Minimizing the Cost of Stand Level Management for Older Forest Structure in Western Oregon

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ABSTRACT: *The area of old-growth forest in the Pacific Northwest is estimated to have declined dramatically from historical levels. Active management involving repeated thinning that leaves substantially fewer trees than a typical commercial thin has been proposed as a way to speed the development of older forest structure in the region. This study uses a random search heuristic and an individual tree simulation model, ORGANON, to search for cost-effective old forest management regimes for a wide range of stand types that occur on private land in western Oregon. The regimes were designed to meet older forest structural criteria, as defined by the Oregon Department of Forestry, for 30 years prior to clearcut harvest. The opportunity cost of managing for older forest structure was estimated for each stand type as the value of forgone timber production under maximum net present value management. Opportunity cost was found to be positively correlated with site quality, stand age, and stocking. Cost-effective management for older forest structure is important because the lower the cost of conservation, the more likely it will occur. West. J. Appl. For. 19(4):221–231.*

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The term "sustainable forestry" has different meanings for different people. However, it is increasingly used to refer not only to wood production and jobs but also to biodiversity and ecosystem health. One high-profile sustainability issue in the Pacific Northwest centers on the changing age-class distribution of Pacific Northwest forests, in particular, loss of old-growth conifer forest. It is estimated that old-growth conifer forest (defined in these studies by stand age and average diameter) probably once accounted for 30–70% of the forested area in western Oregon coastal forests (Teensma et al. 1991, Wimberly et al. 2000), but now accounts for only about 5% (Spies et al. 2002). This change has implications for the long-term sustainability of ecosystem services and preservation of habitat for old-growth dependent wildlife species.

One principal objective of recent federal forest policy in the Pacific Northwest, as manifested in the Northwest Forest Plan (Thomas 1993), is to increase the area of old-growth forest in the region. The Plan takes a passive approach of establishing a system of late-successional reserves in which old-growth forest will develop over time, but the passive reserve approach can take hundreds of years for old-growth forest structure to develop. In fact, stands that have been harvested previously and planted to densities exceeding historical stocking levels may never develop old-growth forest structure (Tappeiner et al. 1997, Carey and Curtis 1996). Old-growth forest structure is defined by the presence of large trees, multiple canopy layers, mixed species, and dead and down woody material (Franklin and Spies 1991, Marcot et al. 1991). An additional concern is that the concentration of old-growth forest on federal land and commercial wood production on private land will result in a static and polarized landscape on which there is little succession of young to old forest.

There is growing empirical evidence that active management, in particular, repeated thinning that removes more volume than typical for commercial thinning, accompanied by ingrowth of mixed species, can speed the development of attributes associated with old-growth forests (Hayes et al. 1997, Bailey and Tappeiner 1998, Carey and Curtis 1996). Forest growth models have been used to simulate the effect of thinning on the development of older forest structure and suggest intense thinning can be effective (Barbour et al. 1997, McComb et al. 1993).

The Northwest and Southwest Oregon State Forests Management Plans prescribe active management to increase the land area of conifer forest with older forest structural attributes on state land in Oregon (Oregon Department of Forestry 2001a, 2001b). The goal is to manage for a diverse

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array of forest stand types. However, state forests account for less than 5% of the forested land area in western Oregon. Over 40% of the forested land area in western Oregon is privately owned, and that land can play an important role in meeting regional conservation objectives, including increased land area of forest with older forest structure.

Efforts to encourage conservation on private land, either through regulation, better education and information, or price mechanisms (such as incentive payments or tax relief) will be more successful if the cost is as small as possible. Often, the largest part of the cost of conservation is the opportunity cost arising from reduced production of other valued forest products, such as wood. Cost-effective conservation that minimizes the cost of achieving its objectives is in the interest not only of private forest landowners, who rely on timber earnings as part of their livelihood, but also the public that values the benefits wood provides as well as conservation.

Where active management can speed the development of older forest structure, wood production and conservation can be compatible forest uses. Lippke et al. (1996) and Carey et al. (1999) demonstrated the potential to increase cost-effectiveness of conservation in the conifer forests of western Washington. They compared an active management approach to a preservation approach. In their model, active management took less than half the time that it took preservation to achieve a target of old forest structure on 30% of a forested landscape on the Olympic Peninsula. At the same time, active management produced over 80% of the timber value of maximum net present value management while preservation produced no timber value. These results were obtained without optimizing management at the individual stand level.

In this study, we used a simple heuristic algorithm to search for cost-effective stand-level even-age management regimes that achieve older forest structure (OFS) within a range of time horizons for a wide range of forest stand types that occur on private forest land in western Oregon. We identified OFS management regimes starting with bare land for a range of site classes, ecological regions, and species mixes (these we refer to as new stand management regimes) and for the actual stands measured by the USDA Forest Service Forest Inventory and Analysis project (these we refer to as existing stand management regimes). The resulting set of management regimes cover a wide range of forest stand conditions and can provide the basis for general guidelines for cost-effective management for older forest structure.

The new stand management regimes we identified are consistent with those developed by ecologists and silviculturists for OFS (e.g., McComb et al. 1993, Carey and Curtis 1996, Barbour et al. 1997); typically, three thinnings were prescribed between ages 40 and 80. These removed from 40 to 65% of the standing volume, on average. Older forest structural attributes were generally obtained by 100–120 years of age. OFS management regimes for existing stand types were more variable because they depend not only on site attributes such as site quality, but also on the attributes of the trees that currently comprise the stand, such as age, height, diameter, and species. However, they also generally involve multiple thinnings that removed more standing volume than typical for commercial thinning.

This study contributes to a growing body of research in which cost-effective conservation strategies are modeled. It extends the Lippke et al. (1996) and Carey et al. (1999) studies by searching for optimal stand-specific strategies for managing for both conservation and timber. It extends earlier studies that applied stand-level optimization techniques to meet forest structure objectives by evaluating a wide range of stand types and generalizing the results.

Data and Methods

The objectives of the study were twofold. The first was to identify stand-specific management regimes that meet criteria for OFS within given time horizons while incurring the least cost in terms of the forgone value of timber production. This is equivalent to choosing the management regime, or the time series of silvicultural treatments, that maximizes the land and timber value of the stand, LTV_i, for stand type i:

$$LTV_i = \max \frac{\sum_{a=a^0}^{A} (P_{ia}Q_{ia} - C_a)(1+r)^{A-a} + SEV_i}{(1+r)^{A-a^0}} \tag{1}$$

subject to meeting OFS criteria within a range of time horizons, ω:

$$A - a^0 \leq \omega \tag{2}$$

where:

SEV_i	=	the value of bare land which we assumed to be the maximum net present value of timber production.
A	=	the final clearcut harvest age.
a^0	=	the age of the existing stand. To model new stand types, we set $a^0 = 0$.
P_{ia}	=	stumpage price.
Q_{ia}	=	the per acre harvest volume from management unit i at age a.
C_a	=	the per acre cost of stand treatments applied at age a.
r	=	the annual real discount rate.

The second objective was to measure the opportunity cost of achieving OFS criteria for each stand type to identify stand types on which conservation objectives might be met at relatively low cost. To that end, we searched for management regimes that maximize Equation 1 with no constraints on forest structure. The opportunity cost of meeting OFS criteria is the value of foregone timber production: it is the difference between the unconstrained and the constrained maximum values of LTV_i.

The elements of the model include: (1) forest inventory data; (2) older forest structure criteria; (3) silvicultural treatments; (4) forest stand development and timber harvest yield projections; (5) economic evaluation; and (6) optimization. Each element is described below.

Forest Inventory Data

The basic data describing private forested land in western Oregon were obtained from the most recent timber inventory compiled by the USDA Forest Service Forest Inventory and Analysis (FIA) unit. The FIA inventory defines 858 stocked conifer stand types, each representing about 6,500 ac on average, based on homogeneity of forest attributes. Unlike controlled plots used in many studies, these stand types represent a wide range of site attributes such as site index, elevation, ecological region, proximity to streams, and slope, as well as a wide range of current stand conditions, including the number of trees and the size and species of each tree. The four ecological regions, western Coast Range, other Coast Range, western Cascade Range, and Klamath, are shown in Figure 1. Key stand attributes are summarized in Table 1.

Older Forest Structure Criteria

The Oregon State Forest Plans define five forest stand structure classes for managed forests to serve as guidelines for managing structurally diverse forests (Oregon Department of Forestry 2001a, 2001b). The stand structure classes were defined by stand attributes that develop over time. In this study, we searched for management prescriptions that met criteria for the fifth, or OFS class, for at least 30 years prior to final clearcut harvest. The Oregon Department of Forestry OFS criteria for northwest Oregon are:

- Two or more cohorts or distinct canopy layers.
- Eight or more live trees/ac with diameter at breast height >32 in.
- Six or more standing dead trees/ac with diameter at breast height >12 inches with two or more with diameter at breast height >24 in.

The OFS criteria also include 600–900 ft^3 of sound down logs, which we did not include due to model limitations.

The criteria for older forest structure specified by the Oregon State Department of Forestry management plan for southwest Oregon were less stringent, e.g., smaller trees. We applied the more stringent northwest criteria to the entire sample. The OFS stand structure class describes a managed stand and, hence, is not the same as old-growth, which typically takes 200 years or more to develop in western Oregon. However, it has stand attributes commonly associated with old-growth and is expected to provide many of the same habitat benefits for wildlife.

Silvicultural Treatments

The decision variables in the optimization are the timing and intensity of various silvicultural treatments. For existing stand types, the choices included doing nothing, which is equivalent to taking a reserve approach, and:

- Up to three proportional (across diameter classes) thins in 5-year increments from age 20 to 110, but no less

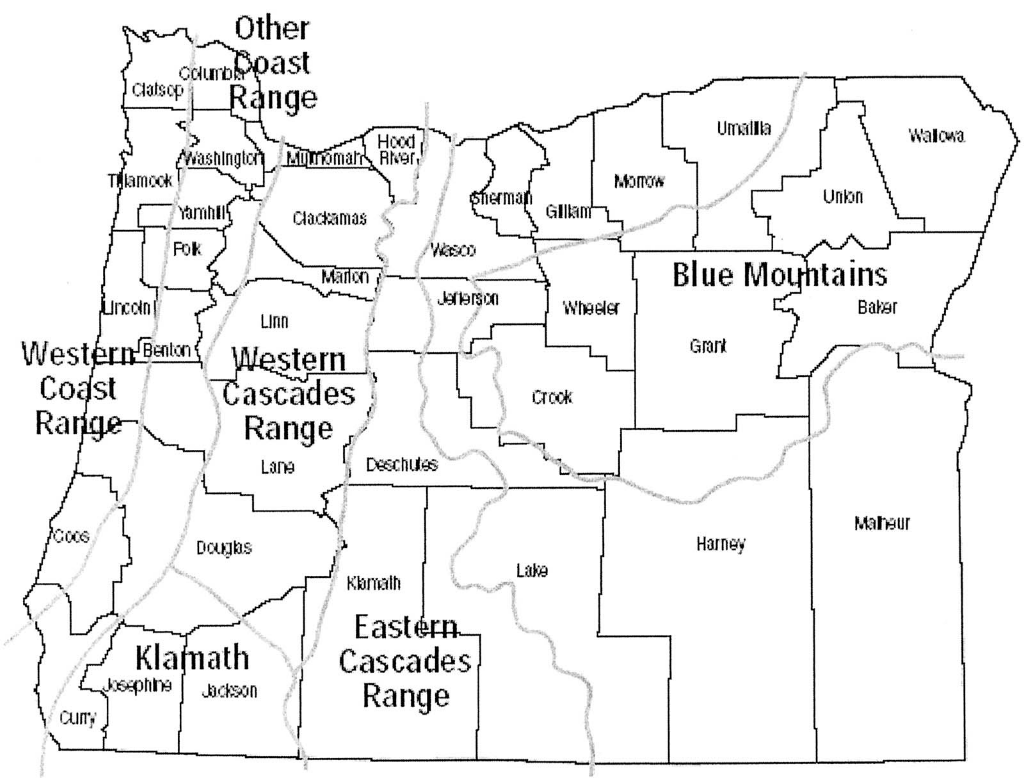

Figure 1. Map of western Oregon showing ecological region boundaries (adapted from Ohmann and Spies 1998).

Table 1. Summary of stand type attributes in percent of total number of stand types by ecological region.

	All regions	Klamath	Other Coast Range	West Cascade Range	West Coast Range
Total number	858	102	192	364	200
Ownership			(%)		
Industry	68	58	60	70	76
Nonindustrial	32	42	40	30	24
Site productivity class[a]					
Class I (over 135)	10	3	14	10	10
Class II (115–135)	40	2	43	41	57
Class III (95–115)	28	24	29	30	24
Class IV (<95)	22	72	14	20	10
Forest type					
Douglas-fir	83	74	91	92	62
Other conifer	17	26	9	8	38
Age of existing stand					
≤20	40	16	41	39	54
20–40	30	22	27	35	30
40–60	18	22	24	17	12
60–80	5	11	6	5	2
>80	7	30	2	5	3
Stocking level (% of normal)					
≤40	43	33	42	42	53
40–80	39	48	36	45	28
80–120	14	15	17	12	16
>120	3	4	5	2	5

[a] Bounds on site productivity class are based on Douglas-fir 50-year site index.

than 10 years apart. Removals could range from 10 to 70% of the standing volume in 5% increments. Ingrowth of 180 trees/ac of mixed species [33% Douglas-fir (*pseudotsuga menziesii*), 33% grand or white fir (*abies grandis* or *concolor*), and 33% western hemlock (*tsuga heterophylla*) or ponderosa pine (*pinus ponderosa*)] was assumed to occur naturally at the time of each thin. An underplanting could be prescribed (with the associated cost) if natural ingrowth is unlikely for a particular stand.

- Final clearcut harvest in 5-year increments within the specified time horizon.

The choice set for new stand types included the activities listed above and:

- Natural regeneration or planting 403–443 trees/ac, depending on site class.
- Precommercial thin to 263 trees/ac in the first 5-year period in which the stand reaches a quadratic mean diameter of 2 in.

Simulation of Forest Stand Development and Timber Harvest Yield

We used the individual tree simulation model, ORGANON (Hann et al. 1997) to model stand development over time. The Stand Management Cooperative version of ORGANON was used for all stand types except those South of the Lane/Douglas county line where the Southwest Oregon version of ORGANON was used. ORGANON was parameterized for each ecological region, based on recommendations of a growth and yield advisory committee for a western Oregon timber supply study conducted at Oregon State University (Adams et al. 2002). The actual tree lists from the inventory data for each of the 858 conifer stand types were input to ORGANON for existing stand types. New stand tree lists were generated using the young stand simulator SYSTUM1 (Ritchie 1993) for a range of site classes for each ecological region and for Douglas-fir stands and other conifer [western hemlock or Sitka spruce (*picea sitchensis*) depending on the ecological region]. There were 79 new stand types.

ORGANON was used to track diameter at breast height, height, and mortality for each tree in the stand. This information was used to evaluate the first two criteria for OFS. The number of cohorts was the number of 30-ft tree height classes with at least 10% of the total stand stocking. Stand stocking and timber harvest volumes, Q_{ia}, for thin and final clearcut harvest were computed using FIA equations (USDA Forest Service 2000). A snag model, based on Graham (1981) and Cline (1977), was used to evaluate the criteria for standing dead trees or snags. If all other criteria were met, but snags were deficit, selected live trees were counted as snags and harvest volumes reduced accordingly.

Economic Evaluation

To evaluate land and timber value, LTV_i, the following real prices and costs (1991 dollars) were used. Stumpage price, P_{ia}, is log price less harvest and haul cost. Log price was an average of #2 and #3 sawlog prices projected for a 50-year base case in a recent western Oregon timber supply study (Adams et al. 2002). We did not use a log price premium for larger logs because, although thinning encourages diameter growth, it also yields more and larger branches, and the effect on log grade is ambiguous. However, stumpage price did vary with stand age, management regime, and stand type because we used logging cost equations that depend on average stand diameter, per acre volume (Fight et al. 1984), and slope. We used higher logging costs if slope was greater than 30% based on logging cost equations from the Oregon Department of Forestry (Gary Lettman, Oregon Department of Forestry, Feb. 8, 2001). Real costs were assumed to remain constant at \$100/ac for site preparation, \$200/ac for planting, \$106/ac for precommercial thin, and \$50/mbf for log hauling. These were mid-range values based on data from a variety of sources including Oregon State University Forestry Extension (Rose and Jacobs 1999) and Oregon Department of Forestry. We used a real discount rate of 6% because sensitivity analysis in the western Oregon timber supply study (Adams et al. 2002) found that bare land values estimated by the model matched observed values most closely at a 6% real discount rate.

Optimization

The optimization problem had two phases. First we searched for maximum soil expectation value, SEV_i, for each stand type i (using the notation for Equation 1):

$$SEV_i = \max \frac{\sum_{a=0}^{A} (P_{ia}Q_{ia} - C_a)(1 + r)^{A-a}}{(1 + r)^A - 1} \qquad (3)$$

Then we searched for maximum land and timber value, LTV_i, (maximize Equation 1 where SEV_i was the maximum of Equation 3) for each stand i for the following problems:

- $a^0 = 0$ and subject to meeting OFS criteria for 30 years prior to final clearcut timber harvest and $A - a^0 \leq \omega$ for $\omega = 155$ for each of the 79 new stand types.
- a^0 = existing stand age and no constraints on stand structure to identify commercial timber management regimes for each of the 858 existing stand types.
- a^0 = existing stand age and subject to meeting OFS criteria for 30 years prior to final clearcut timber harvest and $A - a^0 \leq \omega$ for $\omega = 65$, 95, and 155 (so that OFS criteria must first be met in 35, 65, and 125 years) to identify OFS management regimes for each of the 858 existing stand types. By solving for a range on ω, it is possible to estimate the cost of an accelerated time horizon for meeting OFS criteria.

Because this study introduces conservation objectives that are related to forest structure, it was necessary to track individual trees and, hence, to use a single-tree growth model. As a consequence, traditional methods for optimizing stand management, such as dynamic programming or nonlinear programming (e.g., Brodie and Kao 1979 and Kao and Brodie 1980) could not be used. In recent years, forestry operations researchers have turned increasingly to approximate methods, such as heuristic random search, to solve complex problems that require single-tree growth models (e.g., Bullard et al. 1985, Eriksson 1994, Valsta 1990). Heuristic methods are attractive because they allow problems to be specified with more realism and detail than is possible with traditional methods. Also, while their solutions are only approximately optimal, they have been shown to be capable of identifying management regimes that are likely to be indistinguishable from the global optimum in practice (Bullard et al. 1985, Valsta 1990).

For this study, we used a simple random search algorithm similar to Bullard et al. (1985) because it is versatile, fast, robust, simple to program, and allowed us to solve multiple problems simultaneously. The algorithm randomly samples the solution space, selecting the highest-valued management regime that meets the constraints of the problem. In the random search algorithm developed for this problem, random integers, r, were drawn to determine treatments: the age and intensity of each of up to three commercial thins ($r = 0$ means no thin) and final clearcut harvest age. Each draw is evaluated for feasibility (are constraints satisfied?) and, if feasible, it is evaluated for optimality (is LTV increased?). For the 79 new stand types, the algorithm was run simultaneously for commercial timber management and OFS management. It was stopped when the increment in maximum LTV_i was less than \$1 in 5,000 iterations or after 20,000 iterations if no feasible solution was identified.[1] For the 858 existing stand types, the algorithm was run simultaneously for commercial timber management and OFS management for each of the three time horizons, ω. It was stopped when the increment in maximum LTV_i was less than \$1 in 5,000 iterations or after 15,000 iterations if a feasible solution was not identified.

Results

The resulting set of OFS management regimes for each of the models are cost-effective (at least approximately) in that they minimize the opportunity cost of meeting OFS criteria. These management regimes are summarized below with respect to three questions:

- What types of stands appear to be good candidates for OFS management, in that OFS management is likely to succeed in achieving OFS criteria on the ground?
- What management activities are prescribed in the OFS management regimes?
- How do stand attributes affect the opportunity cost of OFS management?

Good Candidates for OFS Management

Because the search algorithm used for optimization is random, it doesn't necessarily succeed in finding a feasible management regime (that satisfies the OFS criteria) for every stand type. There will be more feasible regimes in the set of possible regimes (and the algorithm's success rate will be higher) for stands for which OFS management is easy than for stands that have attributes that make successful OFS management unlikely. Hence, one way to understand what types of stands might be good candidates for

OFS management is to use regression analysis to examine the algorithm's success rate for different stands and its relation to various stand characteristics.

The algorithm was very successful for new stand types, failing to find regimes for only four out of the total of 79. These four stand types were low quality sites (Douglas-fir 50-year King's site index below 105). For existing stand types, there was more variability and a higher chance that the algorithm would fail. In fact, the algorithm failed to identify OFS regimes for only 3% of the 858 existing stand types when $\omega = 155$, but failure increased as the time horizon was shortened—to 41% for $\omega = 95$ and 83% for $\omega = 65$. Because the success rate was so high for new stands, we only did regression analysis for existing stand types. For those stand types, we estimated a probit binary choice regression model (Maddala 1983) in which the probability of success depends on a linear function of stand characteristics. The model was estimated using the statistical package LIMDEP, version 7.0 (Greene 1998). The stand characteristics in the model were forest type (equal to 1 if primary species is Douglas-fir, 0 otherwise), ecological region, site index, elevation, slope, current average stand age, and percent of normal stocking.

The regression results, shown in Table 2, indicate that:

- The algorithm was more likely to fail in the Klamath region than in other regions, especially as the time horizon was shortened. The Oregon Department of Forestry appears to account for this by setting less stringent OFS criteria in the Klamath region than in other parts of western Oregon.
- Older stands make better candidates for OFS management than do younger stand types. This makes sense because existing trees can contribute to meeting OFS criteria more quickly the larger they are. The average stand age at which OFS regimes could be identified was 35 years when $\omega = 155$, 40 years when $\omega = 95$, and 54 years when $\omega = 65$.
- High site quality, well-stocked stands make better candidates for OFS management than do low site quality, poorly stocked stands.

Table 2. Coefficient estimates for probit regression model for algorithm to succeed in identifying feasible OFS management regime.[a]

Variable	$\omega = 155$	$\omega = 95$	$\omega = 65$
Constant	0.8314	–1.1025***	–3.9778***
Forest type, Douglas-fir	0.2478	0.4476***	0.1682
Ecological region			
West Coast Range	0.3221	–0.1891	–0.4358**
Other Coast Range	0.7823**	0.1733	–0.1269
Klamath	–0.1196	–0.6994***	–0.8222***
Site index (50-year Douglas-fir)	–0.0025	0.0026	0.0193***
Slope	0.0108**	0.0025	–0.0050
Elevation	0.0002	–0.0003	–0.0011***
Stand age	0.0363***	0.0179***	0.0340***
Stocking level	–0.0048	0.0054***	0.0009
Number $Y = 0,1$	24, 834	349, 509	711, 147
McFadden's R^2	0.15	0.14	0.31

[a] Asterisks denote statistical significance of coefficient estimates: *** for 1% level, ** for 5% level, and * for 10% level.

OFS Management Regimes

The timing and intensity of thinning and the timing of final harvest for the OFS management regimes are summarized in Table 3 (new stand types), Table 4 (existing stand types, $\omega = 155$), Table 5 (existing, $\omega = 95$), and Table 6 (existing, $\omega = 65$). These tables are most useful for identifying trends in how the management activities are related to stand characteristics. Ecologists and silviculturists (e.g., McComb et al. 1993, Carey and Curtis 1996, Barbour et al. 1997) have proposed repeated thinning to relatively low stand density to accelerate development of OFS by encouraging tree growth and understory development. In general,

Table 3. Summary of OFS management regime attributes for 858 new stand types by forest type, site class, and ecological region.

Average value of	Age/% volume removed 1st thin	2nd thin	3rd thin	Years until final harvest	Opportunity cost $/ac	% of max LTV
All stand types	40/63	59/56	79/40	148	148	30
Forest type						
Douglas-fir	39/63	57/62	76/46	148	151	27
Other conifer	42/63	63/48	83/32	148	143	35
Site class						
>135	33/61	49/63	68/52	140	243	22
115–135	39/61	54/60	76/40	146	172	29
95–115	45/67	65/51	85/37	151	108	42
≤95	41/60	66/54	86/30	152	81	84
Ecological region						
West Coast Range	35/61	56/54	78/38	150	197	38
Other Coast Range	40/66	57/62	79/34	146	141	26
West Cascade Range	39/61	57/55	75/49	150	150	28
Klamath	55/65	73/53	89/36	143	62	22

Table 4. Summary of OFS management regime attributes for 834 existing stand types by age class and by percentage normal stocking for time horizon ω = 155.

Average value of	Number of thins	Years until thin/% volume removed: 1st thin	2nd thin	3rd thin	Years until final harvest	Opportunity cost: $/ac	% of max LTV
All stand types	2.6	18/68	39/60	72/42	129	1,317	32
Age class							
≤20	2.5	31/67	51/63	78/42	132	444	29
20–40	2.6	12/68	34/59	69/43	128	1,395	31
40–60	2.6	5/68	28/58	68/40	123	2,326	32
60–80	2.8	4/69	28/58	71/36	130	2,596	31
>80	2.9	6/69	35/56	67/42	135	2,241	35
% of normal stocking							
≤40	2.6	28/67	50/61	77/43	131	502	32
40–120	2.6	11/68	32/60	68/40	127	1,628	31
>120	2.5	6/68	28/56	68/42	129	2,568	32

Table 5. Summary of OFS management regime attributes for 509 existing stand types by age class and by percentage normal stocking for time horizon ω = 95.

Average value of	Number of thins	Years until thin/% volume removed: 1st thin	2nd thin	3rd thin	Years until final harvest	Opportunity cost: $/ac	% of max LTV
All stand types	1.98	9/63	32/44	56/29	88	21,92	39
Age class							
≤20	2.28	17/65	34/52	55/32	93	1,063	44
20–40	1.95	10/63	31/44	55/28	89	1,878	38
40–60	1.90	3/64	26/40	62/24	86	3,055	37
60–80	1.77	3/65	35/28	44/18	81	3,645	37
>80	1.67	5/58	49/33	63/33	83	3,442	40
% of normal stocking							
≤40	2.03	17/63	36/50	55/36	90	1,074	44
40–120	1.97	7/64	32/41	58/24	87	2,349	38
>120	1.93	4/63	27/42	52/24	89	3,519	37
Summary of slow (ω = 155) regimes for 147 existing stand types for which fast (ω = 65) regimes were identified							
	2.60	12/68	32/60	67/42	123	1,767	31

Table 6. Summary of OFS management regime attributes for 147 existing stand types by age class and by percentage normal stocking for time horizon ω = 65.

Average value of	Number of thins	Years to thin/% volume remove: 1st thin	2nd thin	3rd thin	Years to final harvest	Opportunity cost: $/ac	% of max LTV
All stand types	1.47	4/52	26/26	48/24	61	4,164	45
Age class							
≤20	1.56	3/58	22/36		62	2,363	45
20–40	1.41	7/53	24/28	30/10	63	3,096	45
40–60	1.55	3/54	28/25	58/40	63	4,190	45
60–80	1.55	2/47	28/19	40/10	58	5,372	46
>80	1.24	1/47	30/25	55/20	57	5,801	44
% of normal stocking							
40% and under	1.51	3/52	25/24	60/45	62	5,846	43
40–120%	1.31	7/44	29/18	55/20	63	2,201	56
>120%	1.50	3/54	26/28	42/18	61	4,031	44
Summary of slow (ω = 155) regimes for 147 existing stand types for which fast (ω = 65) regimes were identified for							
	2.60	3/68	24/57	65/37	115	2,923	32

our minimum-cost OFS regimes are consistent with those proposals because thinning also contributes to the financial objective by making timber revenue available early in the life of the stand.

We used the individual tree simulation model with the optimization algorithm to sample a wide range of management regimes, with the possible number of thinnings ranging from 0 to 3, thinning ages ranging from age 20 to final harvest, and removals ranging from 10 to 70%. Although the particular management regimes that were prescribed varied with the characteristics of the individual stands, some general management implications emerged from the analysis. These include the following:

- OFS management involves multiple thinnings. For new stand types, the algorithm almost always (97.5%) prescribed three thinnings. These occur, on average, every 20 years, beginning at age 40. For existing stand types, as the time horizon was shortened, fewer thinnings were prescribed; the average number of thinnings is 2.5, 2.0, and 1.5, respectively.
- More volume is removed in the thinnings than is typical for commercial timber production. For new stands, the removals are, on average, 63, 56, and 40% for the first, second, and third thinnings, respectively—compared to 20–35% for commercial timber production as reported in a survey of private forest landowners in western Oregon conducted by the Oregon Department of Forestry and the Oregon Forest Industry Council (Adams et al. 2002). For existing stand types, when the time horizon is long (ω = 155), the percent volume removal is a little higher than it is for new stand types, about 67% of the standing volume. As the time horizon is shortened, less volume is removed in each thinning—68, 63, and 52% volume is removed in the first thinning for ω = 155, 95, and 65, respectively.
- The typical OFS management regime for older existing stand types involves thinning right away; over 80% of the existing stand types older than 60 years are thinned within 10 years.
- Thinning occurred and OFS criteria were met earlier for high-quality sites than for low-quality sites.
- The time horizon is a limiting factor for most new stand types. Because postponing final harvest is costly, the algorithm favors regimes that harvest as early as possible. Nonetheless, over half of the new stand types are held for clearcut harvest until the end of the time horizon at age 155, suggesting that lengthening the time horizon might reduce cost for most stand types. The time horizon is less constraining for existing stand types than for new stand types—only 10% of the stands are held the full 155 years before final clearcut harvest. Nearly 10% are held for 100 years or less.

Opportunity Cost of OFS

The opportunity cost was computed as the difference between the unconstrained (maximum *LTV*) and the constrained (subject to meeting OFS criteria) land and timber values, LTV_i from Equation 1. The cost estimates represent the present value of the change in revenue over the life of the existing stand and the cost of postponing future rotations. The largest component of cost is the reduction in present value of revenue from postponing final harvest to achieve older forest structure. That is partially offset by increased revenue from early, relatively heavy thinnings.

OFS opportunity cost estimates are shown in Tables 3–6 in dollars/ac and as a percentage of maximum LTV. For new stands, the average cost for OFS management is \$148/ac. The cost is higher for existing stands because of the value of the standing timber. The cost increases dramatically as the time horizon is shortened, ranging from an average of \$1,317/ac for slow (ω = 155) to \$4,164/ac for fast (ω = 65) OFS management. In Tables 5 and 6, summary statistics are shown for the slow OFS regimes (ω = 155) for just the 147 stand types for which fast (ω = 65) OFS regimes could be identified. The average cost of slow (ω = 155) OFS management is higher for these stand types (\$2,923/ac) than for the full set of 834 stand types (\$1,317/ac). This suggests that the increased cost for fast management is in part due to changes in the OFS regime, but also due to the increasing concentration of OFS management on high cost sites as the time horizon is shortened.

We used regression analysis to investigate the relation between the cost of OFS management and site characteristics. An understanding of how site characteristics affect cost can be useful for setting priorities for OFS management. Equations for each set of OFS regimes were estimated using ordinary least squares with a correction term for sample selection bias to account for the stand types for which OFS regimes were not found (Maddala 1983). The equations were estimated using the statistical package LIMDEP, version 7.0 (Greene, 1998).

The regression results, shown in Table 7, suggest the following:

- For new stand types, OFS management is more costly on high-quality sites than on low-quality sites.
- For existing stands, the link between cost and site quality is not apparent. But stand age and stocking level are clearly important. OFS management is relatively costly on well-stocked older stands.
- The cost of OFS management varies by ecological region, even when site quality is controlled for. OFS management tends to be cheaper in the Klamath region. This appears to be a result of relatively low timber value as well as low-opportunity cost as a percentage of total timber value. OFS management tends to be most costly in the West Coast Range region. The timber value for the West Coast Range region is comparable to the West Cascade Range and the Inland Coast Range regions but the opportunity cost is relatively high as a percentage of total timber value.

Conclusion

In this study, we combined an individual tree simulation model with a random search algorithm to search for cost-effective strategies to manage for OFS on private forest land in western Oregon. The resulting OFS management regimes

Table 7. Coefficient estimates for linear regression model of opportunity cost of OFS management regimes in the specified time horizon for new and existing stand types.[a]

Variable	New stands, $\omega = 155$		Existing stands		
	Opp cost	Max LTV	$\omega = 155$	$\omega = 95$	$\omega = 65$
Constant	–88.8**	–1203.9***	–279.5	–6650.7*	–4552.7
Douglas-fir = 1	–14.0	–3.8	68.4	842.1	109.5
West Coast Range = 1	56.9***	–21.9	169.8	–117.0	1337.4**
West Cascade Range = 1	–16.3	–30.8	79.2	445.5	26.2
Klamath = 1	–50.6**	–56.1	–1352.2***	–3253.5***	–868.0
Site index (Douglas-fir, 50-year)	2.2***	15.7***	1.8	8.9	28.4
Slope			–1.7	1.7	–2.8
Elevation			–0.3**	–1.2	–0.3
Stand age			28.0***	76.7***	50.0
Stocking level			13.3***	33.7***	38.6***
Mills ratio			732.5	5116.9**	34.6
Number of obs.	75	75	834	509	147
Adjusted R^2	0.54	0.60	0.50	0.51	0.55

[a] Asterisks denote statistical significance of coefficient estimates: *** for 1% level, ** for 5% level, and * for 10% level.

are characterized by repeated thinning with relatively high-volume removals. This is consistent with management strategies recommended in recent literature by forest silviculturists and ecologists who are concerned that existing stands, if left unmanaged in reserves, may never develop attributes that replicate the natural old-growth forests that developed historically at low densities. There is also concern about the reserve approach because of its relatively high cost; the opportunity cost of a reserve is the full value of the forgone timber production—the maximum LTV value. The OFS active management regimes contribute to the stand structure objective by encouraging tree growth and multiple story development and to the financial objective by removing timber volume quickly so that revenue is generated early in the life of the stand. Hence, it appears that the active management approach may be a "win-win" approach—more likely to succeed at achieving conservation objectives and at a lower cost than the reserve approach. Nonetheless, there is reason for caution. Although science supports the idea that active management can, indeed, achieve desirable outcomes, that is not known with certainty. Because we haven't had the opportunity to try OFS management regimes and to observe the long-term results, there is uncertainty about the development of the stand and tree attributes predicted by ORGANON. There also is uncertainty about the relation between those attributes and the important functions attributed to old-growth conifer forest. In the face of this uncertainty, a cautious strategy would involve both active and reserve approaches to conservation.

The analysis reported in this article provides information that could be useful to forest policymakers in setting conservation priorities. There are at least two different criteria for prioritization of stand types for OFS management: likelihood of success and cost. Unfortunately, these two criteria lead to two different sets of priorities. The stand types for which OFS management is most likely to succeed in achieving the structural objectives for which it is designed—the high site, well-stocked, older stand types—are also those for which the cost of OFS management is the highest. The result is that policy makers face a tradeoff between cost of managing particular stands for OFS and certainty about the ultimate results of that management.

Taking an active approach to OFS management is appealing because it may allow development of OFS within a time horizon that is meaningful to people now. But, within the framework of our analysis, impatience is costly. It increases the cost of OFS management in two ways. First, as the time horizon is shortened, OFS management regimes are more concentrated on high-cost stand types. Slow OFS management costs an average of $1,317/ac for all existing stand types for which a slow OFS regime was identified. It costs an average of $2,923/ac for the 147 stand types for which a fast OFS regimes was also identified. Second, imposing a shorter time horizon reduces the present value of timber production for some stand types. Imposing the fast time horizon increased the average opportunity cost for the 147 stand types for which fast OFS management regimes were identified from $2,923 to $4,164/ac. Again, this poses a dilemma for policy makers; speeding attainment of regional targets for older forest structure will not only require costlier management on any particular acre, but will concentrate OFS management on high-cost sites.

This study did not attempt to address the question of whether OFS management is worth the cost. The answer to that question depends on the value society places on OFS management and its results, but the study does highlight the complexity of the valuation question. If people are indeed willing to incur some cost to society to increase the area of forests with OFS, do they just want to know that it will occur, or do they also care when it occurs? How much more cost are they willing to incur to have OFS sooner rather than later?

Cost-effectiveness, or minimizing the cost of conservation, is one reason that opportunity cost estimates are potentially of interest to conservation policy makers, but there are other reasons. Conservation organizations, responding to growing resistance by landowners to further environmental regulation, are exploring alternatives to regulation, such as conservation incentive programs, as a way to induce voluntary participation in conservation activities. At the same time, the demand for compensation for losses resulting from environmental regulation is gaining force. For example, a referendum, passed by Oregon voters in 2000 and recently overruled by the Oregon Supreme Court on technical grounds, would have required state and local governments to pay landowners the amount of reduction in market land value resulting from regulation of land use to protect certain natural resource values. The opportunity costs for OFS estimated in this study are measures of the change in the value of a forested site to landowners that use active management to manage for OFS. They represent the level of compensation of lost market value that would be considered "just" if landowners were required by regulation to undertake OFS management. Some classes of landowners might adopt OFS management voluntarily with less compensation if they received adequate technical assistance (Kline et al. 2000). But for landowners who own forest land primarily for financial reasons, these cost estimates represent the minimum level of incentive payments that would induce voluntary OFS management as well as the just level of compensation.

Finally, the analysis reported in this study concerns stand-level forest management for conservation objectives, but conservation policy goals are regional. The benefits of managing for conservation on any particular stand depends on what is occurring in the rest of the region. Cost-effective conservation is important at the regional level for all of the same reasons it is important at the stand level. This stand-level analysis lays the groundwork for a broader regional analysis of OFS management on private land that searches for cost-effective strategies to achieve regional goals and estimates the cost of doing so.

Endnotes

[1] The solution space for new stand types exceeded 100 million possible combinations of thinning ages, percentage removals, final harvest ages, regeneration planting, and precommercial thinning options. Because each iteration involves an ORGANON simulation and an evaluation of the stand attributes over time, each new stand type took approximately 50 minutes to optimize to our convergence criteria using a an 1,800 MHz PC with 1.5 Gb RAM and Pentium 4 processor. The existing stand types had smaller solution spaces depending on the current age of the stands, but because the attributes of the existing stand types differed due to individual stand characteristics, each of the 858 stand types was individually optimized.

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