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ORIGINAL RESEARCH

Financial Outcomes of Harvests Aimed at Diversifying Forests in Western Oregon and Washington

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Abstract
Understanding the financial implications of forest harvest practices aimed at increasing the structural and tree species diversity in homogenous stands is crucial for many landowners when making management decisions. We surveyed landowners interested in managing for a variety of ecosystem services and documented over 80 harvest operations. These showed the wide range of settings, including pre-treatment stands conditions, under which restoration treatments can be profitable. In the documented operations, the profitability of the harvest depended mainly on a suite of factors associated with the initial stand conditions, and environmental and financial settings. Treatments in stands that were previously managed for timber production had higher profitability due to removal of higher value trees. Applying such treatments in stands that already had a diversity of tree species and sizes provided less income. Other factors, such as slope and the amount of removal, were also influential. Four case studies provide examples showing how landowners adjusted their treatments and took advantage of beneficial settings and conditions to make treatments aimed at diversifying forests profitable. This, combined with an understanding that leaving high value trees in the stand is an investment, made it feasible for landowners to achieve ecological goals within their management constraints.

Keywords Restoration treatment · Financial analysis · Partial harvest · Ecological silviculture

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Introduction

Across a range of landscapes, many non-industrial private forest landowners are trying to achieve a variety of management objectives simultaneously (Zhang et al. 2005; Blanco et al. 2015). They may encounter special challenges when their forests consist of young even-aged forests which lack the diversity important for providing a range of long-term financial, social, and environmental benefits, such as timber, recreation, hunting, clean water, carbon storage, and wildlife habitat (Kohm and Franklin 1997; Isbell et al. 2011). In addition, homogeneous forests are of special concern due to their susceptibility to risks (Puettmann 2021), e.g., from wildfires (Odion et al. 2004; Thompson et al. 2007), insects (Needham et al. 1999), diseases (Hansen et al. 2000; Koricheva et al. 2006), and blowdown (Wilson and Oliver 2000; Schelhaas 2008). Consequently, landowners show widespread interest in applying silvicultural techniques to even-aged, homogeneous forests that encourage more diverse stand structures and composition (Tappeiner et al. 1997) through actions such as variable density thinning (Anderson and Ronnenberg 2013; Puettmann et al. 2015).

Existing research on financial aspects of treatments aimed at diversifying forests (Adams and Latta 2005), specifically in dense, homogeneous plantations, has fallen short of what non-industrial private forest landowners need (Puettmann et al. 2015), and much of this work has focused on fuel treatments (Hjerpe and Kim 2008). Modeled estimates have been used to compare the long-term financial results of partial harvests and other ecological forestry techniques to conventional even-aged management (Emmingham et al. 2002; Ralston et al. 2003), indicating that partial harvests and similar management options may lead to similar financial outcomes over the long run. Some agencies have gathered data on financial outcomes of thinning and ecologically-based forest management, such as the Washington Department of Natural Resources. However, conclusions from these long-term and large-scale analyses are difficult to apply at the scale of individual restoration treatments. Non-industrial private forest landowners face unique constraints, typically including higher transaction costs, smaller management units, limited resources supporting management decisions, and the desire to realize multiple ecological and financial objectives (Zhang et al. 2005; Blanco et al. 2015). These constraints lead to the perception that there are limiting tradeoffs and financial performances often outweight the benefits to the ecological impacts of a forest management operation (Dickie et al. 2011; Bradford and D'Amato 2012; Halpern et al. 2013; Himes et al. 2020). Together with a lack of necessary information, these constraints are a major reason why many landowners have been reluctant to apply alternative silviculture practices, such as variable density thinnings (Puettmann et al. 2015).

Many treatments, such as partial harvest operations, are often designed to mimic the processes that unfold in unmanaged natural forests as they progress to older seral stages (Palik et al. 2020), including fine-scale tree mortality from insects, diseases, and blowdown (Lutz and Halpern 2006; Wilson and Puettmann 2007; Anderson and Ronnenberg 2013). Over the long term, such treatment strategies are hypothesized to lead to improved carbon storage, biodiversity, wildlife habitat, productivity, and profitability, all of which are outcomes that enhance forest resilience and the quality of life for forest producers and society as a whole (Franklin et al. 2007; Anderson and Ronnenberg 2013).

The purpose of this research was to gather data that will ultimately enhance landowners' understanding of the financial aspects of treatments designed to diversity forests. Specifically, we aimed to provide an overview of the different conditions which led landowners in the Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) dominated region of western Oregon and Washington to consider such treatments and provide a better understanding of the financial outcomes they could expect.

Table 1 Major information types collected in the survey of landowners in western Oregon and Washington

General setting	Location (county, state)
	Motivation
	Harvest year
	Harvested acres (in single or multiple units)
	Harvest type (Variable density thin, even spacing thinning, Selection cutting, Salvage, Clearcut)
	Slope (%)
	Stand age
Pre-harvest conditions	Composition (single, multiple species, conifer, hardwoods)
	Stand structure (one, two, multiple canopy layers)
	Density (trees per acre; tpa)
Post-harvest conditions	Composition (single, multiple species, conifer, hardwoods)
	Stand structure (one, two, multiple canopy layers)
	Density (tpa)
Harvest results	Total volume removed (MBF)
	Gross income ($)
	Volume sold and income by log sorts (MBF, tons; $)
	Damage to residual trees (tpa)
Harvest operations	Skidding distance (miles)
	Skidding method (cable, tractor)
	Felling equipment (machine, hand-feeling)
	Road building cost ($)
	Logging costs ($)
	Trucking costs ($)
	Harvest administration costs ($)

Methods

We developed a survey with questions that collected general information, ecological settings and stand conditions pre– and post– harvest, and income and costs (Table 1). The full survey is provided as Supplement 1.

Data Collection and Management

Our initial goal was to create a dataset of financial results from 40 to 50 projects, with the aim of analyzing results to show financial returns per volume harvested delineated by variables such as species type, site class, and distance from mills.

The survey was distributed in western Oregon and Washington through landowner groups, professional groups, extension services, consulting foresters, land trusts, and municipalities. Outreach was conducted through mailing lists, individual outreach, in-person requests, and mailers. We reached out to over 300 people individually and over 4,000 indirectly (through mailing lists). A gift certificate to local forestry supply stores was offered to respondents who completed the extensive survey, to thank them for their time. The questionnaire was hosted on SurveyMonkey but was available in pdf or paper form by request for those facing technical barriers.

After gathering over 40 responses in the first round, we determined that the initial dataset did not provide sufficient information to come to robust conclusions due to complexity of statistical analysis stemming from the number of variables. Thus, we conducted a second round of data collection to add an additional 40 responses. At the end of the second round, we had 83 responses. Of these, only 61 and 64 had all variables necessary for the statistical analysis of gross income and costs, respectively. While these were likely not representative of all treatments designed to diversity forests, they reflected a wide range of conditions and treatments found in western Oregon and Washington (Fig. 1).

Survey data were processed and cleaned using Excel and the R language. We identified and corrected structural errors and data irregularities, such as mislabeled variables, inaccurate data types, and string inconsistencies, in selected cases by reviewing harvest records.

Fig. 1 Geographic location of survey responses. Number of respondents per county is portrayed by shading with the darker shades representing more respondents

Statistical Analysis

We focused the statistical analysis on gross income and costs. In practical terms, these are most critical for addressing economic aspects when assessing management options. Two separate linear regression models were created to analyze data related to gross harvest income and gross costs. Gross costs included harvesting and trucking costs, road building, planting costs, and general administrative costs (e.g., consulting fees), since respondents were inconsistent in splitting their costs into the detailed categories. The purpose of the selected models was to statistically test hypotheses about how different operational factors, log sorts, and site conditions, which typically vary across harvest units, are associated with income and costs as reported by the landowners. Both models take a simple linear form, and we used variance inflation factors to determine possible multicollinearities. Post-estimation statistical tests were used to investigate the properties of the regression residuals and the statistical performance of the model specification. The Shapiro–Wilk test was used to test whether the residuals are normally distributed, the Breusch-Pagan test to test for constant variance of the residuals (no heteroskedasticity), and the Ramsey regression specification-error test (RESET) to test for functional form misspecification. Several variables reflecting interactions, e.g., volumes separated by wood quality or by clearcut versus other harvesting operations were included to control potential heterogeneity in the models. We used all survey responses with information about gross income or costs for their respective model, but eliminated one outlier who reported a gross income of $53 per treated acre. After reviewing the survey responses and based on feedback by participants we 1) combined two slope categories (30–50% and > 50%, i.e., steep slopes), as both are basically treated the same with cable logging; versus ground logging on shallow slopes < 30%. We also used the label "selection" instead of "uneven-aged" to reflect that these treatments (selection of individuals or group of trees) were designed to start creating conditions that may end up in unegen-aged stands. Because of the unbalanced numbers of e.g., clearcuts versus partial harvests and shallow versus steep (> 30 degree) slopes and the wide range of variability in conditions and outputs across harvest operations reported in the dataset, we used three conventional statistical significance levels (0.1, 0.05, and 0.01) in testing hypotheses.

Results

The results indicated that concern about stand health and restoration objectives were the main motivation for more than two-thirds of the landowners (Table 2). In contrast, financial reasons were only the main objective for about 14% (note that this is from a sample of only landowners who had implemented treatments to diversity forests), followed by desires to follow an established management plan, and concerns about fire hazards.

The high standard deviations of conditions found in stand that received the harvesting treatments (Supplement 2, Table 1) indicated the wide range of stands that were targeted for restoration, instead of more standard or traditionally used

Table 2 The main motivations for landowners to initiate the harvesting operations represented in the survey

Harvest reason	Percentage
Stand health	55
Restoration	15
Financial reason	14
Management plan	7
Fire hazard	4
No response	3
Salvage	1
Taxation requirement	1

Table 3 Averages incomes and costs in $s for the various treatment groups (Standard deviation in parentheses)

	Clearcut	Even-thinning	Variable density thinning	Selection	All
Per acre					
Gross income	8152 (9330)	3317 (1995)	4239 (5505)	5575 (4797)	5011 (5864)
Total cost	4054 (4004)	1518 (1261)	2269 (3016)	2291 (2600)	2433 (3011)
Net income	3757 (7138)	1671 (1648)	1824 (2778)	2854 (2719)	2346 (3775)
Per MBF					
Gross income	618 (200)	547 (137)	551 (238)	708 (340)	595 (244)
Total cost	313 (183)	236 (152)	341 (256)	288 (189)	300 (213)
Net income	277 (324)	332 (120)	225 (180)	365 (320)	286 (241)
Harvest cost only ($/MBF)	218 (117)	217 (93)	275 (163)	248 (170)	251 (147)
Observations	12	14	25	13	64

management goals. Also, Supplement 2 Table 2 provides an overview of the harvesting processes and equipment used. All types of treatments resulted in profitable outcomes in the reported harvesting operations (Table 3). Clearcut operations had the largest gross and net income per acre followed by selection harvests, variable density thinning and even-spaced thinnings. In contrast, the treatments aimed to create spatial variability, variable density thinning and selection harvests, had the highest harvesting costs per MBF.

The survey also showed a wide range of conditions that allowed landowners to implement profitable treatments that encourage diversity in forests (Fig. 2). On one extreme were homogeneous stands that had been managed primarily for timber production, where landowners implemented treatments to alter the stand dynamics with the goal of developing late successional characteristics. On the other extreme were stands that already had diverse structure and composition. In some of these cases, stand shifted from diverse to more homogenous conditions (see the upper two graphs in Fig. 2). Such treatments, which appear to counter the

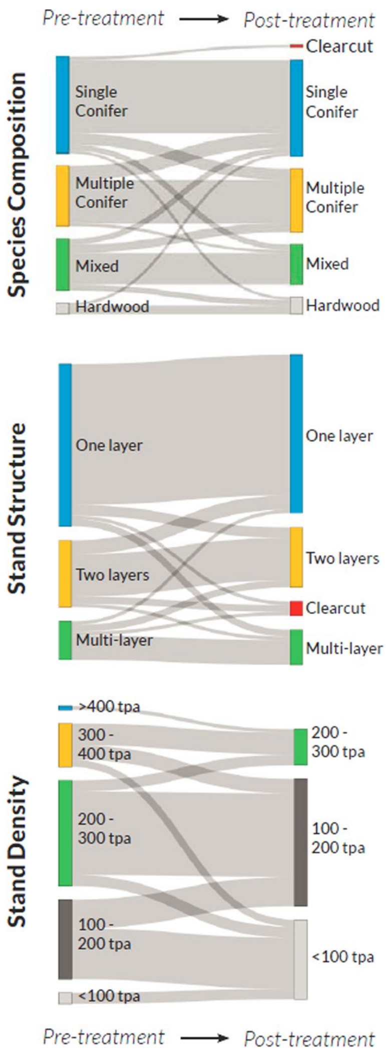

Fig. 2 Species composition, stand structure and stand density attributes of harvested stands before and after restoration treatments. Left distributions show stand attributes before harvesting. Gray lines represent a single survey and lead to the resulting stand attributes after harvesting on the right side

goal of diversifying and creating a more vigorous forests could be due to several factors. For example, harvesting driven by health concerns about one species suffering from drought or insect damage would lead to homogenization in terms of species composition, as would when trees from one species are not merchantable yet, but trees from other species are. Also, concerns about fuel loading would likely result in preferentially removing a selected lower canopy layers, especially when it consists of a high density of flammable trees. The high variability of initial conditions and market factors did not allow a more sophisticated statistical analysis. Instead, we focused on major trends and provided case studies to describe how landowners adjusted their restoration treatments to ensure profits.

Overall, the landowner responses indicated that a wide variety of harvest operations, from clearcutting to various types of treatments, such as uneven-aged selection cuttings or variable density thinnings, were financially viable in a variety of settings. The actual amount of gross income was mainly influenced by the amount but also the quality of the volume harvested (Table 3). The positive parameters in Table 3 indicate the additional income when selling veneer and export quality, although the coefficient estimate on the export sorts is not statistically significant. As to be expected, sorts measured in MBFs receive a much higher price than sorts measured in tons. Gross income is also increasing in the number of acres treated in clearcut harvests. This could mean that stands designated for clearcutting on average contain higher quality timber compared to the other treatment regimes.

In contrast, harvesting costs were influenced by a wider variety of factors. Even though all variance inflation factors were below 5.2 (Table 4), various factors have to be interpreted in context. In other words, while the coefficient estimates measure the marginal effects on gross costs, they should be viewed in the context of net effects. For example, the baseline gross cost in the estimated sample is 28,625 USD (the estimate for the constant term) which should be used as the reference point when considering the marginal effects. In both clearcuts and variable density thinnings,

Table 4 Parameters from income and cost regression models with standard errors in parentheses

	Gross income	Gross costs
Volume in sorts measured in MBF	532.3*** (35.6)	
Export sorts in MBF	215.8 (136.1)	
Volume in veneer sort (MBF)	387.8*** (81.90)	
Volume in sorts measured in tons	27.41*** (6.6)	−4.852 (5.7)
Treated acres in clearcuts	1521.7*** (375.8)	1309.9*** (388.8)
Volume in MBF in 2017	196.2 (136.4)	361.1*** (94.3)
Volume in MBF in 2019	−68.01 (51.32)	188.2*** (35.1)
Volume in clearcuts (MBF)		62.42 (39.3)
Volume in variable density thinnings		73.42** (32.4)
Acres treated		−206.6 (128.2)
Clearcut operation (yes = 1)		−32,931.6 (20,747.5)
Slope		
Slope > 30 degrees (yes = 1)		29,173.2** (13,820.1)
Volume in MBF when slope > 30 degrees		88.23** (36.4)
Constant	14,330.9 (8954.1)	27,108.0*** (6564.2)
Observations	60	63
Adjusted R^2	0.94	0.73
Shapiro–Wilk test (p-value)	0.23	0.40
Breusch-Pagan test (p-value)	0.41	0.41
Ramsey RESET (p-value)	0.20	0.50
Mean Variance Inflation Factor	1.63	2.81

Standard errors in parentheses.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

the volumes harvested increase the gross costs. Additionally, in the case of clearcuts the number of acres is also associated with increasing gross costs. However, note that the indicator variable for clearcut operations takes a negative value, although it is not statistically significant. Furthermore, costs were higher on steeper slopes, and the impact of volume harvested from steep slopes increased costs faster than on less steep slopes. Finally, the cost of harvesting in years 2017 and 2019 was higher than in other years.

The dependent variable is gross income and gross cost (harvesting, trucking, road building, planting, and general administrative costs) in US dollars. The estimated coefficients can be interpreted as the marginal effects from increasing the variable by one unit, while holding all else equal (MBF = 1000 board feet; approximately 7.18 cubic meters for trees of the size harvested; Spelter 2002). All models presented in Table 4 had low variance inflation factors, indicating low multicollinearity. The p-values for the Shapiro–Wilk, Breusch-Pagan, and Ramsey RESET tests were all greater than 0.1, indicating that the model specification is valid for statistical inference purposes.

Discussion

The results indicate that treatments aimed at diversifying forests were applied in many diverse sets of stand conditions. Also, they showed a wide range of treatments in a variety of stands and marketing conditions can result in profitable harvest operations and provide examples of opportunities for financially feasible restoration activities. This is influenced by the likely bias that only landowners responded to our survey who saw the need for and value in such treatments. Landowners with different objectives, such as short-term profits were not sampled and thus these types of operations are not represented in the data set. The variety of ecological, economic, and operational conditions reflected in the dataset only allowed us to interpret the results of the financial analysis in the context of a suite of correlated factors. For one, the choice of restoration treatments (type and intensity) is partially influenced by the pre-harvest stand conditions and thus by the management history of the stand (Tappeiner et al. 2007). The second set of influential factors was associated with the intended restoration goals, e.g., to what degree the treatments were aimed at altering stand characteristics. Thus, the larger the differences between past and current management goals, the more intensive treatments need to be, which potentially leads to more volume harvested. Third, the initial conditions as driven by past management, specifically when it was focused on high stand growth wood quality, and by the trees' size, also influenced the economic results of treatments. For example, as a reproduction cut aimed at initiating tree regeneration, clearcut operations are typically done in older stands than thinning operations, and thus typically result in higher amounts of larger trees and quality logs and associated higher gross income (Supplement 2 Table 1). At the same time, clearcuts remove all trees and thus had higher harvesting costs per treated stands and per acre, but not per MBF than thinnings. Modifications when clearcuts are used as "restoration treatments" can result in additional costs when residual trees need to be protected during the harvesting operation (Note that the number for clearcuts in Supplement 2 Table 1 is likely inflated due to the use of the mean bin values, i.e., 50 TPS when the bin as "< 100). It also indicates the high total harvesting costs (and the per acre costs) are mainly driven by the larger amount of volume removed on clearcut sites. In contrast, variable density thinning and selection harvests, often applied in stands with a mix of species, tree sizes, and spatial arrangements, and designed to improve long-term timber quality and habitat structure (this includes removing clumps of highly valuable trees to benefit nearby patches of smaller trees). The higher net income per MBF for selection harvests suggests that valuable trees were preferentially removed compared to clearcut operations, which removes trees of all sizes and qualities (as reflected in the higher proportion of wood sold as sawtimber; Supplement 2 Table 1). At the same time, the spatial heterogeneity of such operations, as well as variable density thinnings resulted in higher harvesting costs per MBF, which are mostly due to the actual harvesting and not the planning efforts (Kellogg et al. 1998).

On one end of the spectrum, a past management focus on timber production often results in homogeneous stands with full stocking of high-value trees (Puettmann et al. 2009). Our results indicate a high gross income if those stands are clearcut, mainly because of the higher volume that is removed. Apparently, respondents viewed these clearcuts as treatment that qualified as diversifying forests. This suggests that those stands were in conditions where the landowners decided the best management options was to start over, while leaving residual trees of higher ecological values. Such treatments can act as a reference in our study as a choice that leads to highest immediate income. At the same time, even partial harvests in these stands can be profitable. If the goal of such operations is to create more diverse stand structures and thus improve forest health and aesthetics by increasing horizontal variability in stand density. Typically, such operations include skips and gaps (Brodie and Harrington 2020). Compared to low thinnings typical in stands with timber objectives, including gap creation in harvesting operations results in patches in which all trees are harvested, including the dominant and most valuable trees (Puettmann et al. 2016). Replacing – or complementing – low thinnings with operations that harvest patches or rows of trees has been shown to increase harvester productivity (Bergström et al. 2022). At the same time, the spatial variability complicates the actual harvesting operations and thus increases the total harvesting cost per MBF. The addition of gaps in thinning operations had likely little or no impact on planning and layout costs (Kellogg et al. 1998). In contrast, the shape of harvested patches resulted in lower harvesting costs on steep units, if the patches were shaped to align with skyline corridors (Kellogg et al. 1996), Also, the chosen thinning methods has an impact on size and volume of removed trees (Grigoreva et al. 2022) and thus economic outcomes. In contrast to low thinning, when treatments aim to maintain the diversity of tree sizes and thus harvest trees across the whole diameter range, larger, higher value trees are also removed, with the associated positive impact on revenues and average harvesting costs (Kluender et al. 1997).

On the other end of the spectrum of initial stand conditions, a history of limited management often results in stands with variability in tree species, stand structure, and density (Tappeiner et al. 2007; Williams and Powers 2019). Treatments to diversify such stands are typically not aimed at removing the majority of high-value trees. In contrast to clearcutting, such partial harvest operations are aimed, among other goals, at “improving” the stand inventory (“improvement cuts” in the sense of the term as used by the Society of American Foresters, i.e., they preferentially remove smaller and lower quality trees (Dodson et al. 2012; Puettmann et al. 2016). Under these conditions, the lower overall income of the individual restoration treatment when compared to clearcutting operations is partially due to leaving higher-value, more vigorous residual trees for future harvest and thus needs to be viewed as an investment into future stand conditions. Our results suggest that even in stands designated for selection, i.e., not suitable for the other treatments, valuable trees were removed and sold to make the operation profitable. In contrast, once desired stand structure and composition are achieved, harvest treatments in these types of stands will become even more profitable, as fast-growing, high-value trees can then be removed in greater numbers (Roessiger et al. 2016).

The influence of past management and specific goal of the treatments are also reflected in the harvest costs. As indicated above, owners who had managed stands to be more homogeneous were also more likely to implement clearcuts and evenly spacing thinnings. Operating in stands with trees of homogeneous size, higher quality, and even spacing can be done fairly efficiently, which is reflected in lower harvest cost in stands with higher proportions of sawtimber. In contrast, selection harvests in stands with a range of species, tree sizes (canopy layers) and densities resulted in higher harvest costs (Kellogg 1996; Kellogg, Milota, and Stringham 1998; Kellogg and Spong 2004). This was likely due to a combination of the variability in harvested trees in terms of size and quality, the lower harvest volume, and the additional effort necessary to protect the remaining growing stock.

The higher gross income when harvesting more volume and larger units is not surprising. Besides the impact of selling more volume, this may be part of a feedback loop, where positive market conditions increase the owners’ propensity to harvest. Thus, the prospect of higher gross income likely led the owner to harvest larger volumes and apply their harvest prescription to larger units. In contrast, when log prices are lower, owners do the minimum to achieve their management goals, hoping for better markets at the time of their next entry. Potential interacting factors include that larger harvest volumes may attract loggers who have newer, more efficient equipment or are willing to market higher value products. Alternatively, larger volumes may provide a better negotiating position when setting log prices. This suggests that landowners would benefit from combining several harvest treatments into a single contract. As such, our results indicate potential financial benefits of landowner collaborations, e.g., by coordinating harvests and negotiations of wood prices, in addition to other social and ecological benefits (Fischer et al. 2019).

In addition to the factors discussed above, unfavorable terrain, specifically on steeper slopes, resulted in higher harvesting costs. This was also found in other studies, as cable yarding is more expensive than ground-based logging (Kellogg and Davis 2006; Kellogg et al. 1986). Our study conditions did not allow us to statistically quantify the influence of skidding distance, which has been shown to have an impact on logging costs (Kellogg and Spong 2004; Hossain 1998). Both of these factors are of special concern when harvesting smaller trees (Pan et al. 2008), as is typically done in thinning operations (see stand ages in Supplement 2 Table 1). Harvesting costs are also influenced by the planning procedures, e.g., how much extra work is needed in partial versus clearcut operations in terms of timber cruising, marking, and skid trail design (Renzie and Han 2008). Much efficiency can be gained when operational constraints are considered in the treatment planning, e.g., gaps are aligned with cable corridors for efficient skidding, and the use of new technology, such as GIS, GPS, and Lidar (K. Puettmann, pers. observation). Also, our sample was not sufficient to sort out specific impacts of harvesting methodologies and equipment due to the low sample size and because some of these factors are correlated with other variables, e.g., the statistical impact of the choice of ground based versus cable logging is reflected in the impact of the slope variable.

Finally, it is important to note that the data from the survey of past restoration practices is likely biased towards settings in which landowners expected a profitable outcome. It can be assumed that restoration treatments that were expected to provide no income or have high costs were likely not implemented as frequently or not reported. Thus, rather than providing summary information reflecting all possible partial harvest or other treatments aimed at diversifying forests, our sample provides examples under which conditions these treatments could be done to achieve ownership goals with financially viable treatments.

Case Studies

The following four case studies provide examples of treatments aimed at diversifying forests in various settings. A summary of the general setting and financial outcomes are provided in Table 5, with more details in the text. The first two case studies describe treatments in stands with already high structural (case study 1) and compositional (case study 2) diversity. The next two case studies describe restoration treatments in plantations with results driven by the high quality of harvested material (case study 3) and a combination of the setting and the amount of harvested material (case study 4). For the last case study, we provide more detail on the financial factors that went into the decision by the landowners not to clearcut, but instead to implement a partial harvest. In combination, these case studies provide examples in a variety of ecological and financial settings of how landowners managed their treatments to take advantage of desirable circumstances to make these treatments profitable and thus possible in order to achieve a suite of management goals.

Case study 1 is an example of a selection harvest in a mature Douglas-fir-dominated stand that yielded solid financial returns per acre despite a light harvest prescription that removed just 16% of the pre-harvest volume of 50 MBF per acre. When planning the harvest, it became obvious that much of the area could not be treated due to stream buffers and steep slopes, leaving only nine acres accessible for thinning. The ownership goals were to improve stand health and improve wildlife habitat in the short term, while making the forest more resilient to climate change and enhancing biodiversity in the long term. After harvest, some small openings

Table 5 Details of case studies described in text

Case study	Region	Acres	Pre-treatment stand description	Prescription	Volume of timber removed	Value of timber removed	Net revenue	Net revenue per acre
1	Hood Canal	9	50- to 80-year-old Douglas-fir stand, 100–160 tpa, 2 canopy layers	Uneven-aged light selection harvest	64 MBF SW + 1.4 MBF HW + 46 tons pulp	$57,278	$22,489	$2500
2	Cascade foothills	48	40- to 60-year- old stand of Douglas-fir, western hemlock and silver fir	Variable density thinning	362 MBF SW + 693 tons chip-n-saw + 95 tons pulp	$324,389	$128,149	$2698
3	Coast Range	37	30- to 40- year- old Douglas-fir forest, 300 to 400 tpa	Variable density Thinning	175 MBF	$ 117,000	$ 56,200	$1159
4	Puget Trough	20	30- to 40-year-old Douglas-fir plantation, 300 to 400 tpa	Even spacing thinning	74 MBF SW + 360 tons pulp	$61,760	$13,583	$679

in the stand were planted to fill in gaps in the canopy and initiate a new cohort of western red cedar.

Logging and hauling costs amounted to about 45% of gross revenue—a relatively low percentage for such a small job. This low fraction likely resulted from the high prices realized for the relatively large and high-quality logs, which were mostly sold for export. The profitability of the harvest also benefited from short hauling distances, which ranged from 10 miles for pulp and sawlogs to 48 miles for export logs. The $8200 cost of harvest administration, paid to a consultant, represents 14% of the gross revenue from the job—an unusually high fraction that reflects the fixed costs of initiating and overseeing a harvest job, regardless of its size, but potentially justified due to the need for marking trees and oversight of the harvest operation. Nevertheless, owing to the value of these high-quality logs from this mature stand, this harvest returned significant profit despite its small scale.

Case study 2 represents the results of a harvest in a 40- to 60-year- old mixed-species stand of Douglas-fir, western hemlock, and true fir in the Cascade foothills. The second-growth forest had been clearcut in the 1970s by the previous owners and the stand established with substantial amounts of natural regeneration, leading to the higher species diversity. Due to a pre-commercial thinning about 30 years ago the stand was not overstocked, with under 200 stems to the acre before the harvest. A major factor influencing the financial results was that the harvest operation stretched out across three seasons of logging, owing to equipment breakdowns, seasonal constraints on operability of the terrain, and the logger's intermittent availability. Nevertheless, the landowner realized solid financial returns from the removal of about one-third of the standing merchantable volume.

Even though this harvest took place in a younger stand than case study 1, this harvest yielded a similar net income per acre. Reasons for this included a slightly more aggressive prescription (removing more volume per acre) and the economies of scale when implementing a harvest across 48 instead of 9 acres, even though the advantage of scale was mitigated by the duration of the harvest operation across three successive years. This resulted in higher mobilization costs, which in this case were absorbed by the logger, who had bid a fixed percentage of the logs' selling price (50 percent, including hauling). Spreading the harvest across three years hedged the owner against the market risk of fluctuations in log prices, in this case resulting in the marketing of logs in eight different sorts, from export logs to chip-n-saw, reflecting changes in market demands and prices.

Case study 3, as well as case study 4, is an example of treatments aimed at diversifying forests that are fairly common and a result of changing ownership values, specifically when values of current owners do not match the ownership values at the time of stand establishment. In the Pacific Northwest, millions of acres of even-aged, monoculture Douglas-fir plantation were successfully established in the 1980s and are now the subject of treatments aimed at increasing within-stand diversity or accelerate development of late successional structures (Olson and Van Horne 2017). As indicated in the statistical analysis, the influence of past treatments was a major factor driving the financial results. For this stand, the gross income was heavily driven by past management which had led to the presence of high-value trees, with the majority sold as peeler logs, about one-third as chip'n'saw (the lowest grade above pulpwood), and 10 percent as pulpwood. Major costs associated with the harvesting included the logger, who received 50% of the gross receipt, and about $ 1,800 in road building costs. The owners avoided administrative costs, estimated to total between $ 4,000 and $ 8,000, by overseeing the harvest themselves.

Case study 4 focused on a 38-year-old third-growth Douglas-fir plantation that had been established in 1982 following a clearcut harvest of the second-growth forest. The density prior to the harvest suggested that a pre-commercial thinning had been fairly light and the stand had not been commercially thinned. The stand was fully stocked and the pre-treatment volume reflects the high site quality. Motivated by a desire to generate recurring income over time from her forest and to reduce fire hazard, the owner opted for a commercial thinning instead of a clearcut harvest. This treatment consisted of a variable density thinning that was not very intense. However, as indicated by the post-thinning density range, the treatment increased the spatial variability of the remaining trees. The main product was rough peeler logs averaging 9 inches in diameter, with a range of diameters from 4 to 20 inches. Key elements that lead to the profitability of this treatment included the simplicity of the plan and permitting process, which kept harvest administration fees to just under $3,000; the flatness of the terrain (maximum slope 5 percent); and the short hauling distance (20 miles).

Since in case study 4 the landowner considered the choice of whether to thin or clearcut the stand, we explored the financial implications of the landowner's option to clearcut or harvest the stand through multiple entries over time. We calculated the combined value of the residual stand plus the net harvest income and the net income the landowner could have achieved if they had opted to clearcut instead. The value of the standing timber left behind after thinning was estimated using standard appraisal methods by deducting the estimated logging and hauling costs from the estimated selling price of the standing timber.

In this instance, the residual stand was estimated to contain 198 MBF of standing saw timber, valued at $80,000—a net stumpage value of just over $400 per MBF. The $13,500 net income to the landowner from the partial harvest represents a "withdrawal" of principal from the forest's balance of growing stock, while leaving $80,000 worth of timber to continue growing. Thinning operations in this region lead to natural regeneration of a variety of species (Kuehne and Puettmann 2008; Dodson et al. 2014), but successful establishment of a new cohort may require some investment in regeneration, e.g., repeated canopy openings (Shatford et al. 2009), weeding, or pre-commercial thinning (Berger et al. 2012). Because of the uncertainty of the treatment needs, timing, and extent, we did not include regeneration costs for this scenario.

In contrast, if the landowner had clearcut the stand, they would have realized much higher gross revenues immediately, as a result of removing approximately three times the timber volume and incurring lower logging costs per unit volume (due to greater ease of operations). The removal of 292 MBF of sawlogs would have yielded approximately $118,000 in net harvest income before taxes. The owner would have incurred reforestation costs estimated at $12,000 for the 20-acre stand ($600 per acre), reducing her net cash income to $106,000.

In the short run, the difference in income between a clearcut and the chosen partial harvest is about $12,500. This is due in part to the higher per-MBF cost of a thinning harvest compared with a clearcut harvest, minus the cost of reforestation (not addressed in the thinning scenario). This can be viewed as an investment into the stand and payment for all the ecological and social benefits of partial harvests. A majority of non-industrial private forest landowners in the region appear to be very interested in these benefits, especially scenic and wildlife related values (Creighton et al. 2002). Especially landowners with timber and non-timber related objectives have been shown to be willing to invest in such benefits (Kline et al. 2000).

Conclusion

Our survey responses indicated that the majority of the reported harvesting activities aimed at diversifying forests were initiated by concerns about stand health and ecological goals, even though economic outcomes will always be part of any management decisions. Keeping in mind that our sample of activities did not include treatments with a main economic focus, this result reflects findings about the diversity of motivations of people for owning and managing forest lands, with an emphasis on scenic and wildlife related values (Creighton et al. 2002). Recent trends suggest that this set of values is becoming more common with woodland owners (Sass et al. 2023). Our results highlight financial implications for landowners that are interested in exploring options to emphasize ecological values as it is reflected in their forest ownerships. Also, landowners interested in restoration treatments may interpret their role in a different context. When the lower combined value of the remaining stand and removed material is purely a function of the higher cost of more labor-intensive selection harvests, they may see this as a contribution to the local economy. However, the relatively lower income from harvests aimed at diversifying forests compared to standard clearcutting operations is partially offset as assets (merchantable trees) remain on the land and thus the stand growth in the next few years will be higher due to the residual trees' growth response to the increased growing space (Dodson et al. 2012; Dagley et al. 2018). A more complete financial comparison of the two type of management approaches would, require projections of future cash flows and alternative investments to be able to determine and compare the resulting net present values of the two alternatives.

The reported operations, including the four case studies, highlight the variety of ecological, economic, and operational settings in which landowners were able to implement restoration treatments, while at the same time obtaining income from their forests. Specifically, the findings show how landowners accommodated different initial stand conditions as well as different environmental and financial settings to implement profitable restoration treatments (Table 4). For example, owners took advantage of low transportation or low administration costs to enter stands which otherwise would not have been profitable due to small acreage or low harvest volumes. In other cases, entering dense areas within stands of high-value trees allowed them to make more expensive harvest operations in other parts of the stand profitable. Where stands were too young to have high-value trees, landowners resorted to more intensive operations to ensure sufficient harvest volume. All of these factors allowed owners to obtain financial benefits, manage stands for more structural and compositional diversity and the associated benefits in terms of a more diverse understory plant community (Ares et al. 2010; Davis and Puettmann 2009), contribute to the local economy in the short and long term through more frequent, repeated entries. Notwithstanding assertions that harvest methods other than clearcutting are less efficient in removing wood from a site, the results from this survey demonstrates that landowners (at least those who responded to the survey) may emphasize instead the potential ecological benefits of viewing partial harvesting, i.e., the trees remaining after harvests, as an investment in the medium-term productivity of the stand. Associated changes in stand structure and composition can even help prepare forests for future conditions, e.g., by increasing the likelihood of providing selected ecosystem services despite the impacts of anthropogenic climate change (Neill and Puettmann 2013). Finally, any treatment needs to be viewed as part of a long-term management strategy. Landowners should be prepared for careful monitoring and potentially follow-up treatment to ensure development towards the desired stand structure and composition (Dodson et al. 2014).

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Declarations

Competing interests The authors declare no conflict of interests.

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