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Single-tree salvage logging as a response to Alaska yellow-cedar climate-induced mortality maintains ecological integrity with limited economic returns

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ABSTRACT

Cost-benefit analyses of salvage logging have generally focused on large-scale, landscape disturbances salvaged at high intensity, and there is limited research on the ecological and economic outcomes of low-intensity salvage implemented for the benefit of forest-dependent communities. Here, we assess the potential impacts of small-scale, single-tree salvage logging of a foundation tree species (yellow-cedar, *Callitropsis nootkatensis*) on ecological integrity against the viability of salvaged wood as a source of timber for cultural and economic purposes. We designed a salvage logging demonstration project in southeast Alaska, USA, and leveraged adjacent salvaged and unsalvaged, reference stands to: 1) investigate the degree to which salvage alters ecological integrity, defined by the abundance of yellow-cedar and post-disturbance stand trajectories, 2) track the volume and kinds of timber products generated by salvage logging activity, and 3) analyze the costs and revenues associated with the harvest and manufacturing of these products. Our results suggest that small-scale, single tree salvage logging has limited impact on yellow-cedar abundance and its potential to serve its foundation species role in forest successional trajectories while providing small to modest economic returns, though with large heterogeneity in net revenue among mill operators. Our findings indicate that salvage at this scale and intensity maintains ecological integrity but with limited economic viability. This management tool is thus best suited for land managers addressing multiple resource objectives in communities dependent on small, continuous streams of forest products.

1. Introduction

Tree mortality is an intrinsic driver of forest ecosystem dynamics. This process of constant change may be overlooked when occurring at a fine scale (e.g., single tree senescence) but viewed as catastrophic when apparent at the landscape scale (e.g., bark beetle epidemic). Landscape-scale tree mortality events can fall within the bounds of a forest's natural disturbance regime; however, forests worldwide are increasingly impacted by novel disturbance types, frequencies, and severities that are amplifying the scale and extent of widespread tree mortality (Allen et al., 2015; Anderegg et al., 2019; Berner et al., 2017). Uncharacteristic tree mortality events are anticipated to become more commonplace as the climate continues to change, and forest ecosystem integrity may be compromised when disturbances are out of character (Johnstone et al., 2016; Turner, 2010). Coupled socio-ecological systems are doubly challenged as new climate stresses unbalance established practices and tradeoffs between ecosystem services, management, and integrity. In managed landscapes or areas where local communities rely on forest-derived timber or cultural resources, these emerging disturbance conditions thus incentivize identification and adaptation of potentially novel and creative strategies that simultaneously promote forest management objectives and the maintenance of ecosystem functions and services.

Salvage logging is one of the most widespread management responses to high-severity forest disturbances and, although highly contentious, a practice increasing in pace and scale of application as

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widespread tree mortality becomes more common (Dobor et al., 2020; Leverkus et al., 2018). The practice of salvage logging is traditionally used to recoup economic losses and ensure sustained revenue following a catastrophic disturbance event (Müller et al., 2019). However, the application of salvage logging has expanded to meet other forest management objectives as tree mortality events have increased in scale and severity (e.g., ~148 million trees lost as a result of the 2012–2016 California drought, USDA 2020). Such events have forced land managers to repackage this practice to achieve other objectives, including reducing wildfire hazard and the risk of subsequent disturbances (Collins et al., 2012; Thompson et al., 2007) as well as maintaining culturally important resources (Turner and Cocksedge, 2001). Yet, the objectives and benefits of salvage logging continue to be heavily debated amongst managers and scientists, and evidence of undesirable ecological consequences are well-documented (see Lindenmayer et al., 2012, Thorn et al., 2018, Leverkus et al., 2021 for comprehensive reviews).

Cost-benefit analyses weighing the outcomes of salvage logging have generally centered around a handful of forest types that have been subject to large-scale, landscape disturbances and salvaged at high intensity (Thorn et al., 2020), with little research assessing ecological and economic outcomes of low-intensity salvage implemented for the benefit of forest-dependent communities. Further, research generally presumes that the decision to salvage was based on a single objective – economic or ecological – rather than on attempting to balance multiple, competing needs. Salvage operations modeled after uneven-aged silvicultural systems (i.e., single tree or group selection), although historically limited in application, may be one mechanism for meeting such seemingly competing objectives, as selection harvest techniques support ongoing extraction of salvaged timber or wood products yet are documented to have limited long-term ecological impacts (Knapp and Ritchie, 2016; Royo et al., 2016). This method allows foresters to achieve silvicultural objectives of promoting economic recovery via large-tree harvest and targeted reforestation efforts but do so on a scale that minimizes the potential ecological consequences often attributed to high-intensity salvage operations (Lindenmayer et al., 2012). Research pairing assessments of the economic and ecological viability of such operations are, however, lacking despite the intertwined nature of these silvicultural objectives. Understanding the potential outcomes of meeting multiple land-use objectives will be particularly critical to responsible forest management in the face of the increasing frequency and severity of disturbances related to the ongoing climate crisis (Burton, 2010).

In the North Pacific coastal temperate rainforest (NPCTR) of North America, Alaska yellow-cedar (*Callitropsis nootkatensis*, D. Don; Oerst. ex D.P. Little) is a culturally, economically, and ecologically important tree species that has been subject to extensive climate change-driven tree mortality (>400,000 ha, Buma et al., 2017). Mortality occurs following low snowpack periods where shallow roots lacking thermal insulation freeze during spring frosts, and one or more freezing events can lead to tree death (Buma, 2018; Hennon et al., 2012). This tree mortality event is consequential for ecosystem functioning, as yellow-cedar is a foundation species in the NPCTR. Prior to this climate-induced mortality event, yellow-cedar was once locally abundant and regionally common, while its occurrence across the NPCTR delineates ecological communities and determines ecosystem functioning and stability – the defining traits of foundation tree species (Ellison et al., 2005). Specifically, yellow-cedar serves an essential role by facilitating the cycling of nitrogen and, uniquely, calcium in forest soils (D'Amore et al., 2009) and providing habitat for bark and bole nesting species (Boland et al., 2009; Kellner et al., 2000), while its longevity and decay resistance make its presence –live or dead - a key structural component of low-diversity NPCTR forests (Hennon et al. 2016). Yellow-cedar mortality is also consequential for forest-dependent communities, as it has a rich history of cultural use. Indigenous peoples of the NPCTR have long used yellow-cedar wood for carving and bark for weaving (Turner and Cocksedge, 2001, Sutherland et al. 2016), and forest conservation icon John Muir even remarked on the value and durability of yellow-cedar, noting that its decay-resistance means timber remains viable long after death and subsequent tree fall (Muir 1882). In fact, snags may remain standing for 80 to 100 years after death (Hennon et al., 1990a) and retain wood properties comparable to live trees for decades (Green et al., 2002; Hennon et al., 2000; Kelsey et al., 2005). This decay-resistance confers high economic value on this species, and yellow-cedar is recognized as one of the most valuable timber species in Alaska (Hennon et al., 2016). Accordingly, yellow-cedar has value in both its retention on the landscape as well as its extraction to meet cultural and commercial timber demands. Its recent decline thus provides a unique opportunity to evaluate the viability of achieving competing ecological and economic silvicultural objectives following a tree mortality event.

Here, we use the extensive yellow-cedar mortality across the NPCTR to concurrently assess the potential impacts of small-scale, single-tree salvage logging of a foundation tree species on ecological integrity against the viability of salvaged yellow-cedar as an ongoing source of timber for cultural and economic purposes. We selected ecological integrity as our metric of ecological impact, because it is a guiding framework for monitoring and restoration on federal lands (Wurtzebach and Schultz, 2016), upon which this study was implemented. This benchmark for management or restoration success is defined by an ecosystem's ability to maintain post-disturbance compositional, structural, and functional characteristics comparable to its baseline or pre-disturbance state (Parrish et al., 2003), and significant changes in the abundance or success of a foundation tree species, such as yellow-cedar, would be a key indicator for detecting changes in ecosystem health and functioning (Ellison et al., 2005). We then assessed ecological integrity against economic viability by designing a salvage logging demonstration project on the Tongass National Forest in southeast Alaska, USA, and leveraging adjacent salvaged and unsalvaged, reference stands to: 1) investigate the effects of single-tree salvage harvest on ecological integrity, specifically the degree to which salvage alters the abundance of yellow-cedar and its potential to serve its foundation species role in post-disturbance stand trajectories, 2) track the volume and kinds of timber products generated by that salvage logging activity, and 3) analyze the costs associated with the harvest and manufacturing of these products, their market value, and the revenue generated. Overall, this study is intended to evaluate the viability of addressing multiple, competing objectives in the application of small-scale salvage logging, with an aim of assessing the tradeoffs made and potential outcomes on ecological and forest-dependent communities.

2. Methods

2.1. Experimental design

We focused our demonstration on two islands in southeast Alaska, USA, that serve as important regional sources of timber for economic and cultural purposes but that also have large areas of yellow-cedar decline: Kupreanof and Prince of Wales (Fig. 1). Kupreanof has one community and two small mills, while Prince of Wales (POW) has eleven communities and is home to several small logging and mill operations. In collaboration with Tongass National Forest foresters, we identified stands suitable for salvage logging, defined as those stands in which yellow-cedar decline occurred within 76.2 m of a road and with dead yellow-cedar trees at least 30.5 cm (12 in.) diameter at breast height (DBH, >1.37 m in height) as well as a range of snag age (i.e., decay) classes (Hennon et al., 1990b). Minimum distance and tree size marking criteria were established to limit salvage to stands easily accessible to small, local operators that also possessed trees large enough for traditional milling equipment. Marking occurred across the range of snag decay classes, including trees presumed dead within the last decade (snag class 1), the past 25 years (snag class 2), up to 52 years ago (snag class 3), and as long as 100 years ago (snag class 4) (Hennon et al., 1990b). Ultimately, 66 dead yellow-cedar trees were marked for single-tree salvage on Kupreanof, with an estimated volume of 20.74 m^3 (8.79

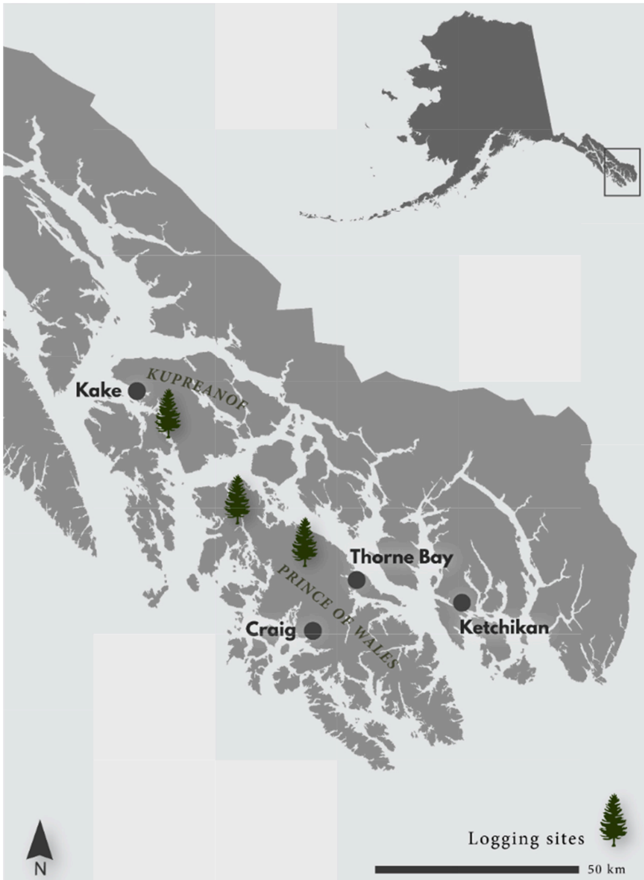

Fig. 1. Location of yellow-cedar salvage logging sites (trees) and mill operations (circles) in southeast Alaska, USA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

thousand board feet [MBF]) gross Scribner and 9.67 m^3 (4.10 MBF) net Scribner. On POW, the USFS marked 182 trees for single tree salvage and estimated that these contained 66.05 m^3 (27.99 MBF) gross Scribner volume and 31.15 m^3 (13.20 MBF) net Scribner volume. No green trees were marked for removal.

Despite mortality occurring over varying ecosystem types and conditions, steep slopes were avoided to reduce the probability of impacts to soils and watercourses (FRPA 2018). All trees were within USFS designated small sale or salvage areas on the islands, and trees were salvaged under a special use permit. Each roadside salvage stand had a nearby (within ~ 30 m) reference stand of comparable species composition and degree of yellow-cedar mortality that remained unsalvaged. Reference stands were established to quantify naturally-occurring changes so that changes in salvaged stands could be properly ascribed to salvage as opposed to other processes (e.g., a windstorm and associated wounding or ongoing yellow-cedar decline impacts).

2.2. Ecological impact assessment - plot surveys

To create a baseline dataset for post-salvage comparison, we established 20 m × 20 m (400 m^2) permanently-marked plots in each salvage and unsalvaged, reference stand in 2015 and 2016. We ultimately sampled eight salvaged plots and ten unsalvaged, reference plots (total n = 18). For the pre-salvage ecological survey, all trees > 10 cm DBH were measured for species, status (live or dead), snag class (if dead, based on Hennon et al., 1990b), diameter, and foliar health (0–100% green foliage; termed "canopy" health for trees, "foliar" health for saplings and seedlings). On a nested 10x10m (100 m^2) plot, we measured these same traits for all saplings (<10 cm DBH) and additionally sampled seedlings > 10 cm tall but less than breast height for species and height (cm). Wounding and broken tops were noted (presence/absence) for all individuals in the tree and sapling size classes, and all individuals falling within the 400 m^2 and nested 100 m^2 plots were tagged for long-term monitoring. Hemispherical photographs were taken at 1 m height at five points in each plot - at the plot center plus the four corners of the nested plot - to estimate canopy transmissivity of light. Trees were tagged with unique numerical metal tags to facilitate exact repeat measurements. All plots (salvaged and reference) were resurveyed after salvage in 2018 using identical methods to track survival, growth, and recruitment of yellow-cedar.

Tree, sapling, and seedling densities as well as basal area, prevalence of wounding, seedling growth, snag classes of marked trees, and canopy/foliar health were compared between the pre- and post-salvage datasets, as well as the reference plots (original measurement and second measurement), using unpaired t-tests for continuous data (e.g., density changes) and a two proportions z-test for proportion data (e.g., percent wounded, seedlings surviving). To estimate seedling mortality, we used tagged individuals. We assume that tags not found represent dead individuals given the limited number of untagged individuals present post-salvage, which would have been indicative of lost or removed tags. Differences in the magnitude of change observed on salvage plots in the various metrics above vs. differences observed on the unsalvaged, reference plots over the same time-period are attributed to the salvage logging activity. All analyses and data processing were conducted in R (R Core Team, 2020).

2.3. Economic viability assessment - logging and milling

To control for salvage impacts, one local logger was contracted for the roadside salvage operation on each respective island. Trees were salvaged by hand using a chainsaw and then loaded and transported using either a self-loading log truck or a rubber-tired shovel loader with choker and hydraulic drum and cable. Loggers were required to maintain records of the following to assess economic viability of salvage: log length and diameter obtained from each tree, number of person-hours needed for the logging operation as well as gallons of fuel and other consumables used. Loggers were additionally encouraged to assign a snag decay class to logs if confident in their assessments. Actual logging costs were calculated using these logger-provided data. Distinct from actual costs were contracted logging costs, which was the agreed upon amount of money the loggers would be reimbursed for their work regardless of actual logging costs. Transportation costs from logging site to mill, such as gallons of fuel used, mileage, and person-hours, were included in the contracted logging costs with the exception of the costs to barge some logs from POW to a mill an adjacent island. Contracted logging costs (as opposed to actual costs) were used in the mill net revenue calculations, as contractual costs were the payments made to loggers and include capital costs in the total.

Logs were delivered to four southeast Alaska mills (henceforth Mills W, X, Y, & Z) that expressed interest in participating in the project and that represent a suite of operation sizes and product capabilities. The number of logs delivered to each mill was based on mill capacity. Mills W and X are located on POW; Mill Y is located in Ketchikan on Revillagigedo Island; and Mill Z is located on Kupreanof. Mill operators were also required to collect detailed data, including the size and estimated volume of logs received, volume milled, and types and amounts of resulting products (e.g., dimensional lumber, beams, and firewood). Overrun, or the difference between log scaling values and lumber output, was used as an indicator of milling efficiency. The larger the overrun, the more efficient the milling operation was at extracting value-added products from the lumber they received. Mill operators also tracked the entire suite of explicit costs along the production process, including cost of labor and cost of operating machinery.

3. Results

3.1. Pre-salvage plot characteristics

Prior to salvage logging, we tagged a total of 2,105 trees, saplings, and seedlings across all plots. Both reference and salvaged plots were similar in pre-salvage ecological conditions. Neither total stem density (any tree > 1.37 m) (unpaired *t*-test; p = 0.35, df = 16) nor basal area were significantly different between reference and salvaged plots (p = 0.36, Table 1, Fig. 2A). The plots similarly did not differ in their yellow-cedar densities (live or dead; p = 0.74) or basal areas (p = 0.62). Percentage of total basal area of these stands in yellow-cedar ranged from 26% to 79%, with a mean of 58% (57% in reference plots; 58% in salvaged plots, p > 0.10). The remaining basal area and stems were hemlock (*Tsuga heterophylla* and *mertensiana*), western redcedar (*Thuja plicata*), Sitka spruce (*Picea sitchensis*), unknown dead stems, and a single green alder (*Alnus viridis*) sapling. Average yellow-cedar seedling density prior to salvage was the same between reference and salvaged plots at 0.08 seedlings/m^2 (SD = 0.05 and 0.1, respectively). Canopy light transmissivity (percent) averaged 35% in the salvage plots and 34% in the reference plots prior to salvage. Due to rain damage to the camera, three reference plots have no pre-salvage photos and so were not included in the light analysis. Pre-existing tree wounding levels were not significantly different; 8% across reference plots and 5% across to-be-salvaged plots.

3.2. Logging and milling

Of the 66 marked trees on Kupreanof, 48 were salvaged; the remainder were culled or left standing due to defect or because, if felled, they would be beyond the ability of the logger to yard with the available equipment. All logs were transported by the logger via truck to Mill Z. On POW, 195 yellow-cedar were ultimately logged within the cruised area, including eleven trees beyond those originally marked that were cut during salvage operations for safety purposes or to allow for the salvaging of marked trees. Eleven of the cut yellow-cedar were culled and left on the ground due to rot or other deficiencies. On average, salvaged logs on both islands fell into snag decay class 2 (1.95 mean; 1.3 SD, data from ecological assessment). Only the logger on Kupreanof felt confident in their assessment of snag decay class; here, logs selected as sawlogs were classified as snag decay class 3 (3.03 mean; 0.61 SD), while those selected specifically for firewood came from snag classes 3 and 4 (3.94 mean; 0.42 SD, p < 0.01). Logs were delivered to two mills on POW (Mills W and X) via truck and to one mill in Ketchikan (Mill Y) via commercial barge (Table 2).

The four mills each milled between 9.01 m^3 (3.82 MBF) and 54.16 m^3 (22.96 MBF) of wood (including dimensional lumber, slabwood, and firewood) with returns ranging from a net negative return of \$724/m^3 (\$307/MBF) to a net positive return of \$3510/m^3 (\$1488/MBF; Table 3). All mills produced dimensional lumber, the majority of which was 1x and 2x boards, with some non-standard and larger beams (4x, 6x) as well as high quality slabs for use in traditional carving. One mill made a picnic table, another milled some live-edge slabs for countertops and tables, but, overall, very little value-added or specialty products were made. There was little variation among mills in finished wood products, and no mills marketed their products as sustainable (e.g., Forest Stewardship Council certified) or specialty items. Wood quality (as estimated by calculated overrun, Table 3) varied substantially. Firewood was made from lower quality or smaller logs (data not shown), from portions of logs that were deemed unsuitable for lumber (Mill W), or from milled wood that was later rejected for sale (Mill Y).

Table 1
Pre-salvage mean stem densities and basal areas (and standard deviation) for unsalvaged, reference and salvage logged plots. All trees, dead or alive, >1.37 tall included (reference n = 10; salvage n = 8).

	Stem Density (per ha)		Basal Area (m^2 per ha)	
	All species	Yellow-cedar	All species	Yellow-cedar
Reference	3455 (2261)	1015 (907)	84.7 (26.4)	46.0 (15.5)
Salvage logged	4594 (2796)	1172 (1159)	74.0 (20.8)	42.6 (12.2)

3.3. Post-salvage change

We relocated 98% of tagged trees in our post-salvage survey. Post-salvage, mean total basal area was reduced significantly to 56.3 m^2/ha (SD = 17.7) on salvaged plots, a 25% mean reduction. This decline was driven by the salvage of dead yellow-cedar, dropping mean yellow-cedar basal area from 42.7 m^2/ha (SD = 12.3) to 24.6 m^2/ha (SD = 12.9, Fig. 2B). Residual yellow-cedar trees had a significant increase in wounding from salvage operations, and some were crushed by machinery or falling trees. The number of wounded trees on reference plots increased slightly from 8% to 9.3%, whereas the number of wounded or dead trees on the salvaged plots increased significantly from 5% to 18% (p < 0.001, CI 95%: 16–22%). If including salvage-cut trees in this estimate, the total number of wounded or dead trees was, on average, 25% on salvaged plots. This damage was accompanied by a greater decline in canopy health on salvaged plots at 16% vs. an 8% decline in reference plots over the same period. Plot level variability was high, however, and the difference was not significant (p = 0.32). Foliar health declined significantly (p < 0.001) for seedlings and saplings on salvaged plots, from 76% to 59% green foliage (95% CI = 12 – 22% decline). This health decline was not observed in saplings on the reference plots (59% pre vs. 61% post).

Canopy light transmissivity increased on salvaged plots by an average of 16% (SD 11%) compared to an average of 3% (SD 12%) on reference plots. The difference between the two groups was large but variable. A single reference site had a dramatic increase in light compared to the other four, which were essentially unchanged (-4, −3, −2, +2, vs. + 25%). As expected, canopy light transmissivity on the eight salvaged sites all increased, with three sites changing marginally (2, 2, and 6%) and the other five changing sharply (14, 23, 24, 27, and 27%).

In general, tagged seedlings of all species persisted through salvage (Fig. 3), with average survival of 86% (SD = 15%) on reference sites and 78% (SD = 17%) on salvaged sites. The proportion of seedlings surviving was not significant by treatment nor by species (p > 0.10, salvaged vs. reference) with the exception of Sitka spruce, in which survival averaged 84% (SD = 20%) on reference sites and 65% (SD = 20%) on salvaged sites (p < 0.001). Western redcedar survival was also lower on salvaged sites at 61% versus 83% on reference sites, but this species only was present on two salvaged sites and one reference site, thus limiting species-level analysis of salvage impacts. Hemlock species also persisted in both reference and salvaged sites; on average, 75% (SD = 12%) of western hemlock and 91% (SD = 12%) of mountain hemlock survived salvage, while 86% (SD = 9%) and 92% (SD = 10%) remained on reference sites (p > 0.10). Yellow-cedar seedlings, specifically, remained in high abundance with a mean of 84% (SD = 19%) and 83% (SD = 18%) surviving on reference and salvaged sites, respectively (p > 0.10), and indicating that even salvaged sites are likely to support a yellow-cedar forest type as these stands develop over time. Although there were significant differences in mean yellow-cedar seedling height growth at the plot level (6.1 vs. 0.54 cm for salvaged and reference plots, respectively), the number of seedlings occurring per plot ranged from 0 to 84, and there was no difference in height increases when weighted by the number of seedlings per plot (4.52 cm on salvaged plots (n = 101) and 4.61 cm on reference plots (n = 154)).

4. Discussion

Climate-induced disturbances and mortality events in forests have prompted increases in the use of salvage logging across many landscape

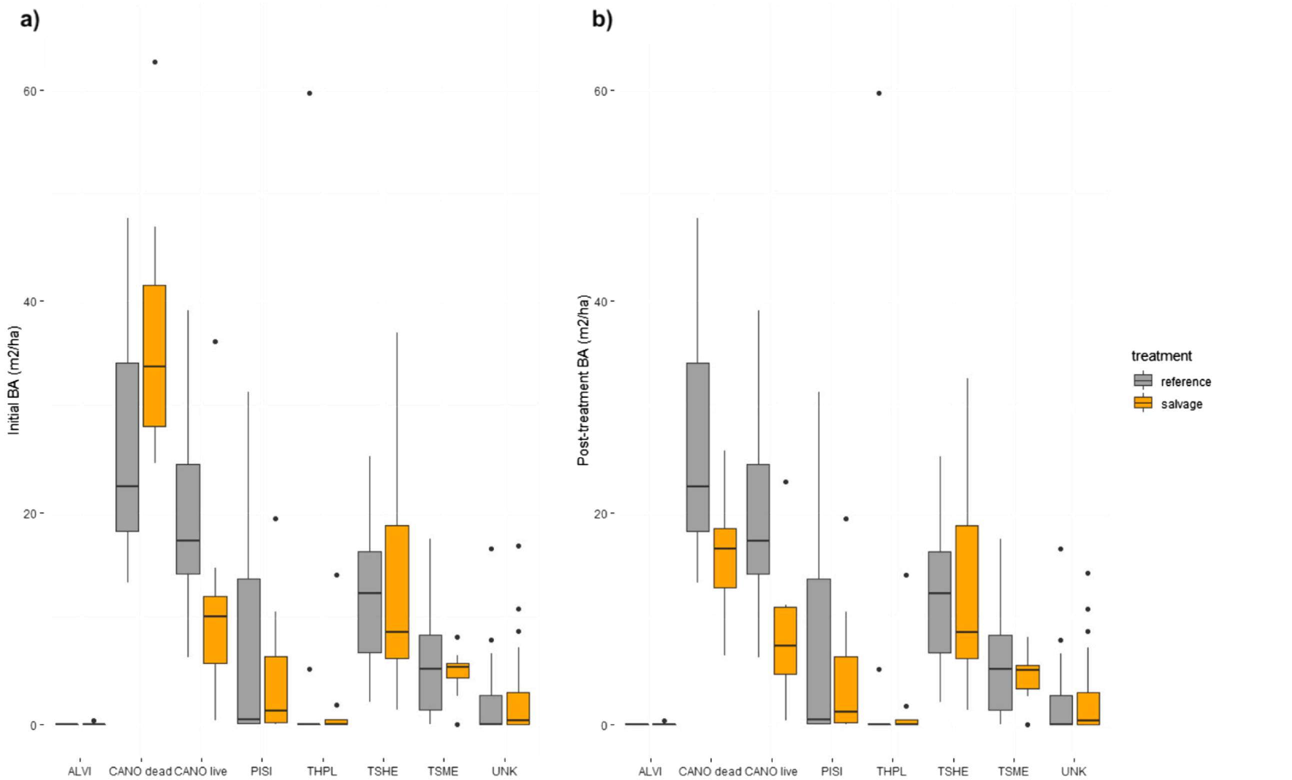

Fig. 2. Basal area (m^2/ha) by species and treatment. Total basal area (live and dead) is presented for each species with the exception of yellow-cedar (CANO = *Callitropsis nootkatensis*), which is separated into live vs. dead to illustrate the impact of the salvage operation on dead yellow-cedar canopy abundance. a) Pre-harvest basal areas were equivalent by species. b) Post treatment, salvage plots had a substantial decline in CANO basal area driven by salvage of dead CANO, but little to no change in the other species. Species acronyms are as follows - ALVI: *Alnus viridis*; PISI: *Picea sitchensis*; THPL: *Thuja plicata*; TSHE: *Tsuga heterophylla*; TSME: *Tsgua mertensiana*; UNK: Unknown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Number of trees logged, mean lengths and small-end diameters of logs, and costs for logging per m^3 (English units in parentheses).

Location	# trees salvaged	Mean log length m (ft)	Length range m (ft)	Mean log dia cm(in)	Diameter range cm (in)	Logging cost/m^3 [*]
Kupreanof	48	5.49 (18)	2.44–12.19 (8–40)	33 (13)	15–86 (6–34)	$375[ǂ]; *$745* ($159[ǂ]; *$316*)
POW	195	8.84 (29)	3.05–12.19 (10–40)	28 (11)	15–86 (6 – 34)	$825; *$944* ($350; *$400*)

[*] Costs/m^3 are actual (time, fuel, materials, and capital costs such as depreciation and equipment maintenance) with contracted costs in italics (costs/MBF [thousand board feet] in parentheses).
[ǂ] Actual costs did not include equipment (capital).

scales and forest types. Despite this, however, little is known about the tradeoffs in ecological and economic outcomes. Here, we find that small-scale, single-tree salvage logging of a foundation tree species has limited impact on yellow-cedar abundance and forest successional trajectories, and thus at least short-term ecosystem functioning, while providing small to modest economic returns. This application of salvage has the potential to accomplish multiple-use objectives by providing a minor alternate log and revenue stream for forest-dependent communities and do so with relatively little short-term impact on ecological integrity. Even in this regional assessment of economic versus ecological tradeoffs, however, the outcomes of small-scale, single-tree salvage are highly individualized, highlighting the continued need for localized evaluations of potential ecological impacts against economic conditions when considering salvage operations. Our findings indicate that salvage at this scale and intensity maintains ecological integrity but with limited economic viability. This management tool is thus best suited for land managers addressing multiple resource objectives in communities dependent on small, continuous streams of forest products.

4.1. *Ecological impacts of salvage logging*

Salvage logging, like any forest management activity, will leave an ecological impact, where the magnitude of its effect on ecological functioning varies considerably based on the type and intensity of salvage, the proportion of the landscape salvaged, and the time since salvage occurred (Bottero et al., 2013; Royo et al., 2016; Thorn et al., 2020). Legacy retention of snags or live trees can mitigate the deleterious effects of salvage at the stand level, while creation of a spatial mosaic of treated and untreated areas maintains heterogeneity at the landscape scale (Morimoto et al., 2011; Waldron et al., 2014). These management strategies can minimize the homogenizing outcome of high-intensity salvage, which can decrease species diversity and abundances in the regenerating community (Kurulok and Macdonald, 2007; Purdon et al., 2004). Retaining half of the disturbed forest when salvaging may maintain nearly three quarters of its unique taxonomic and species richness, and increasing retention to 75% can facilitate persistence of up to 90% of the pre-disturbance richness (Thorn et al., 2020). Species richness is also strongly linked to time since disturbance,

Table 3
Volume of timber processed at each mill (in m^3, with MBF in parentheses), and associated costs and revenue.

Mill	W	X	Y	Z
Estimated Gross Volume	22.17 (9.40)	7.97 (3.38)	41.97 (16.53)	38.12 (16.16)
Dimensional Volume (1X, 2X)	4.18 (1.77)	4.93 (2.09)	17.48 (7.41)	13.68 (5.80)
Volume Other Products	3.14 (1.33)	3.85 (1.63)	24.82 (10.52)	1.39 (0.59)
Total Volume Sawn	7.76 (3.09)	8.78 (3.72)	42.32 (17.94)	15.07 (6.39)
Firewood	12.46 (5.28)	0.26 (0.10)	11.79 (5.00)	13.54 (5.74)
Total Manufactured Volume	19.74 (8.37)	9.01 (3.82)	54.12 (22.94)	28.61 (12.13)
Overrun[‡]	0.75	1.14	1.56	0.61
Gross Revenue	$6,457	$5,377	$55,806	$13,791
Contracted Logging Cost[*]	$3,848	$1,537	$6,940	$5,104
Contracted Logging Cost/m^3	$944 ($400)	$944 ($400)	$944 ($400)	$745 ($316)
Milling Cost	$2,803	$1,396	$6,751	$5,628
Milling Cost/m^3	$2137 ($906)	$885 ($375)	$887 ($376)	$2076 ($880)
Firewood Processing Cost	$2,379	$0	$375	$3,502
Barge Transportation Cost[¥]	$0	$0	$7,610	$0
Total Costs	$9,029	$2,933	$21,676	$14,234
Net Revenue	-$2,572	$2,443	$34,131	-$443
Net Revenue/m^3	-$724 (-$307)	$1507 ($639)	$3510 ($1,488)	-$87 (-$37)

[‡] Overrun is equal to the volume sawn divided by the estimated gross volume minus the firewood volume. It is a measure of log quality and reflects the amount of product that is milled in excess of the estimated gross volume (based on the small end diameter of a log).

[*] Contracted logging costs were the agreed upon amounts of money the loggers would be reimbursed by us for their work, including transportation from logging site to mill. This differs from the actual logging costs that include labor, equipment ownership costs, and consumables, (see Table 2).

[¥] Barge transportation costs are from POW to Ketchikan.

and the negative effects of salvage can be short-lived, declining within the first decade (Knapp and Ritchie, 2016; Royo et al., 2016). In the small-scale, single-tree salvage assessed here, an average of 74% of the total basal area was retained, and the ecological impacts on this yellow-cedar community, though driving some significant differences between salvaged and reference areas, appear to be relatively minor immediately post-salvage and thus likely short-lived.

Persistence of ecological integrity through salvage operations can be attributed to our experimental single-tree salvage of yellow-cedar – a low-intensity practice possible given the nature of this climate-induced, single-species decline. Marking and salvage of stands targeted yellow-cedar from two angles: 1) retention of yellow-cedar as a foundation of ecosystem functioning and, 2) removal of valued yellow-cedar to support the cultural and timber needs of local communities. Although yellow-cedar salvage was the driver of basal area reductions and changes in overstory community composition, yellow-cedar also remained a co-dominant component of the overstory as well as the understory regenerating community following salvage (Figs. 2 & 3). This is counter to some findings in more severely disturbed ecosystems and at other scales in which salvage is documented to reduce tree seedling recruitment and abundances, leading to declines in forest community species richness (Donato et al., 2006; Greene et al., 2006). Such deleterious outcomes can be attributed to greater cumulative severity from compounding natural and anthropogenic disturbances, which increases the probability of an ecosystem reaching its threshold for long-term compositional change; lower severity compounding disturbances can, on the other hand, have limited detrimental effects on the regenerating community (Peterson and Leach, 2008). Here, yellow-cedar seedlings and saplings persisted in relatively high abundances despite salvage (Fig. 3), results in line with research on other low- and moderate-intensity salvage operations (Peterson and Leach, 2008; Royo et al., 2016). Our findings indicate that targeted, single-tree salvage of yellow-cedar allows foresters to maintain the relative abundance of this foundation tree species on the landscape to facilitate subsequent ecological functioning and post-disturbance stand dynamics.

Despite the limited impacts to forest community composition, salvage of this foundation tree species had the potential to affect soils and the understory community, two ecosystem metrics not quantified here but commonly assessed in salvage studies (e.g., Fornwalt et al., 2018; García-Orenes et al., 2017; Peterson and Dodson, 2016). In particular, salvage may lead to persistent changes to the forest floor that shift recovery trajectories by reducing infiltration and altering exposure of the establishment environment (Fischer and Fischer, 2012; Kishchuk et al., 2015; Morimoto et al., 2011). Salvage is also documented to impact biodiversity through the removal of critical habitat trees (Lindenmayer and Ough, 2006). However, the low-intensity operations performed in this study contrast the high-intensity salvage occurring following many wildfire and windthrow events and from which the majority of salvage logging research is based. Here, trees were felled by hand towards, or on, a pre-existing road, and yarding distances were extremely short (often less than the < 76.2 m roadside limiting distance). No heavy machinery went on the plots, so damage was limited to incidental cutting for access/safety or skidding trees to the road, leaving little opportunity for alteration of soils or the understory community. Additionally, not all marked trees were suitable for salvage once further examined and thus left onsite as snags or coarse wood due to the level of snag decay (classes 3–5, Hennon et al., 1990b). Furthermore, this single-tree salvage was not a wholesale removal of all dead yellow-cedar (Fig. 2), and the snags remaining onsite are likely to provide an ongoing source of critical wildlife habitat despite the removal of some dead yellow-cedar. Higher intensity and larger-scale salvage practices leave a more significant imprint on the landscape in which soils are scarified and compacted by the use of heavy equipment and canopy removed (Brais and Camiré, 1998; Harvey and Brais, 2002). Our low-intensity salvage retained an abundance of structural and biological legacies with minimal soil disturbance – key factors in mitigating negative outcomes of salvage and maintaining ecological integrity.

Finally, although we quantified limited ecological impacts following salvage, the trajectories of these stands remain unknown due to past and ongoing climate-induced mortality of yellow-cedar. Our post-salvage assessment identified substantial wounding to residual trees as well as a decline in canopy health of saplings after the salvage operation concluded (consistent with previous work; e.g., Sidle and Laurent, 1986), and these wounded trees may succumb due to a variety of diseases or compounding disturbances (Vasiliauskas, 2001). Declines in canopy health following salvage or harvest operations are difficult to explain and may be due to the rapid increase in light intensity or may simply be an ephemeral phenomenon. In this study system, the long-term impacts of wounding and the implications of the observed decline in foliar health are unknown at this point but likely minimal. Overall, the long-term ecological impacts of the compound disturbance event of yellow-cedar mortality followed by salvage logging appear to be relatively minor for this foundation tree species. It is, however, worth emphasizing that, despite its ongoing persistence following salvage, yellow-cedar decline is still unfolding across this landscape (Buma, 2018) and driving forest successional changes via shifts in dominance to other co-occurring tree species (Bisbing et al., 2019; Oakes et al., 2014). Continued loss of yellow-cedar will further reduce available seed and spouting sources and may be the ultimate driver of changes to this foundation species and its ecosystem regardless of management action. Few salvage studies are long-term or revisited after the initial post-salvage sampling campaign (Thorn et al., 2020, 2018), but tagged trees will allow us to track stand trajectories and ecological integrity long term.

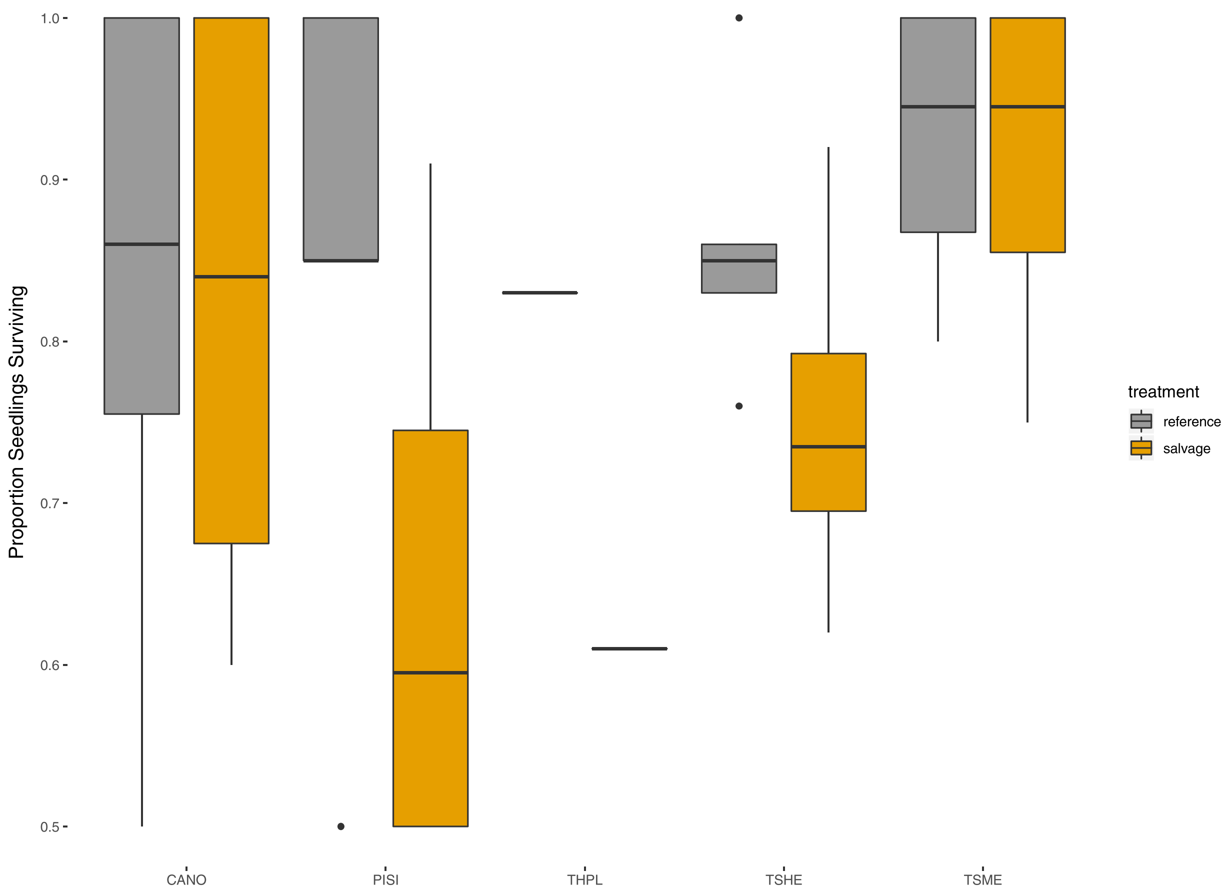

Fig. 3. Proportion of seedlings found in post-salvage resurvey by species and treatment. Tagged seedlings not found in the resurvey were presumed dead. Species acronyms are as follows - CANO = *Callitropsis nootkatensis*; PISI: *Picea sitchensis*; THPL: *Thuja plicata*; TSHE: *Tsuga heterophylla*; TSME: *Tsgua mertensiana*.

4.2. Economic impacts of salvage logging

Very few studies focus on the economics of small, single-tree selection logging and milling operations, although there are examples from the tropics (Uhl et al., 1991), those investigating the relative costs and benefits of converting from even-aged to uneven-aged forestry (Price, 2003), and those comparing methods of timber cutting and extraction (Becker et al., 2006). Economic outcomes of the single-tree salvage operations in this study varied widely, but net revenue was generally limited and highly individualized. In the woods, fewer trees were viable for salvage than anticipated, with loggers predominantly cutting snags from decay classes 1 and 2 (i.e., those dying within the last 25 years, Hennon et al., 1990b; Kelsey et al., 2005), while, on the milling side, trees in higher decay classes (classes 3 & 4, dead up to 50–100 years) were processed for firewood. Although operators were optimistic about using higher snag decay classes for sawn wood, these results are not surprising given the changes in wood chemistry documented for snags in decay classes three and beyond (Kelsey et al., 2005), and a 25-year window for salvage is an exceedingly long recovery time as compared to average log viability in other species and systems (Holmes, 1991; Prestemon et al., 2006). The most striking result from our economic assessment was the heterogeneity in net revenue among mill operators (Table 3), which was driven by differential utilization of salvaged logs. While the highest valued use of the wood was to sell it as whole logs or dimensional lumber, some mill operators chose to split logs for firewood. This led to net negative returns for the two mills that produced a large amount of firewood from their logs (63% and 47% of manufactured volume for Mills W and Z, respectively). Another factor contributing to the large apparent differences in net revenue was the value assigned to finished products. All mills except for Mill Y assessed or sold dimensional products for approximately $3.54/m^3 ($1.50/BF). Mill Y assessed value at $7.07/m^3 ($3/BF), though this value may be inflated because these products were used internally for co-owned businesses instead of sold on the open market. If the value assigned to Mill Y's products were brought in line with the other mills at $3.54/m^3, their net revenue would equal $743/m^3 ($315/BF). It is possible that dimensional yellow-cedar products from Mill Y garner higher local prices than products sold on POW or Kupreanof, because Ketchikan is a larger market. Quality of wood, as well as localized market opportunities, were clearly important to revenue.

Net revenue from salvaged logs varied widely based on costs associated with logging, milling, transportation costs, and method of firewood processing. Milling costs varied substantially among mills, from a low of $885/m^3 ($375/MBF; Mill X) to over $2120/m^3 ($900/MBF; Mill W). Whether this range is attributable to poor cost tracking or real differences in mill efficiencies is impossible to say given uneven accounting practices of collaborating small business partners. Transportation costs were highest for Mill Y, as these logs were shipped from POW to Ketchikan via barge. Costs for producing firewood also varied widely, and Mill Y used only low-quality milled wood as firewood, rather than bucking and splitting logs specifically for that purpose, increasing overall costs. Overall revenue of the individual mills with this fine-grained salvage opportunity came down to balancing local or niche market products and costs, both of which were highly specific to the milling community.

Many of the businesses participating in this project lacked prior experience in recording costs and revenues, so despite our best attempts at data collection training and oversight, data quality issues may exist.

Two potential paths through which bias may have been introduced include incomplete or questionable data. Inasmuch as the data is incomplete (e.g., under-reported fuel costs or person hours), costs will be biased downward. Questionable data, on the other hand, would have an indeterminate effect on magnitudes and directions of bias. For example, there were inconsistencies in how individual logs were tracked through the milling process. Some operators had problems determining the volume delivered to the mill, which could lead to over- or under-reporting. Despite these caveats, we believe the data provide a reasonable picture of small mill costs and revenues when working with salvaged yellow-cedar because of the heterogeneous cross-section of representative small-scale operators surveyed. Overall, the economic benefits of single-tree salvage are likely to be limited and affected by quality of wood, types of end products, transportation costs, and ready access to larger markets. However, small-scale salvage may also be one means by which to maintain a source of revenue and yellow-cedar logs to consistently meet market demand. This cost-benefit tradeoff must be made by each individual producer.

4.3. Opportunities and challenges

Forest management decisions concerning salvage logging must consider both ecological and economic consequences and opportunities in order to match actions to forest management objectives. This study examined the ecological integrity of small-scale salvage logging as well as the economic feasibility of producing value-added products from dead trees of a foundation species. Overall, the initial ecological impact of single-tree salvage was minimal, but long-term trajectories following yellow-cedar decline and compounding salvage harvest are still unknown. In terms of economic impacts, this study suggests that salvage logging may present an opportunity to maintain a small supply of valuable timber in the face of declining availability of live trees of marketable size, despite the variation among mill operations in costs and returns. Single-tree salvage logging of this climate-impacted species may additionally reduce conflict around regional old-growth logging while generating positive revenues and holding ecological consequences to a minimum (Prestemon et al., 2013; this study).

Salvage logging may also provide other economic benefits to local small businesses. Although not used to their advantage in this study, single-tree salvage logging has potential as a sustainable source of lumber for niche timber markets (similar to “blue stained” mountain pine beetle killed wood; Lum et al., 2006). Many mills have gone out of business in the NPCTR and across the western US over the past few decades (Marcille et al., 2020; Parrent and Grewe 2018), and there is high turnover in the industry. For small mills, the ability to pivot to opportunistic revenue streams afforded by disturbances may be a viable means to persist, and state or regional economic development organizations could reasonably assist operators and small mills with the marketing of such products. While single-tree salvage logging may not sustain the full gamut of traditional forest industry jobs, increasing supply and creating niche markets for dead timber sources may help small mill operators and loggers to survive with relatively low impact to ecological systems and traditional cultural practices.

Finally, yellow-cedar is highly-valued by Indigenous peoples of the region and local communities for traditional building and artistic reasons (Hennon et al. 2016), and the decline of yellow-cedar over the last few decades has caused great concern (Oakes et al., 2015). Providing an ongoing source of yellow-cedar for cultural carving and building may depend on a salvage market if decline continues. The wood properties and decay resistance of yellow-cedar may allow for ongoing harvest to meet cultural wood demands. Our primary aim was to determine the ecological and economic impacts of small-scale salvage logging of this unique, decay resistant and climate-threatened foundation species. It appears that both economic and ecological impacts are low, at least in the short term, and highly location dependent. Targeted harvest, carefully managed and with specific markets in mind, may be sustainable with relatively little ecological impact beyond wood removal.

Author statement

A.L.B. & B.J.B. conceived of the idea and secured funding. S.M.B., A.L.B., & B.J.B. developed methodologies and collected data. SMB led writing with writing, editing, and revisions by A.L.B., B.J.B., & B.V.N. BJB led statistical analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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