to detect Armillaria root disease, but dead trees could be more thoroughly examined.

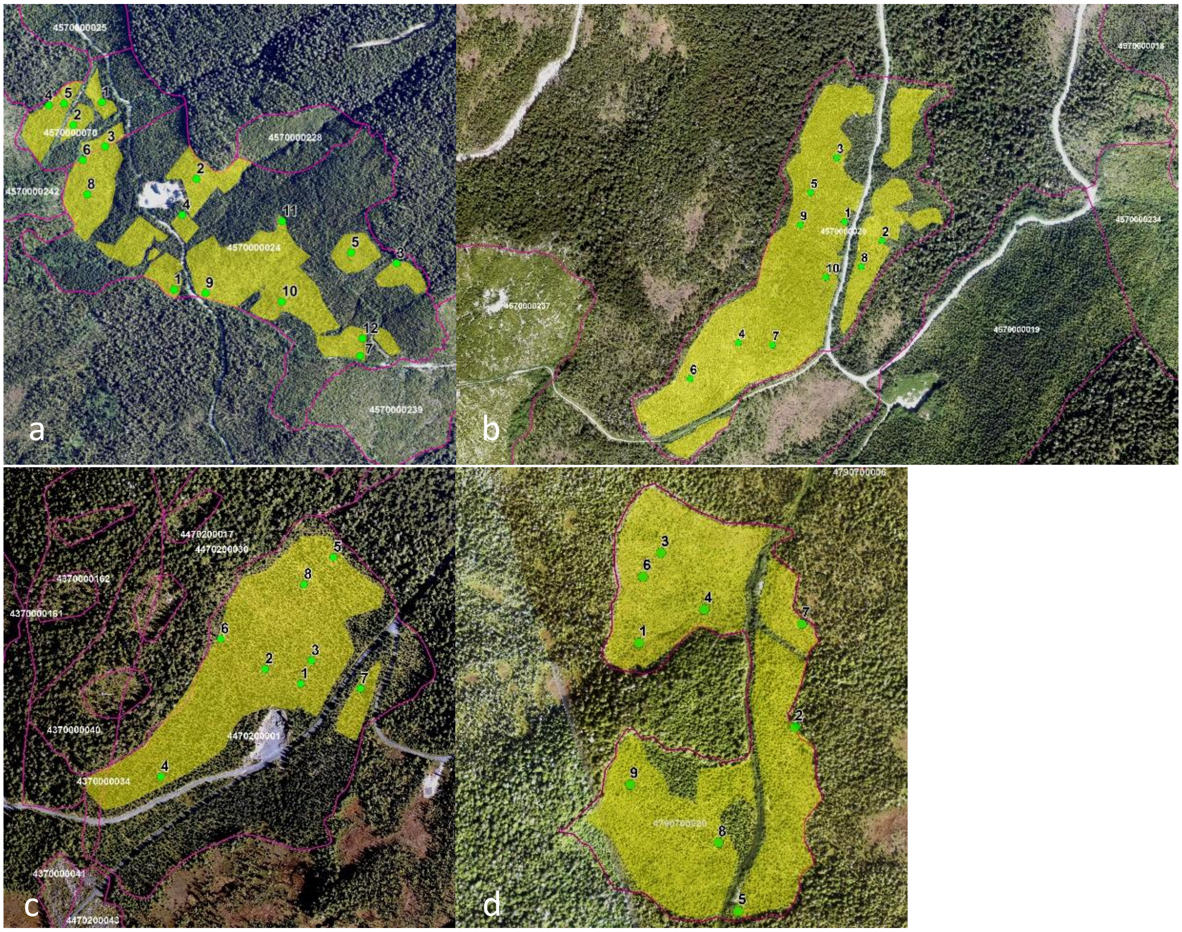

Figure 3. Low altitude imagery overlaid with unit boundaries (pink) and potential yellow-cedar habitat (yellow) based on tree spacing, tree texture and tree color for stands (a) 4570000070 and 4570000024 on Zarembo Island, (b) 4570000020 on Zarembo Island, (c) 4470200001 on Kupreanof Island, and (d) 4790700020 on Wrangell Island. Random plot locations are shown as green dots.

While slope and aspect measurements were collected in the field, elevation was calculated by importing the plot locations into ArcGIS and extracting the corresponding elevation from the 5-meter Interferometric Synthetic Aperture Radar (IfSAR) Digital Terrain Model. IfSAR heights can underestimate elevation in southeast Alaska by about 8.6 meters (RMSE; Guritz et al. 2016), but relative values within stands are expected to be reasonably consistent.

Table 1. Total area (ac) and area of yellow-cedar habitat identified from low-altitude imagery in five young-growth stands with notable yellow-cedar decline on Zarembo, Kupreanof and Wrangell Islands, along with the year of harvest, thinning and decline detection and the number of plots installed in 2018.

Island	Managed Stand ID	Harvest Year	Thinning Year	Decline Detected Year	Area (ac)	Yellow-Cedar Habitat (ac)	# Plots
Zarembo	4570000020	1975	2008	2012/13	51	33.9	9
Zarembo	4570000024	1973	1983, 2005	2012/13	150	51	12
Zarembo	4570000070	1975	2005	2012/13	25	8.2	4
Kupreanof	4470200001	1981	2009	2015	62	29	7
Wrangell	4790700020	1984	2010	2018	49	38	6 (9)*

*Individual tree data was collected in 6 of 9 plots, plot centers were monumented in all 9.

Results

Forty-one random plots were installed within yellow-cedar habitat across the five stands. Three plots in Wrangell stand 4790700020 are not included in the summary statistics because individual tree data was not collected due to time constraints. The three plots did not contain symptomatic yellow-cedar trees. Tree data was collected on 1,402 yellow-cedar trees and 2,351 total trees ≥ 3 inches in diameter at breast height. Assessments based on tree basal area were comparable to those based on tree-level incidence, so results based on tree-level incidence are presented here.

The delineation of yellow-cedar habitat within stands based on low-altitude imagery effectively classified yellow-cedar habitat; yellow-cedar was generally abundant in randomly selected plots in this habitat matrix. Only one plot in the Wrangell stand and one plot in the Kupreanof stand had insufficient yellow-cedar for plot installation; one plot in Wrangell that contained only 3 yellow-cedar trees was still installed because decline symptoms were detected. Yellow-cedar composition was 60% overall, and ranged from 34-80% per stand (within the yellow-cedar habitat matrix). There were 3 to 77 yellow-cedar trees per plot (average 37 yellow-cedar trees; data not shown) and percent yellow-cedar composition ranged from 6-92% per plot (average 58%) (Table 2). Sitka spruce and western hemlock were the most common associated species, with overall composition of 15% and 13%, respectively. Western redcedar was present in all stands on Zarembo and Wrangell Islands (but not on Kupreanof Island) with overall composition of 11%. Yellow-cedar mortality (percent of yellow-cedar trees that were dead) was low at the stand-level (0-8% per stand), but was as high as 20-26% in individual plots (Table 2). Mortality rates for other tree species were negligible (less than 4 trees total).

Crown discoloration symptoms and signs of bark beetle were used to categorize relative impacts to yellow-cedar trees within stands. Percent crown dieback was not reliably correlated with decline, because trees that died rapidly had red-brown discolored crowns (no live foliage), but no branch dieback/defoliated branches. For this reason, percent dieback was not used to summarize results. Two levels of crown discoloration symptom-severity were defined: (a) yellow-cedars with at least 20% crown discoloration, and (b) yellow-cedars with at least 40% crown discoloration (Table 2). Overall, ≥20% crown discoloration was observed in 30% of monitored yellow-cedar trees (421 of 1,402 trees; data not shown), and up to 89% of yellow-cedars per plot and 41% of yellow-cedars per stand (Table 2). Overall, ten percent of yellow-cedar trees had ≥40% crown discoloration; however, this higher level of crown discoloration affected up to 63% of yellow-cedars in some individual plots and up to 20% of yellow-cedars per stand (Table 2).

Evidence of *Phloeosinus* bark beetle attack was common; frass, exit holes or larval galleries were noted on 241 (or 17% of) yellow-cedar trees (data not shown). Of yellow-cedar trees with signs of bark beetle activity, 135 trees had limited crown discoloration (defined as <20% crown discoloration), indicating very recent or failed beetle attack. Revisiting the plots in two years will provide critical information about yellow-cedar survival following beetle attack. In total, 555 of 1,402 (40%) yellow-cedar trees had at least 20% crown discoloration *or* signs of bark beetle attack, affecting up to 89% of the yellow-cedar trees in individual plots and up to 61% of yellow-cedars at the stand-level (Table 2).

Table 2. Proportion of yellow-cedar composition and the proportion of yellow-cedar trees with mortality, crown discoloration of ≥20% and ≥40% of the tree crown, signs of *Phloeosinus* bark beetles, and crown discoloration or bark beetle attack in five stands and 37 plots installed in 2018.

Stand/Plot	Yellow-Cedar Composition	Yellow-Cedar Mortality	Yellow-Cedar Discoloration ≥20%	Yellow-Cedar Discoloration ≥40%	Evidence *Phloeosinus* Attack	Evidence *Phloeosinus* or Discoloration ≥20%
Zarembo 4570000020	**0.80**	**0.02**	**0.20**	**0.07**	**0.16**	**0.32**
Plot 01	0.87	0.04	0.24	0.13	0.24	0.39
Plot 02	0.75	0.04	0.50	0.28	0.26	0.57
Plot 03	0.92	0.00	0.32	0.00	0.00	0.32
Plot 04	0.86	0.00	0.09	0.00	0.22	0.31
Plot 06	0.90	0.00	0.07	0.02	0.07	0.15
Plot 07	0.87	0.00	0.04	0.00	0.19	0.23
Plot 08	0.62	0.15	0.56	0.29	0.15	0.56
Plot 09	0.78	0.00	0.05	0.02	0.14	0.19
Plot 10	0.65	0.00	0.04	0.00	0.18	0.22
Zarembo 4570000024	**0.58**	**0.01**	**0.41**	**0.12**	**0.16**	**0.48**
Plot 01	0.16	0.00	0.00	0.00	0.27	0.27
Plot 02	0.83	0.00	0.53	0.06	0.00	0.53
Plot 02X	0.69	0.00	0.49	0.15	0.40	0.66
Plot 04	0.56	0.02	0.16	0.07	0.02	0.19
Plot 05	0.81	0.00	0.36	0.01	0.01	0.37
Plot 06	0.27	0.00	0.15	0.00	0.00	0.15
Plot 07	0.74	0.00	0.25	0.02	0.14	0.33
Plot 09	0.49	0.00	0.46	0.26	0.26	0.63
Plot 10	0.74	0.05	0.72	0.35	0.43	0.82
Plot 10X	0.40	0.04	0.40	0.16	0.32	0.48
Plot 11	0.85	0.00	0.53	0.13	0.02	0.53
Plot 12	0.46	0.00	0.29	0.10	0.13	0.39
Zarembo 4570000070	**0.34**	**0.06**	**0.41**	**0.20**	**0.05**	**0.41**
Plot 01	0.42	0.00	0.12	0.04	0.00	0.12
Plot 02	0.31	0.26	0.89	0.63	0.21	0.89
Plot 03	0.37	0.00	0.30	0.00	0.00	0.30
Plot 05	0.28	0.00	0.44	0.22	0.00	0.44
Kupreanof 4470200001	**0.58**	**0.08**	**0.40**	**0.19**	**0.46**	**0.61**
Plot 01	0.56	0.00	0.64	0.14	0.29	0.79
Plot 02	0.66	0.21	0.53	0.26	0.79	0.84
Plot 03	0.69	0.23	0.68	0.55	0.55	0.82
Plot 04	0.41	0.00	0.07	0.00	0.33	0.33
Plot 05	0.48	0.00	0.08	0.00	0.42	0.50
Plot 06	0.55	0.00	0.29	0.06	0.12	0.29
Plot 08	0.76	0.04	0.36	0.12	0.56	0.60
Wrangell 4790700020	**0.39**	**0.00**	**0.07**	**0.02**	**0.09**	**0.14**
Plot 01	0.48	0.00	0.00	0.00	0.00	0.00
Plot 02	0.06	0.00	0.00	0.00	0.33	0.33
Plot 04	0.42	0.00	0.00	0.00	0.00	0.00
Plot 06	0.58	0.00	0.13	0.07	0.30	0.33
Plot 07	0.38	0.00	0.21	0.00	0.05	0.26
Plot 09	0.46	0.00	0.00	0.00	0.00	0.00

Plot-level summaries focused on the presence of decline and site factors (Table 3). The three plots in Wrangell 4790700020 from which tree data was not collected were considered for plot-level comparisons based on the presence of decline. Decline was detected in 27 of 41 plots (66%), and the proportion of plots affected per stand ranged from 33% in the Wrangell stand to 83% in Zarembo 4570000024. The proportion of plots with decline per stand increased with relative time since decline detection (Tables 1 and 3). The aspects most strongly correlated with decline presence were SW, W and SE (Table 4). On average, plots with decline tended to have more gradual slopes (19% slope) than plots without decline (26% slope) (data not shown), but decline occurred in plots with slopes as steep as 56% (Table 3). The relationship between elevation and presence of decline was not always consistent, but in individual stands (e.g., Zarembo 4570000024 and 4570000070) plots without decline tended to be at relatively higher elevations compared to plots with decline (Table 3). In Wrangell 4790700020, the few plots with decline were at relatively lower elevations.

Table 3. Decline presence, slope (%), aspect and latitude/longitude of 41 plots established in five stands with yellow-cedar decline in 2018. Three plots in which individual tree data was not collected are in red font.

Stand/Plot	Decline Present (Yes/No)	Slope (%)	Aspect (°)	Elevation (m) IfSAR 5-m	Latitude (°, WGS84)	Longitude (°, WGS84)
Zarembo 4570000020	Decline present in 6 of 9 plots (67%)					
Plot 01	Yes	20	228	211	56.37697	-132.92006
Plot 02	Yes	5	130	179	56.37645	-132.91834
Plot 03	No	30	110	224	56.37811	-132.91926
Plot 04	Yes	35	150	248	56.37559	-132.92401
Plot 06	No	18	145	257	56.37521	-132.92575
Plot 07	Yes	10	130	220	56.37515	-132.92283
Plot 08	Yes	0	100	185	56.37637	-132.91903
Plot 09	Yes	35	129	246	56.37735	-132.92102
Plot 10	No	30	100	206	56.37614	-132.92064
Zarembo 4570000024	Decline detected in 10 of 12 plots (83%)					
Plot 01	No	20	280	110	56.38234	-132.97646
Plot 02	Yes	15	216	155	56.38516	-132.97378
Plot 02X	Yes	12	250	157	56.38040	-132.97018
Plot 04	Yes	25	210	124	56.38430	-132.97533
Plot 05	Yes	20	225	225	56.38185	-132.96747
Plot 06	No	5	304	87	56.38664	-132.97893
Plot 07	Yes	12	277	160	56.37915	-132.96869
Plot 09	Yes	14	236	122	56.38205	-132.97513
Plot 10	Yes	20	226	153	56.38124	-132.97156
Plot 10X	Yes	5	282	104	56.38301	-132.97679
Plot 11	Yes	0	210	202	56.38331	-132.97010
Plot 12	Yes	12	274	167	56.37962	-132.96820
Zarembo 4570000070	Decline detected in 3 of 4 plots (75%)					
Plot 01	No	5	345	107	56.38799	-132.97695
Plot 02	Yes	5	260	94	56.38776	-132.97882
Plot 03	Yes	14	285	97	56.38672	-132.97766
Plot 05	Yes	4	288	93	56.38831	-132.97889
Kupreanof	Decline detected in 5 of 7 plots (71%)					
Plot 01	Yes	30	150	129	56.70403	-132.99388
Plot 02	Yes	43	150	161	56.70444	-132.99491
Plot 03	Yes	37	160	129	56.70438	-132.99334
Plot 04	No	60	160	157	56.70314	-132.99933
Plot 05	No	45	160	179	56.70603	-132.99182
Plot 06	Yes	56	150	206	56.70522	-132.99571

Plot 08	Yes	35	160	168	56.70561	-132.99264
Wrangell 4790700020	Decline detected in 3 of 9 plots (33%)					
Plot 01	No	28	100	337	56.27470	-132.25041
Plot 02	Yes	13	120	227	56.27250	-132.24739
Plot 03	No	27	148	326	56.27587	-132.24917
Plot 04	No	28	100	285	56.27486	-132.24833
Plot 05	No	6	120	216	56.27016	-132.25007
Plot 06	Yes	26	123	333	56.27543	-132.24979
Plot 07	Yes	10	105	241	56.27412	-132.24631
Plot 08	No	17	120	248	56.27134	-132.25029
Plot 09	No	46	170	343	56.27261	-132.25217

Table 4. Number of plots with decline, total number plots, and percentage of plots with decline at eight cardinal aspects (no plots had NE and NW aspects).

Aspect	**Number of Plots with Decline**	**Total Plots**	**Plots with Decline (%)**
N	0	2	0
E	2	6	33
S	2	6	33
SE	9	12	75
W	7	8	88
SW	7	7	100

Discussion

The incidence of crown discoloration symptoms among live yellow-cedars provides the most reliable measure of current and potential future impacts to yellow-cedar in young-growth stands with yellow-cedar decline. About one-third of yellow-cedar trees in random plots within yellow-cedar habitat in the five assessed stands showed elevated crown discoloration symptoms compared to what is expected in healthy trees. At present, yellow-cedar mortality in these stands is low, but still exceeds mortality of associated tree species by a factor of eight. The condition of symptomatic trees is expected to continue to deteriorate based on the progressive nature of individual tree death observed in declining old-growth forest trees, which often take over a decade to die. Tree death is hastened by secondary bark beetles and root rot fungi in the genus *Armillaria*, which attack trees stressed by abiotic damage and accelerate tree death. These damage agents are frequently observed in declining yellow-cedar trees in old-growth forests and we have consistently observed them in affected young-growth stands.

The highest rate of yellow-cedar mortality (8%) was observed in the stand on Kupreanof Island, where there was also the greatest activity of secondary bark beetles. Several *Phloeosinus* species are known to occur in Alaska, the most common of which is *Phloeosinus cupressi*. Western redcedars are also susceptible to attack by bark beetles within this genus, but western redcedar trees in these stands were vigorous and healthy with no signs of bark beetles. Evidence of *Phloeosinus* bark beetle attack was common on yellow-cedar trees; however, more than 100 attacked trees did not have notable crown discoloration symptoms. The fate of asymptomatic beetle-attacked yellow-cedar trees will be important to follow, since trees may successfully defend against initial attack. Forty percent of yellow-cedar trees had either elevated discoloration or signs of beetle attack. Unless trees were dead or nearly dead, they were not excavated to determine the success of bark beetle attack. The bleakest picture of yellow-cedar survival in these stands may come from the moderate percentage (40%) of yellow-cedar trees with signs of bark beetle attack *or* greater than 20% crown symptoms, as the long-term survival of these trees may be compromised. However, healthy trees with no trace of crown discoloration, dieback or bark beetles may become symptomatic in time. We found that one of the largest asymptomatic yellow-cedar young-growth trees that we began monitoring on Zarembo Island in 2013 had died by 2015.

Decline was noted in 27 of 41 plots, with the lowest decline incidence in plots found in the stand with the most recent decline detection (decline probably began in this stand on Wrangell Island within the last 2 years). In addition to time-since-onset, evaluation of plot data suggests possible relationships between aspect, slope and elevation and the presence of decline. There may be further interactions between these site factors. Decline is expected on wet sites with gentle slopes, and conversely on steep, rocky sites, since both conditions restrict rooting depth and confer greater susceptibility to fine root freezing injury. Relatively lower elevations and aspects with greater sun exposure are associated with reduced snowpack, another key risk factor for yellow-cedar decline. Site characteristics influencing hydrology and snowpack are predisposing environmental factors for the development of yellow-cedar decline.

Further assessment of soil and site characteristics within these plots will contribute to our understanding of decline patterns within affected stands. Detection of site and soil traits common to severely affected areas within managed stands will build our capacity to predict where decline in managed stands is likely to occur. It will also be important to compare, in greater depth, stands affected by decline with healthy stands with similar site characteristics and management history. One geospatial tool that we have used to evaluate hydrology patterns in stands with prevalent decline is the Compound Topographic Index (CTI), which assigns a relative wetness value to pixels by predicting water movement and accumulation on the landscape based on slope derived from a Digital Terrain Model. The stand on Wrangell Island had the best correlation between the wettest portions of the stand according to the CTI model and decline detection (Fig. 4), but the model did not perform as well in other stands in which decline has occurred for longer duration.

Changes in thinning prescriptions have the potential to mitigate damage and crop tree loss from yellow-cedar decline in young-growth stands in vulnerable areas. In old-growth stands, it is understood that decline initiates on wet sites with open tree crowns that facilitate greater soil temperature fluctuation in the absence of snowpack. As trees die, stand conditions become more open in adjacent forest, contributing to the spread-like progression of decline. Thinning similarly exposes stands to greater soil temperature fluctuation in the absence of insulating snowpack by opening the tree canopy. There may be interactions between the time of thinning and the number of decline events that occur while stand conditions remain open. In less productive parts of stands where yellow-cedar tends to be most common, crown closure following thinning may take far longer than on more productive sites, lengthening the period of risk to freezing injury.

Thinning, in addition to opening the tree canopy, may also provide breeding habitat in logging slash one or more years after thinning. Yellow-cedar (and possibly western redcedar) thinning slash may boost *Phloeosinus* populations in affected stands, increasing the likelihood that stressed trees are attacked. Although these bark beetles are considered secondary to abiotic injury, they may play an important role in accelerating yellow-cedar mortality in young-growth stands. It is possible that thinning in late fall could decrease bark beetle establishment in slash compared to thinning earlier in the summer.

Management alterations that could most effectively mitigate damage to young-growth yellow-cedar include decreasing spacing between trees in portions of stands with yellow-cedar, or ranking western redcedar above yellow-cedar in thinning priority. The potential role of thinning in triggering or exacerbating decline by increasing crown openness or providing slash habitat for bark beetles warrants research given the large number of young-growth yellow-cedar stands on the central Tongass that await thinning in the coming years.

Figure 4. The left image shows the location of random plots in Wrangell Island stand 4790700020 with the yellow-cedar habitat matrix in yellow, while the right image shows the Compound Topographic Index model (dark blue pixels are wettest and light green pixels are driest) in the same stand overlain with yellow-cedar decline mapped in the stand by aerial detection survey in 2018. Decline was detected in plots 2, 6 and 7.

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Guritz, R., Ignatov, D.M., Broderson, D., and T. Heinrichs. 2016. Southeast Alaska LiDAR, Orthoimagery, and IFSAR Mapping for ADOTPF Roads to Resources, Alaska Surveying and Mapping Conference, Anchorage, 17 Feb 2016