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Productivity and Cost of Retention Harvesting Operation in Conifer Plantations

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Abstract: Retention forestry is a harvesting system that intentionally retains important forest structures at harvest time. We examined the effect of dispersed retention on the productivity and cost of harvesting operations in a large-scale field experiment in conifer plantations in Hokkaido, Japan. For dispersed retention, we retained broad-leaved trees in three levels (10, 50, or 100 trees/ha). We used daily operator reports and investigated time consumption (h/m^3) of felling and pre-hauling operations and the total cost to roadside. Compared with clearcutting, mean felling time was 7% and 17% longer, and mean pre-hauling time was 20% and 19% longer in 50 and 100 retained trees/ha, respectively. The other operations were not affected by tree retention because they were conducted at pre-existed strip roads or landings where no trees were retained. Increased time consumption caused an increased cost of felling and pre-hauling. Compared with clearcutting, the combined cost of felling and pre-hauling was 14% and 18% higher in 50 and 100 retained trees/ha, respectively. However, the total cost to roadside increased only by 3% compared with clearcutting because these two operations in total occupied 19% of the overall cost, and the cost of the other operations was not affected by tree retention. This suggests that the impact of tree retention on the total cost was small and that the harvesting system used in the present study can reduce cost increment due to tree retention unless trees are not retained on strip roads.

Keywords: daily operator report; dispersed retention; felling; green tree retention; Japan; logging; retention forestry; revenue; Sakhalin fir (*Abies sachalinensis*); time analysis

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1. Introduction

Because forests provide us with various ecological goods and services, it is important to find management approaches that will sustain their economic and ecological values [1–3]. Retention forestry is a harvesting system that intentionally retains important forest structures and organisms at harvest time [4]. One of the goals of retention forestry is to balance timber production and biodiversity conservation [5]. In contrast to traditional harvesting systems, retention forestry selects trees (including snags and logs) with more emphasis on what is retained over the long term than what is removed [6]. Retention forestry is highly adaptable and has great variations in its application, including the pattern and amount of retention. Practices of retention forestry include retaining single trees (dispersed retention) and retaining small intact forest patches (aggregated retention).

Retention forestry was developed in North America in the 1980s to accommodate the non-timber values of managed forests [6]. Since then, it has expanded globally and is practiced on more than 150 million ha of boreal and temperate forests as an alternative to clearcut harvesting [4]. Many studies have assessed the biodiversity response to retention forestry [7]. These studies show that retention forestry is a promising way to maintain forest biodiversity in managed forests (meta-analyzed by [8–10]), although only a few studies have been conducted in plantations and/or in Asia [11].

Despite the number of studies that have found positive effects on biodiversity, published studies examining the economic impacts of retention forestry remain scarce. Economic impacts associated with retention forestry take three forms [6]; compared with clearcutting, retention forestry will (1) increase the cost of harvesting operations, (2) reduce harvesting timber production, and (3) reduce the survival and growth of regenerated trees due to the effects of the retained overstory. For the harvesting costs, the impacts of retention forestry may depend on the amount and pattern of retention [12]. Harvesting costs for dispersed retention are likely to be greater than for clearcutting because machines have to avoid retained trees in the harvested area [6], which leads to greater restriction of machine and boom movements [13]. Felling and forwarding costs will also increase due to the reductions in the number of harvesting trees per harvested area [14]. However, harvesting costs for aggregated retention will not be greater than for clearcutting, although the area for retention patches is lost for timber production [6]. Three published studies examined harvesting costs of dispersed retention [14–16]. These studies showed that felling and forwarding (or skidding) productivity decreased with the increasing level of dispersed retention and that harvesting cost to roadside was 2%–25% greater in 5%–50% retention compared with clearcutting.

Retention forestry is being widely implemented in boreal and temperate forests in North America and northern Europe as an alternative to clearcutting [4]. However, retention forestry has not prevailed in Asia, including Japan, and it has scarcely been applied in plantation forests. The ongoing global expansion of plantations increases the need to develop silvicultural practices that conserve biodiversity in plantations [17]. In this context, we have undertaken a large-scale field experiment called the Retention Experiment for Plantation Forestry in Sorachi, Hokkaido (REFRESH as an abbreviation), to examine the efficacy of retention forestry in native Sakhalin fir (*Abies Sachalinensis* (F. Schmidt) Mast.) plantations in central Hokkaido, northern Japan [11]. The aim of the experiment was to establish a forest management system that balances the ecological, social, and economic values of conifer plantations. To meet this aim, we established study sites harvested with dispersed (three levels) and aggregated retention. For dispersed retention, we retained broad-leaved trees naturally regenerated in conifer plantations to restore structures and elements of original natural forests in the region.

The present study aimed to reveal the effect of dispersed retention on harvesting operations in the REFRESH project. Daily operator reports were used to investigate how dispersed retention with different retention levels affected felling and pre-hauling productivity by comparing the productivity of dispersed retention with that of clearcutting. The impact of dispersed retention on the harvesting cost to roadside was also examined.

2. Materials and Methods

2.1. Study Site and Experimental Design

This study was conducted at the REFRESH research site in Hokkaido prefectural forests in the Irumukeppu highland area (ca. 6 km × 12 km, 43°34′37′′–39′26′′ N, 142°05′27′′–09′33′′ E). Mt. Irumukeppu (864 m a.s.l.) is in the northern part of the area, and gentle slopes run eastward and southward from the mountaintop. Plantations cover 59% of this area, and 79% of the plantations consist of Sakhalin firs [11].

We used 15 study sites (5–9 ha) assigned to five harvest treatments (clearcutting, three levels of dispersed retention, and aggregated retention) in mature Sakhalin fir plantations that reached harvest age (51–61 years old at the year of harvesting). Thus, the experimental design included three replicates (sets 1–3) for each treatment. For dispersed retention, broad-leaved trees that reached the canopy layer were retained in three levels: small, medium, and large amounts of retention corresponding to 10, 50, and 100 retained trees/ha, respectively. These treatments resulted in proportions of the retained volume of 0.9%–1.7%, 4.1%–11.9%, and 16.7%–26.5% in small, medium, and large amounts of retention, respectively [18]. These retained trees mainly comprised birch (*Betula platyphylla* Sukaczev var. *japonica* (Miq.) H. Hara, *B. ermanni* Cham., and *B. maximowicziana* Regel), linden (*Tilia japonica* (Miq.) Simonk.), and Mongolian oak (*Quercus crispula* Blume). For aggregated retention, we established a 0.36 ha (60 m $\times$ 60 m) undisturbed forest patch of Sakhalin fir at the center of each clearcut site. Each study site was on a gentle or moderate slope with slope inclination <20° for most of the area.

All trees $\geq$ 5 cm in diameter at breast height in the study sites were counted, and their diameter at breast height was measured one year before harvest [18]. We also selected the broad-leaved trees to retain for dispersed retention. We tried to select trees so that retained trees were evenly distributed within the study sites. The retained trees were marked using flagging tape, and the operators harvested or retained trees on the basis of this tape. Study sites of sets 1, 2, and 3 were harvested from May to September (i.e., in the snow-free season) in 2014, 2015, and 2016, respectively. The harvested areas were prepared for tree planting until winter. Sakhalin fir seedlings were planted the next spring with 2400–2700 trees/ha in rows at 3 m intervals, and weeding was conducted during the summer. Areas 1.5–2 m wide along the planting rows were weeded. Weeding was conducted once or twice annually, depending on the growth of herbs and shrubs.

2.2. Harvesting Productivity and Cost

Generally, the operation system used in this experiment was as follows (Table 1): trees were felled using HUSQVARNA 560XPG chainsaws (felling) (Husqvarna, Newton Aycliffe, UK) and transported to strip roads, which are tracks in the forests for machines to move, using an IWAFUJI GS90LI grapple loader (pre-hauling) (IWAFUJI, Chiyoda, Japan). Strip roads run at approximately 50 m intervals. Then, branches were removed from the trees, and stems were cut to a predetermined length using a KESLA 25SH harvester (processing) (KESLA, Joensuu, Finland). The cut stems (logs) were loaded onto an IWAFUJI U6B rubber-crawler forwarder with an IWAFUJI GS90LI grapple loader (loading), transported through strip roads to the landings (forwarding), and unloaded and piled at the landings with an IWAFUJI GS90LI grapple loader (landing operation).

Table 1. Machine technical and economic parameters for cost caluculation. Data are from Japan Forest Technology Association [19].

	Chainsaw	**Grapple Loader**	**Harvester**	**Forwarder**
Parameter	HUSQVARNA 560XPG	IWAFUJI GS90LI	KESLA 25SH	IWAFUJI U6B
Purchase price (JPY)	202,000	18,100,000	25,000,000	12,000,000
Machine weight (ton)		12.8	12.7	5.6
Engine power (kW)		63	63	81
Expected life (hour)	3330	9480	4968	4413
Expected life (year)	3.7	7.9	4.6	4.9
Annual operating hours (hour/year)	900	1200	1080	780
Depreciation (JPY/hour)	54.6	1718.4	4529.0	2447.3
Repair and maintenance (JPY/hour)	111.6	496.4	2634.8	1033.3
Fuel consumption (L/hour)	1.0	8.2	9.3	8.3
Fuel and oil consumption cost (JPY/hour)	259.4	1064.0	1401.0	1054.0

We surveyed harvesting productivity using daily reports of operations from two logging contractors that accomplished harvesting. In the reports, the number of persons engaged in each operation on each day (daily labor inputs) was recorded for each site. We totaled daily labor inputs for each operation, multiplied by daily working hours (6 or 7 h shifts depending on the contractor), and divided by the harvested volume to calculate the time consumption (h/m^3) at each site.

For time analyses, we analyzed felling and pre-hauling operations because the other operations were conducted at strip roads or landings; thus were not affected by tree retention. In the study sites, tree retention did not affect the strip road layout because we used pre-existed strip roads and did not retain trees on the strip roads. We assumed that retention patches (0.36 ha) in aggregated retention did not affect harvesting productivity, similarly to [16], and we lumped this treatment into the same category as clearcutting. Therefore, clearcutting (including aggregated retention) was compared with three levels of dispersed retention.

In the statistical analyses, we used analysis of covariance (ANCOVA) with time consumption per harvested volume (min/m^3) as a response variable (dependent variable) and harvest treatment (clearcutting, and three levels of dispersed retention), average stem volume of harvested fir and contractor as explanatory variables (independent variables). Stem volume was used as a covariate because harvesting productivity is most affected by tree size [20–23]. We also used contractors as an explanatory variable because time consumptions for felling and pre-hauling are known to differ between contractors [16,24]. The two contractors (A and B in Table 2) were treated as a categorical variable, and their difference was calculated. Response variables were Box–Cox-transformed prior to the analyses to alleviate heteroscedasticity. Differences among the harvest treatments were indicated with least squares means, which are means adjusted for the other explanatory variables. All statistical analyses were performed using R (Version 4.1.1, Vienna, Austria) [25].

Table 2. Stand characteristics of the study site. Data are from Akashi et al. [18].

Harvest Treatment *	Area (ha)	Pre-Harvest Stem Density (stem/ha)	Pre-Harvest Stem Volume (m^3/ha)	Post-Harvest Stem Density (stem/ha)	Post-Harvest Stem Volume (m^3/ha)	Contractor	Mean Stem Volume of Harvested Fir (m^3/stem)
Clearcut	6.89	379.5	351.2	0.00	0.00	A	0.98
Clearcut	7.87	548.4	329.7	0.00	0.00	A	0.65
Clearcut	6.17	669.9	420.8	0.00	0.00	A	0.67
Clearcut	6.42	705.5	391.8	0.00	0.00	A	0.63
Clearcut	7.87	622.1	442.7	0.00	0.00	A	0.73
Clearcut	6.03	347.1	324.8	0.00	0.00	B	1.03
Small	6.30	694.9	285.7	11.11	4.90	B	0.43
Small	7.49	337.5	258.1	12.68	4.05	B	0.88
Small	5.91	609.1	425.9	10.49	3.67	A	0.82
Medium	7.85	469.9	353.3	50.96	34.44	A	0.89
Medium	7.10	822.7	368.3	59.72	15.20	A	0.63
Medium	7.72	637.4	334.4	56.99	39.72	B	0.78
Large	7.94	688.8	303.1	103.02	50.69	B	0.70
Large	7.92	604.5	310.6	109.47	66.34	B	0.76
Large	6.99	608.3	246.2	107.15	65.30	A	0.41

* Small, medium, and large in harvest treatment indicate dispersed retention with 10, 50, and 100 retained trees/ha, respectively.

The direct operational cost (JPY/m^3) for each operation was estimated using time consumption (h/m^3) and hourly operational expenses for labor and machinery [26,27]. Labor expenses were set to JPY 2550/h (USD 19.77/h) [24]. Machinery expenses were set to JPY 448/h (USD 3.47/h) for the chainsaw, JPY 4497/h (USD 34.86/h) for the grapple loader, JPY 10,308/h (USD 79.91/h) for the harvester, and JPY 5979/h (USD 46.35/h) for the forwarder [19]. The exchange rate was USD 1 = JPY 129 on 2 February 2023. Machinery expenses consisted of costs for depreciation, management, maintenance, fuel, and oil. These were calculated from economic data in Table 1. Because the aim of estimating operational cost is to examine the net impact of dispersed retention on total cost to roadside, we standardized time consumption using the least squares means for felling and pre-hauling, and using means of all study sites for the other operations.

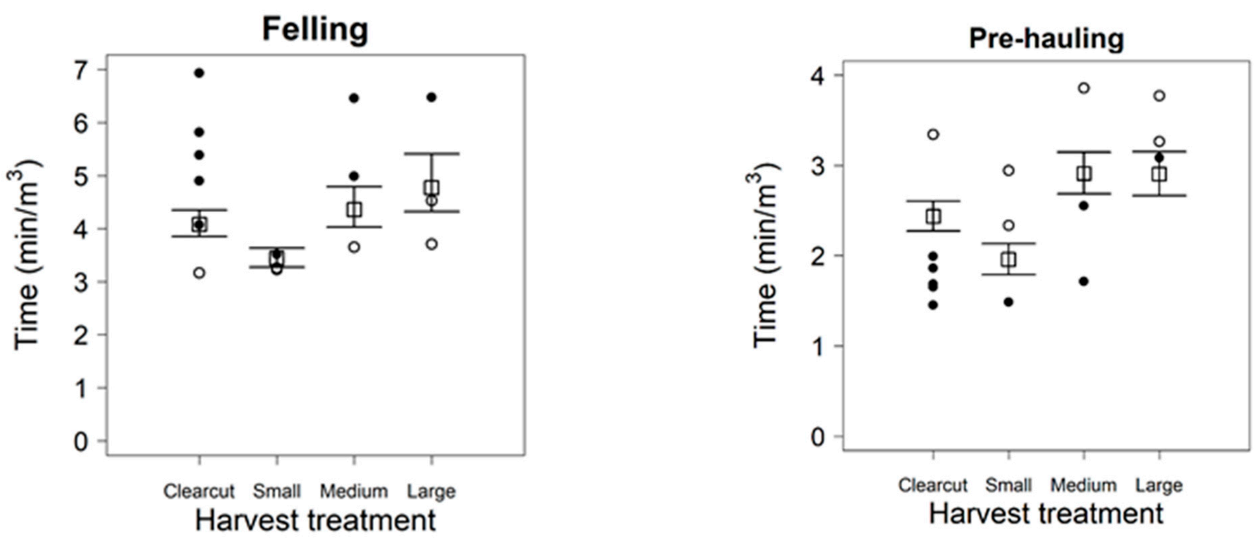
3. Results

The pre-harvest stem density in each study site was 545.41 ± 137.74 stems/ha (mean ± SD) in clearcut sites, 547.19 ± 152.34 stems/ha in sites assigned to a small amount of retention (10 trees/ha), 643.35 ± 144.07 stems/ha for a medium amount of retention (50 trees/ha), and 633.88 ± 38.86 stems/ha for a large amount of retention (100 trees/ha) (Table 2). The pre-harvest stem volume was 376.86 ± 44.86 m^3/ha in clearcut sites, 323.23 ± 73.46 m^3/ha in sites assigned to a small amount of retention, 351.98 ± 13.88 m^3/ha for a medium amount of retention, and 286.66 ± 28.75 m^3/ha for a large amount of retention.

ANCOVA showed that time consumed for felling significantly differed among harvest treatments (Table 3). Compared with clearcutting, the least squares mean time per m^3 was 16% shorter for a small amount of retention, but 7% and 17% longer for medium and large amounts of retention, respectively (Figure 1). Felling time consumption differed significantly between the two contractors, but average stem volume did not significantly affect felling time consumption.

Table 3. Analysis of covariance (ANCOVA) results for the effect of harvest treatment on felling and pre-hauling time consumption per m^3. Average stem volume of harvested fir and contractor were used as covariates. Response variables were Box–Cox-transformed prior to the analyses.

Operation	Source	Coefficient	SS	DF	F Value	P
Felling	Harvest treatment		5.04×10^{-4}	3	3.960	0.0471
	Average stem volume	−0.007	1.5×10^{-5}	1	0.349	0.5694
	Contractor		6.75×10^{-4}	1	15.927	0.0032
	Residuals		3.82×10^{-4}	9		
Pre-hauling	Harvest treatment		0.5119	3	5.392	0.0212
	Average stem volume	−0.725	0.1728	1	5.461	0.0443
	Contractor		1.3388	1	42.307	0.0001
	Residuals		0.2848	9		



(**a**) (**b**)

Figure 1. Time consumption per m^3 for (**a**) felling and (**b**) pre-hauling operation in each harvest treatment. Small, medium, and large indicate 10, 50, and 100 retained trees/ha, respectively. Squares and bars show back-transformed least squares means and SEs, respectively. Dots represent values from each study site, where black or white circles denote different contractors.

Time consumed for pre-hauling significantly differed among harvest treatments (Table 3). Compared with clearcutting, the least squares mean time per m^3 was 20% shorter for a small amount of retention, but 20% and 19% longer for medium and large amounts of retention, respectively (Figure 1). Both contractor and average stem volume had significant effects on pre-hauling time consumption. Pre-hauling time consumption decreased with increasing average stem volume.

The total cost to roadside consisted of the cost of six operations (Figure 2). On average, processing accounted for the highest percentage (32%), followed by forwarding (22%) and landing operations (17%). Felling and pre-hauling occupied only 8% and 11% of the overall cost, respectively. Harvest treatments changed the costs of felling and pre-hauling. Compared with clearcutting, the combined cost of felling and pre-hauling was 18% lower for a small amount of retention, but 14% and 18% higher for medium and large amounts of retention, respectively. This is equivalent to the difference in the least squares means in time consumption. However, because these two operations in total occupied only 19% of the overall cost, the effect on the total cost to roadside was small; the total cost decreased by 3% for a small amount of retention but increased by 3% for both medium and large amounts of retention compared with clearcutting (Figure 2).

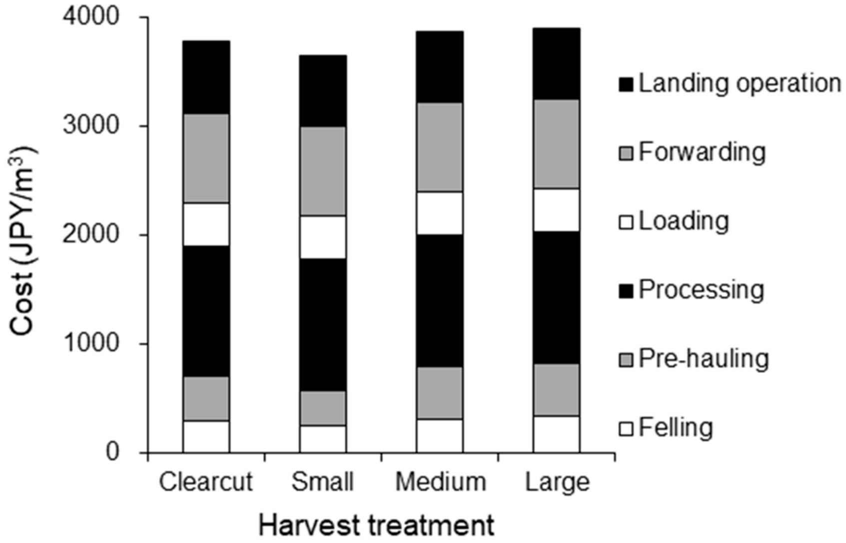


Figure 2. Direct operational cost for six operations in each harvest treatment. Costs of operations other than felling and pre-hauling were standardized using the mean time consumption per m^3 for all study sites.

4. Discussion

One of the goals of timber harvesting is to maximize revenue while reducing costs [27–29]. This cost-efficient harvesting operation is particularly important for plantations in Japan because plantations were established primarily for timber production [30], and logging cost in Japan is generally high from an international perspective [31]. A criticism of retention forestry is that ecological benefits may come at the losses of revenue for landowners [32], which reduces the feasibility of retention forestry [11]. Because one of the goals of retention forestry is to reconcile timber production and biodiversity conservation, it is important to evaluate its economic value, as well as ecological value.

According to the time analyses, a small amount of retention led to a shorter felling and pre-hauling time compared with clearcutting. Although the reason for these time reductions is unknown, these results suggest that a small amount of retention did not negatively affect harvesting productivity. Retaining 10 trees/ha would be negligible to restrict harvesting operations. In British Columbia, Canada, the felling cost was also similar to clearcutting when 25 trees/ha were retained in dispersed retention and trees were felled manually [15]. In contrast, medium and large amounts of retention increased felling and pre-hauling time. In Japan, felling cycle times with chainsaws were longer in thinning than in clearcutting because of the time needed to handle hung-up trees [21,22]. Similar to the thinning operation, dispersed retention may cause harvesting trees to hang up in retained trees. Thus, handling hung-up trees would increase felling time for medium and large amounts of retention where more than 50 trees/ha were retained. Pre-hauling time increased for medium and large amounts of retention, probably because grapple loaders need longer moving and maneuvering times to avoid retained trees.

The present study indicated that medium and large amounts of retention increased the combined cost of felling and pre-hauling by 14% and 18%, respectively. However, the total cost to roadside increased by only 3% because felling and pre-hauling in total accounted for 19% of the overall cost. This suggests that the impact of tree retention on the total cost was small. The operation system used in the present study is one of the common ground-based logging methods implemented in Japan [23]. In this system, felling and pre-hauling account for 10%–40% of the total cost to roadside [22,24]. The remaining cost stems from operations conducted at strip roads or landings; thus, it is not affected by tree retention. However, in the whole-tree harvesting system in Canada, felling and skidding were affected by retained trees, and these two operations accounted for 66% of the total cost to roadside [16]. In addition, the whole operation was affected by retained trees in the cut-to-length harvesting system in Sweden [14]. As a result, harvesting cost to roadside was 2%–25% greater for 5%–50% retention compared with clearcutting [14–16]. This suggests that the harvesting system used in the present study, which is a common ground-based logging method in Japan, is less affected by tree retention unless trees are not retained on strip roads.

In the present study, we selected trees to retain and marked them with flagging tape, but we did not consider the cost of selecting retained trees. In Alberta, Canada, no leave-tree marking was performed [16]. The feller buncher operators achieved the various retention levels by counting stems in a predetermined way. This method does not incur additional costs for preselection, but it necessitates time to select retained trees during the felling operation. Further studies are needed to estimate the cost of selecting retained trees before harvest and to compare it with the cost of selecting trees during the felling operation.

5. Conclusions

We examined the effect of retention harvesting on the productivity and cost of harvesting operations in a large-scale field experiment in conifer plantations in Hokkaido, Japan. The study revealed that although tree retention reduced the productivity of felling and pre-hauling operations, the impact on the total harvesting cost was small. This result would improve the feasibility of retention forestry. Because 80% of the costs were from operations conducted at strip roads or landings, the layout of strip roads is important to determine the harvesting cost. This suggests that trees should not be retained in places where efficient strip-road layouts are disturbed. For example, when strip roads are not permitted to go through uncut patches in harvested areas, strip road length would become longer than in ordinary clearcutting, which increases the forwarding time [13].

In addition to the cost of harvesting operations, economic impacts associated with retention forestry include reduced timber production and reduced growth of regenerated trees due to the effects of the retained overstory [6]. In Sweden, reductions in harvested timber volumes associated with tree retention are the main cause of reductions in revenues [14,32]. Therefore, the retention of broad-leaved trees was more cost-effective than the retention of conifer trees because the wood value of conifers was higher than that of broad-leaved trees [33]. In Japan, wood values are also higher for conifers than for broad-leaved trees [34] because conifers are usually used for saw timber, and broad-leaved trees are usually used for pulpwood. Broad-leaved trees regenerating in conifer plantations are key structures for conserving forest-dwelling species in conifer plantations [35,36]. These facts suggest that broad-leaved trees should be chosen for retention targets in conifer plantations to enhance both the economic and the conservation value of plantations.

For the effect of retained overstory on regenerating trees, retained trees can inhibit the survival and growth of regenerating trees by reducing light, soil moisture, or nutrients [37]. In British Columbia, Canada, the growth of both planted and naturally regenerated seedlings tended to decrease with increasing overstory retention and the associated decrease in light availability [38]. Other studies also showed that light availability is a primary determinant of the growth of planted trees under retained overstory [37,39,40].

These findings indicate that the degree of growth reduction in planted trees depends on the light transmittance of retained overstory and the shade tolerance of planted tree species. In the REFRESH project, we planted Sakhalin firs, which is a typical shade-tolerant species [41], under deciduous broad-leaved trees, which allow a certain amount of light to penetrate into the understory [39,42]. These physiological characteristics suggest that the combination of retained and planted trees chosen in the REFRESH is suitable for alleviating growth reduction in planted seedlings. However, it is likely that ecological succession alters the importance of retained structure over time [43]. For example, the influence of the retained overstory on the microclimate in harvested areas changes with the growth of planted trees. Therefore, long-term studies until the next harvesting period are needed to elucidate dynamic interactions between the retained overstory and planted trees, which can determine the final harvesting timber volume of regenerated plantations.

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