The Cost of Achieving Old-Growth Forest Structure

Claire A. Montgomery, Greg S. Latta, and Darius M. Adams

ABSTRACT. *Dwindling area of old-growth forest is of concern in many regions of the world. Forest reserves provide one solution. But highly productive timberlands are typically excluded from reserves due to cost. In this study, old-growth forest is defined by structural attributes believed to be important for old-growth-dependent wildlife species. Management practices are allowed that accelerate the development of these attributes while permitting timber harvest. A minimum area of old-growth forest is protected at any time, but the spatial location of old-growth can shift over time. We demonstrate our approach using a case study on private land in western Oregon.* (JEL Q23)

I. INTRODUCTION

Loss of indigenous forest to agriculture or timber harvest is a global concern. It is estimated that the current area of frontier forest[1] is about 20% of what it might have been in the absence of human disturbance (World Resource Institute 2004). In the Pacific Northwest region of the United States, estimates of the extent of remaining indigenous old-growth forest in the early 1990s ranged from 13–17% of the pre-logging area (Booth 1991). In attempting to protect and restore indigenous forest, it is common to employ fixed reserves (mostly on public lands) in which natural processes are allowed to restore the forest to its pre-logging state—a lengthy process and one fraught with uncertainties. It may also be possible, however, to create "old-growth-like" forests, ones with the critical structural properties of natural forests, using active management in shorter time periods while also allowing some timber harvest. Such an approach could supplement a fixed reserves system and might yield "structurally old forests" at a lower social cost than reserves. This paper examines the process of creating structurally old forests by active management and provides estimates of the costs of such a program as applied to private lands in the Douglas-fir region of western Oregon.

Some landowners who manage forests as income-earning investments have, in the past, characterized old-growth as "overmature" because its commodity value is growing at a lower rate than other productive investments, and they have considered its preservation wasteful. The resulting plantation forests have lost much of the diversity in forest structure, wildlife species, and associated ecological processes that characterize old-growth forests. The extent to which indigenous forests, including the old-growth forest of the Pacific Northwest, play an essential role in providing ecosystem services, such as clean water, stable local climates, and habitat for certain specialized species, is poorly understood but thought to be important. Hence, the loss of these forests could substantially and negatively impact the quality of human life. Although the benefits of protecting and restoring old-growth forests are not well-represented in markets and,

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[1] A frontier forest is a relatively undisturbed forest area, comprising primarily indigenous species, and large enough to support viable populations of species associated with that forest type (World Resources Institute 2004).

hence, there is little market incentive to do so, these benefits could exceed the reduction in the market value of wood production that would result.

The use of fixed reserves undisturbed by human activity as a strategy to restore and protect indigenous forests has at least three problems:

1. Fixed reserves tend to be located predominantly on land of low commodity value because the opportunity cost of forgoing timber harvest can be high. The resulting reserve network may not represent the full range of historical forest types.
2. The resulting landscape is static, with islands of old-growth forest (and the biodiversity it supports) surrounded by intensely managed forest or agricultural land. In reserves, the forest grows old except where a stand-replacing natural disturbance occurs. Outside reserves, timber is harvested at the financially optimal age, which may be quite young. There is no progression from one state to the other.
3. Restoring old-growth forest by "letting nature take its course" may be risky. Existing forest stands have been impacted by human activities (such as fire control, timber harvest, replanting, and brush control) in such a way that they may develop, over time, into something quite different from the natural old-growth forests that people value (Carey and Curtis 1996; Tappeiner et al. 1997). Although age alone is an important factor in defining old-growth forest, ecological definitions of old-growth also emphasize species mix, ecosystem function, and structural attributes, such as number of large trees, deadwood, and canopy layers (Franklin et al. 1981; Spies and Franklin 1991; Er and Innes 2003; Helms 2004). Ecological definitions recognize that some young forests may support the ecosystem services for which old-growth is valued, while some very old forests may not.

In contrast to this latter point, almost all previous studies of old-growth forest in the economics literature define amenity services solely as a continuous function of stand age or a dichotomous function of whether the stand has ever been harvested or not.[2] These studies demonstrate at the stand-level how the optimal timber harvest age might diverge from financial maturity when amenity values are included in the analysis (e.g., Hartmann 1976; Strang 1983; Snyder and Bhattacharyya 1990; Swallow, Parks, and Wear 1990; Reed and Ye 1994). Depending on the relation between amenities and stand age, it may be optimal to hold a timber stand beyond financial maturity for some time and then harvest it, there may be local optima that are not globally optimal, or it may be optimal never to harvest a stand and protect it as old-growth in a fixed reserve. Plantinga and Birdsey (1994) and Alaouze (2004) report applications to carbon sequestration and water yield, respectively. Swallow, Talukdar, and Wear (1997) model spatial dependencies by specifying benefit functions for individual stands as a function of their age and the age of neighboring stands. Conrad and Ludwig (1994) model the optimal stock of old-growth forest to preserve.

In this study, we consider an alternative to the natural-processes, fixed-reserves approach to restoration and protection of old-growth forests. Old-growth forest is defined using a set of structural criteria believed to be important components of habitat for old-growth dependent wildlife species. Management practices are allowed that would accelerate the development of these structural attributes while also per-

[2] These studies assume even-age forest management that involves treating timber as an agricultural crop; it is planted at one point in time and clearcut harvested when mature. Uneven-aged forest management involves maintaining a steady-state forest inventory and age- or size- class distribution through periodic thinning (Montgomery and Adams 1995). There is a growing literature that models tree size diversity as an indicator of amenity value in uneven-aged stands (Buongiorno et al. 1994; Önal 1997; Kant 2002). Boscolo and Vincent (2003) provide an interesting example in which biodiversity is represented by an index constructed from tree size and species mix.

mitting extraction of timber. Old-growth forest may be clearcut-harvested in this approach as long as some minimum area of the forest is maintained as old-growth by our structural definition. Hence, a minimum area of old-growth forest is protected at any point in time, but the landscape is dynamic; the spatial location of old-growth can shift over time; and there can be a full representation of age classes at any point in time. This approach is similar in spirit to studies in the forest planning literature that develop forest-level timber harvest schedules constrained to meet minimum area and patch size requirements for mature forest habitat that can shift spatially over time (e.g., Öhman and Eriksson 1998; Öhman 2000; Sessions et al. 2000; Rebain and McDill 2003). Also, recent models that incorporate spatial aspects of wildlife habitat in joint production with timber implicitly model conservation reserves that shift over time (e.g., Lichtenstein and Montgomery 2003; Nalle et al. 2004).

We consider an array of targets for the area of private forest that functions as structurally old forest; where the targets vary by the extent of the area and the time required to reach a given area. To estimate the opportunity costs of achieving these targets, we employ a regional intertemporal model of the market for logs harvested from private forests, imposing the targets and observing the shifts in market surpluses. For comparison, we also simulate the costs of the natural-processes, fixed-reserves approach. As a specific case example, we model application of the structurally old-forest approach and fixed reserves on private land in the Douglas-fir region of western Oregon.

The following section describes the economic model of private harvest and timber management behavior. Old-growth-related issues specific to the case study area in western Oregon and data sources are described in the third section. The results of the application are described in the fourth section. The paper closes with a discussion of policy implications and caveats.

II. A MODEL OF PRIVATE FOREST MANAGEMENT BEHAVIOR

We explain private timber harvest and investment behavior and their response to a structural old-forest policy by means of an intertemporal model of a competitive log market. Market equilibrium over all periods occurs when the discounted sum of consumer surplus for wood processors and producer surplus for timber land owners is maximized. Consumer surplus is the area under the derived demand functions for logs in the production of lumber and plywood less expenditure on logs. Timber landowner (log producer) surplus is revenue from log sales less production costs (for timber harvest, log transport, and stand management treatment). Timber landowners are constrained by the initial conditions of the forest inventory, the biology of forest stand development over time (as modified by management actions), and regional targets for structurally old-forest.

A condensed version of the model is given in Appendix relations [A1]–[A7] along with assumptions upon which model parameters were based. The decision variables are the area, X_{nj}, of stand type n to be enrolled in various management prescriptions, j, the level of investment in processing capacity, I_t, in period t, and the average rotation age for stands after the end of the projection period, $\overline{A}$. The objective function [A1] and constraints [A2]–[A7] define intertemporal equilibrium in the log market and associated management and harvesting regimes on private lands. Constraint [A2] is the market balance equation indicating that harvest over time depends on the allocation of land to the various management prescriptions, plus net trade and any exogenous harvest contribution from public lands.

Constraints [A3] and [A4] control capital stock. Constraint [A3] defines the change in capital stock over time as investment less depreciation. We assume that producers adjust capacity over time so as to maintain a desired operating rate (ratio of output to capacity), λ, as described in constraint [A4]. Regional wood processors are part of competitive national wood products markets. Changes in regional factor costs, without offsetting shifts in products prices, will lead to changes in the profitability of firms and ultimately some adjustment in milling capacity (firm entry/exit and changes in scale of operation). Capacity adjustment is assumed to entail costs following a two-tier scheme. All operating capacity incurs a minimum per unit maintenance expenditure, k_m, in each period. Capacity expansion or investment, I_t, entails higher costs per unit, k_u. Both costs are deducted from the market surplus objective [A1]. In the market model, capacity limits the level of log input (product output) in [A4] and shifts the log demand equations, $P_t(q, K_t)$, as a measure of the flow of capital services in [A1].

Constraint [A5] approximates the average perpetual harvest volume in all years after the final period, Q_T, by means of a version of von Mantel's formula (Davis and Johnson 1987). The average perpetual harvest is based on the terminal period inventory and the average rotation age in harvested stands over the last five periods of the projection, $\bar{A}$. This assumes timber management beyond the time horizon that is roughly similar to that in periods prior to time T. Constraint [A6] requires that all land be assigned to some management prescription.

Constraint [A7] sets regional conservation targets for old forest structure; it requires that the fraction of the private land area that meets structural criteria for old-growth equal or exceed α from time τ to the end of the planning horizon. To estimate the opportunity cost of meeting old forest conservation targets, the model was solved repeatedly for a range of target values of α (minimum fractions of old forest in the total forest base) for a given τ (the latest time by which the target α percentage can be reached). Opportunity costs were measured as market welfare changes relative to a base case with no requirements for old-forest structure.

III. A CASE STUDY IN WESTERN OREGON'S DOUGLAS-FIR REGION

Western Oregon's Douglas-fir forests are among the most highly productive timberlands in the world. As a result, the opportunity cost of the traditional fixed-reserves approach to old-growth forest restoration is high. Structural management reduces, but does not eliminate, the cost of producing forests with old-growth structural attributes. Although timber harvest is allowed, management for old forest structure differs markedly from wealth-maximizing timber management regimes. Carey, Lippke, and Sessions (1999), in a stand-level case study set in the Olympic Peninsula of western Washington, used simulation to demonstrate that the cost of creating structurally old forest may be substantially reduced by using management that involves periodic thinning. In our study, we extend the Washington case study in three ways: (1) minimum-cost stand-level management regimes are identified using optimization methods (described in Latta and Montgomery 2004); (2) these regimes become options in a forest-level, log supply model to simulate region-wide behavior; and (3) we explore a range of targets and time limits for achieving structurally old forest.

As noted at the outset, current restoration programs using fixed reserves with no management (see Thomas 1993 for details) pose an array of ecological problems:

1. Reserves of old-growth are concentrated on federal land (about 50% of the forestland in western Oregon) which is typically of lower site quality, higher elevation, steeper, and further from streams and roads than private land.
2. The resulting landscape is static with old-growth forest (typically taking 200+ years to develop) in reserves on federal land and plantation forestry (typical harvest age is 40-to-50 years) on private land.
3. Timber management activities within reserves on federal land are severely constrained. As a result, the legacy of past

management will determine how the forests develop over time. Research suggests that the old-growth forests of the Pacific Northwest developed from young stands that were quite different from regenerated young stands of today; they were far less dense and held trees of many ages. It appears that repeated thinning will be required to promote tree growth and reduce density (Carey and Curtis 1996; Tappeiner et al. 1997). Even if natural processes do eliminate weaker trees and old-growth forest structure develops, it may take a very long time. The recent Healthy Forests Restoration Act of 2003 may facilitate thinning on national forests. It is unlikely to aid the expansion of old-growth area, however, because its primary purpose will be fire risk reduction and, hence, restoration activities will be limited in scale and concentrated near communities at risk of fire damage (USDI 2005).

In contrast, the State of Oregon is implementing an active structural management approach similar to the one we explore as an alternative on state forests (Bordelon, McAllister, and Holloway 2000). However, state lands account for only 5% of the forestland in western Oregon. Private lands, which comprise about 45% of the western Oregon forest base, have almost no remaining old-growth. These lands are regulated under the Oregon Forest Practices Act which contributes indirectly to old-growth forest development by restricting timber harvest in streamside buffers, but the extent of area affected is small. If appropriately managed, private lands could play an increasing role in meeting regional conservation objectives.

The following sections describe components of the resource data and model that are specific to the study area—private forest land in western Oregon (Figure 1).

Forest Inventory Data

Data describing forest inventory stand types, n in equations [A1]–[A7], for private forest land in western Oregon were obtained from the most recent forest inventory compiled by the USDA Forest Service Forest Inventory and Analysis unit (Azuma et al. 2002). There are 1,260 forest inventory stand types based on homogeneity of forest attributes, each representing about 5,000 acres on average. These units represent a wide range of site attributes such as site productivity, elevation, ecological region, location by county, proximity to streams, and slope, as well as current stand conditions, including the number of trees and tree height, diameter, age, and species.

Old-Forest Structure

The old-forest structural (OFS) criteria used to determine if forest inventory stand type n assigned to management prescription j meets structural criteria for old growth in time period t ($y_{njt} = 1$ in equation [A7]) were based on standards developed by the Oregon Department of Forestry.[3] These structural class definitions were developed to serve as guidelines for managing structurally diverse forests and to assess accomplishment of sustainability objectives based on the "Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests" (Montreal Process Working Group 2004). The specific criteria used in this study were those for the "old-forest structure" class[4] which requires that stands have: (1) at least two cohorts or distinct canopy layers; (2) at least eight live trees per acre with diameter at breast height exceeding 32 inches; and (3) at least six standing dead trees per acre, with diameter

[3] Definitions of forest stand structure classes for managed forests were derived from the State Forest Management Plan (Oregon Department of Forestry 2001).

[4] Sound down logs on the ground are also thought to be important components of the old-growth Douglas-fir ecosystem. Models that predict downed log generation are unavailable at this time. But we note that if it were necessary to leave harvested trees to meet these additional criteria, the cost of old-forest structural management would be somewhat higher than we estimate.

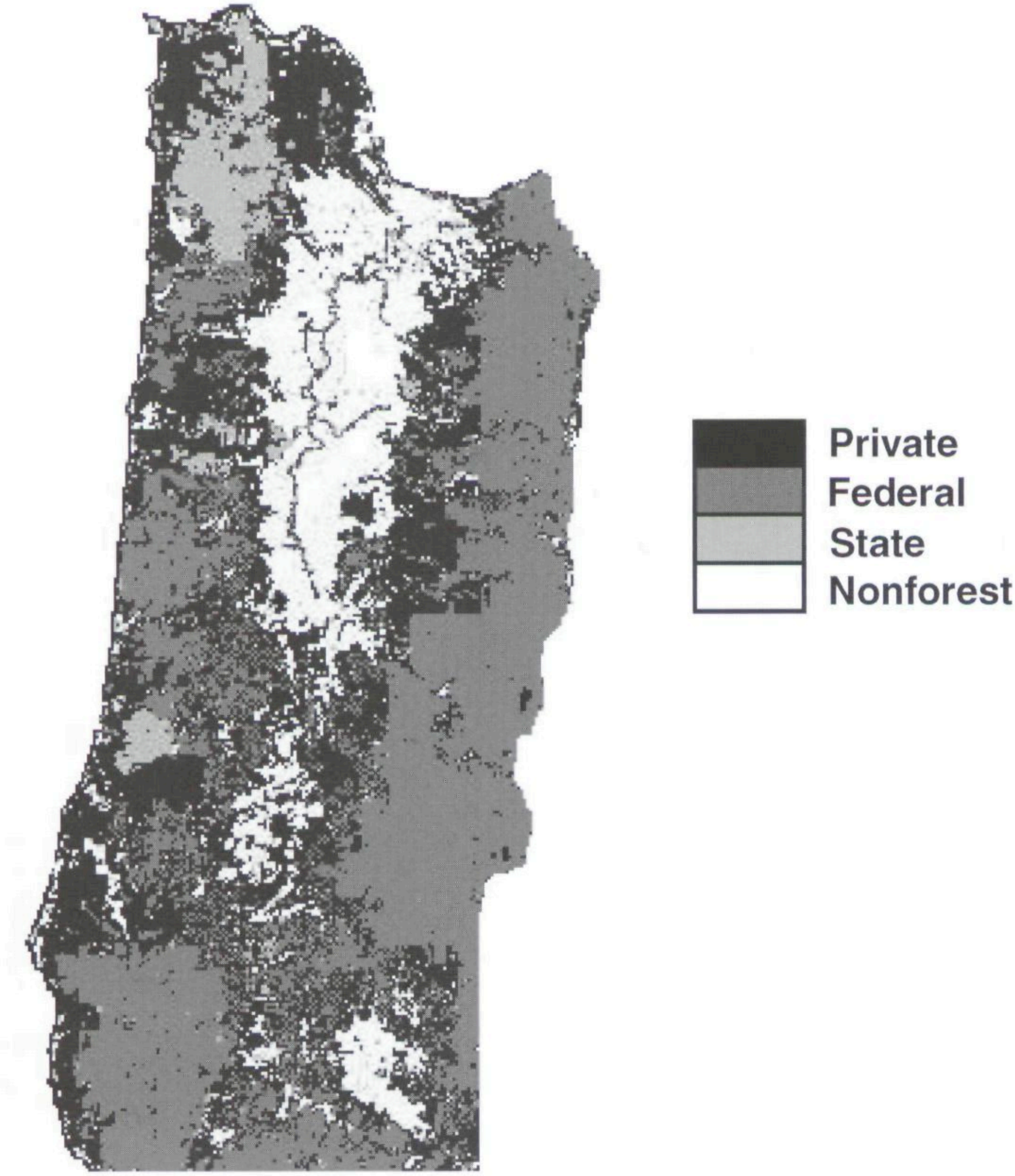

FIGURE 1
MAP OF WESTERN OREGON SHOWING OWNERSHIP OF FORESTED AREA

at breast height exceeding 12 inches of which at least two must exceed 24 inches.

Forest Management Prescriptions

A forest management prescription, subscript j in equations [A1]–[A7], is a time series of silvicultural activities (e.g., planting, thinning, final harvest, and so on) to be applied to a site over the planning time horizon. It consists of a series of activities for the existing stand and, if that involves clearcut timber harvest, for subsequently regenerated stands as well. Four types of management prescriptions were developed for each inventory stand type: (1) commercial timber management, (2) structural old forest management, (3) uneven-aged management (for streamside buffers), and (4) reserve (no timber management activities allowed). The development of prescriptions for the first two types of management is reported in Latta and Montgomery (2004) and described briefly here (further details are in the Appendix).

Commercial management prescriptions were found by an optimizing search procedure that found the combination of management actions (including thinning frequency, intensity, and timing) and harvest age that maximized the present value of future net returns. For newly planted stands, this is the prescription of maximum soil expectation value (SEV_n in Appendix equation [A8]). For stands that exist at the start of the projection, it is the prescription of maximum land and timber value (LTV_n in Appendix equation [A9]). Prescriptions to produce structural old forests were found in a similar fashion, except that OFS criteria must be met by the stand for at least 30 years prior to the clearcut harvest age (Appendix equation [A10]). For commercial management, this process found that no more than one commercial thinning was optimal in all cases. For structural old-forest management, in contrast, the optimization typically prescribed repeated thinning with relatively high volume removals to encourage development of large trees. For example, the algorithm almost always (97.5%) prescribed three thinnings for regenerated stands, occurring, on average, every 20 years, beginning at age 40 and removing, on average, 63%, 56%, and 40% of the standing volume. The old-forest structural management prescriptions for existing stands were quite variable because of the wide range of existing stand conditions.

The management prescription for reserves was to do nothing. Prescriptions for uneven-aged management were included in the model to satisfy riparian zone management restrictions under the Oregon Forest Practices Act. These were not optimized but were developed to maintain a steady residual volume stocking per acre with periodic volume removals of 15%, 33%, or 50%.

IV. RESULTS

The results of the analysis are reported in Table 1 and Figure 2. They include opportunity cost estimates, distribution of the cost burden, timber harvest impacts, and cost relative to the natural-processes fixed reserves approach.

Opportunity Cost Estimates

In the base case, the percentage area target, α, was set to zero to represent unconstrained commercial timber production. The opportunity cost of meeting a particular regional area target by a specified time limit, τ, was estimated by the change in the objective function value, Equation [A1], from the base case when the constraint, Equation [A7], is imposed. Opportunity cost estimates are shown in Table 1 for three levels of the time limit: τ = 120 years, 95 years, and 70 years (so that OFS area targets must be met by 2122, 2097, and 2072 respectively and sustained until the end of the planning horizon in 2157) and for each of three levels of the OFS area target: α = 20%, 40%, and 60%. Note that the area target α = 60% could not be met by the shortest time limit τ = 70 years. These estimates are suggestive of increasing marginal cost both for increasing the area target, α, and for decreasing the time limit, τ. For example, for τ = 95 years, increasing the area target by 20 percentage points (from 20% to 40%) costs $611 million, while increasing it 20 more points (from 40% to 60%) costs $1,279 million. As the area target increases, more highly valued timberland must be allocated to old-forest structural management. Likewise, at α = 40%, decreasing the time limit by 25 years (from 120 to 95 years) costs $641 million, while decreasing it 25 more years (from 95 to 70 years) costs $3796 million. Postponing a cost reduces its present value and shorten-

TABLE 1

OPPORTUNITY COST ESTIMATES FOR OLD FOREST STRUCTURAL MANAGEMENT FOR TIME LIMITS τ = 120 YEARS, τ = 95 YEARS, AND τ = 70 YEARS AND PERCENTAGE AREA TARGETS α = 20%, α = 40%, AND α = 60% DISAGGREGATED BY WOOD PROCESSORS, LANDOWNERS THAT UNDERTAKE OFS MANAGEMENT, AND LANDOWNERS THAT DO NOT, AND OPPORTUNITY COST ESTIMATES FOR NATURAL-PROCESSES FIXED RESERVES (COSTS ARE NEGATIVE, WINDFALL GAINS ARE POSITIVE)

Cost in Million \$ 1992 (as Percentage of Total Cost)	τ = 120 Years			τ = 95 Years			τ = 70 years	
	α = 20%	α = 40%	α = 60%	α = 20%	α = 40%	α = 60%	α = 20%	α = 40%
Total opportunity cost	−69	−224	−504	−254	−865	−2,144	−1,358	−4,661
Cost to wood processors	−64 (93%)	−170 (76%)	−280 (56%)	−171 (67%)	−383 (44%)	−959 (45%)	−765 (56%)	−2,575 (55%)
Cost to landowners	−5 (7%)	−54 (24%)	−224 (44%)	−83 (33%)	−482 (56%)	−1,185 (55%)	−593 (44%)	−2,085 (45%)
Cost on OFS-managed land	−36 (52%)	−116 (52%)	−257 (51%)	−146 (57%)	−520 (60%)	−1,171 (55%)	−713 (53%)	−2,302 (49%)
Cost on commercially managed land	31 (45%)	62 (28%)	33 (7%)	62 (25%)	38 (4%)	−14 (1%)	120 (9%)	217 (5%)
Natural-process fixed reserves total opportunity cost	−3,089	—	—	−4,426	—	—	−6,481	—

ing the time limit requires allocating existing stands (which may already hold large trees) and higher quality sites (on which trees grow faster) to old forest structural management. In fact, high quality sites, which are also relatively high opportunity cost sites due to their value in timber production, tend to be preferred for OFS management in all of the model solutions except for the longest time limits. This is because the attributes that make them valuable for timber production (the ability to grow large trees quickly) also make them valuable for their contribution to meeting OFS targets.

Distribution of Cost Burden

The opportunity costs of achieving OFS targets shown in Table 1 are borne jointly by timber landowners and wood processors in western Oregon. It is important for conservation policymakers to see how cost is distributed across these groups to identify who will pay the cost of conservation and who may profit. Cost estimates can also be used to estimate the minimum payments required to induce landowners to undertake conservation voluntarily or to compensate landowners whose property value is reduced by conservation regulations.[5] In Table 1, the total opportunity cost is disaggregated into the costs borne by (1) wood processors, (2) owners of land allocated to old forest structural management, and (3) owners of land kept in commercial timber production.

Log prices average 1% to 8% higher than in the base case across the scenarios, with the highest price increases (up to 20%) occurring in periods near the time limit. In the less constrained scenarios (low area target and/or long time limit), landowners that keep their land in commercial timber production are able to shift the timing of harvest to benefit from these higher prices and, hence, they receive a

[5] For example, in a 2004 referendum, Oregon voters approved a ballot measure (B.M. 37) that required state and local governments to provide compensation to landowners whose property was devalued as a result of changes to state or local land use laws or to waive the regulation.

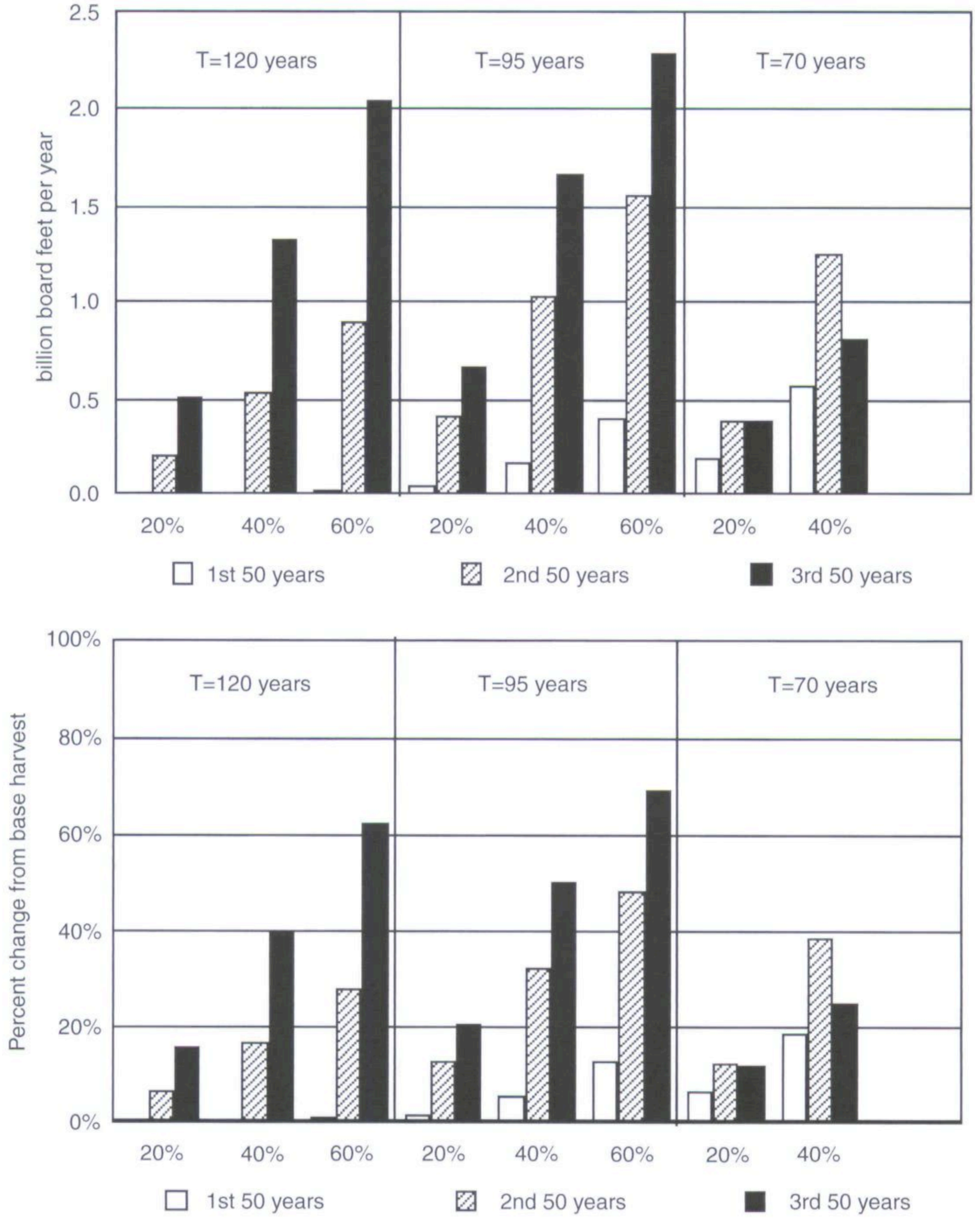

FIGURE 2
AVERAGE CHANGE IN ANNUAL TIMBER HARVEST, IN MILLION BOARD FEET AND IN PERCENTAGE OF AVERAGE ANNUAL TIMBER HARVEST FROM BASE CASE LEVELS, FOR THE FIRST, SECOND, AND FINAL 50 YEARS OF THE PLANNING HORIZON FOR AREA TARGETS $\alpha = 20\%$, $\alpha = 40\%$, AND $\alpha = 60\%$ AND TIME LIMITS $\tau = 120$ YEARS, $\tau = 95$ YEARS, AND $\tau = 70$ YEARS

windfall gain at the expense of wood processors. Private timber landowners in the region benefited in a similar way from log price increases in the 1990s resulting from federal timber harvest reductions for conservation of the northern spotted owl. In the more constrained scenarios (high α, low τ), there are large changes in the log supply from lands allocated to old forest structural management. These changes affect the trajectory of timber harvest from land in commercial timber production in such a way that the windfall gain is largely dissipated and the burden on wood processors is reduced as a percentage of total cost (although it is larger in absolute terms in some cases).

The price increase is insufficient to compensate landowners who undertake old-forest structural management for the reduction in timber harvest from those lands. These landowners bear 50% to 60% of the cost across scenarios. An incentive program to induce voluntary old-forest structural management would cost at least as much as the cost burden for this group (probably more because each individual landowner would see the higher log prices associated with regional OFS targets as the basis for valuing forgone timber harvest).

Timber Harvest Impacts

In Figure 2, annual timber harvest reductions are shown for three levels of the area target, $\alpha = 20\%$, 40%, and 60%, and three levels of the time limit, $\tau = 120$ years, $\tau = 95$ years, and $\tau = 70$ years (again, except $\alpha = 60\%$ and $\tau = 70$ years). Timber harvest reductions are shown as averages over the first, second, and third 50-year periods of the time horizon both in absolute values (billion board feet per year) and in relative values (percentage of average annual timber harvest in the base case, $\alpha = 0$).

With the longest time limit ($\tau = 120$ years), the percentage reduction in timber harvest is roughly equal to the percent area target in the long run. With $\tau = 95$ years, the percentage reduction in timber harvest exceeds the percentage area target because larger areas of high site quality land must be allocated to meet the structural old-forest target 25 years earlier.

With the shortest time limit ($\tau = 70$ years) in the 20% and 40% scenarios, the effect of geographic shifting of old-forest areas can be seen. The biggest reduction in timber harvest occurs in the second 50 years when the targets must first be met. Then, as additional sites achieve the OFS criteria, some of the initial areas can be harvested, and the reduction in timber harvest becomes smaller. Fully 25% of the area that contributes to meeting OFS targets when the time limit first comes into effect is harvested by the end of the time horizon.[6]

Comparison to Natural-Processes Fixed Reserves

In Table 1, we also report opportunity cost estimates for achieving regional OFS targets using natural-processes fixed reserves. To obtain these estimates, we imposed constraint [A7] on the regional log market model, as before, but removed the old-forest structural management prescriptions from the model, requiring that OFS criteria be met only by reserving forest area and letting it develop naturally. Within the time frames considered, it was only possible to achieve area targets of 20% without allowing thinning to stimulate tree growth. The reserve approach did, indeed, prove much more costly than structural management because: (1) no thinning revenue is generated from reserved areas, and (2) large areas of the most productive sites must be reserved since they are the only ones that can grow trees fast enough to

[6] Caution should be used in interpreting timber harvest behavior in the last periods of the model. Although the value of the ending inventory was computed using an assumption of management in the post-projection period that is roughly similar to that within the time horizon of the simulation, there are some differences (e.g., even-flow timber harvest in the post-projection period) that may have some effect on behavior in the last periods of the model.

meet the criteria within the time limits. The reserve approach is the status quo approach to old-growth forest restoration in the region of the Pacific Northwest, but has been primarily implemented on public land.

VI. CONCLUSION

Policymakers increasingly recognize sustainable forest management as a compelling policy objective. The structural composition of forests, indicated by the extent of area covered by different forest types and successional stages, is one important measure of sustainability identified in the "Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests" (Montreal Process Working Group 2004). Of particular global concern is the diminishing extent of old or indigenous forest area. Cost-effective strategies for its restoration are desirable because they minimize the impact on other forest uses.

The analysis developed in this study illustrates a method for identifying cost-effective strategies that achieve regional goals for restoration of forest with old-forest structural attributes. Knowledge of the attributes of the forest stand types that are selected for old-forest structural management by the model (such as site quality, slope, elevation, current stand age and stocking, and ecological region) can help policymakers focus conservation effort where it will be most efficient. This information can easily be extracted from the model solutions (summaries can be obtained from the authors). We found, for instance, that in the case study area, it is not generally cost-effective to allocate stand types to OFS management on the basis of stand-level opportunity cost estimates. In the intertemporal and regional context of this study, high-productivity sites were preferred for OFS management, all else constant, because they contribute to OFS objectives relatively quickly thus reducing the overall cost, even though the opportunity cost of forgone timber production on these sites is relatively high.

The analysis also provides a means for quantifying tradeoffs associated with achieving such goals. For example, we estimated the aggregate cost to forest landowners and wood processors of achieving old forest structure on 20% of the private forest land in western Oregon in 95 years to be $254 million. That is roughly equivalent to an aggregate perpetual annuity of $15 million per year (using a real discount rate of 6%), a one-time payment of $96 per adult Oregonian (at least 18 years old in 2003), or a perpetual annuity of $5.80 per adult Oregonian (ignoring population growth). Likewise, we estimated that compensating the landowners who contribute to that target would cost at least $146 million, roughly $114 per acre allocated to old forest structural management.

The forests that will result from the structural management approach modeled in this study are likely to be imperfect substitutes for the old-growth forests of the past. An old-growth forest is a complex system that is neither fully understood nor fully replicable. A forest that develops through natural processes over a long time will be subject to a wide array of disturbances and, hence, be more diverse, in terms of patch sizes, openings, species composition, tree sizes, and so on, than a forest in which the disturbances are planned (e.g., timber harvest, thinning, planting). Furthermore, there may be existence values associated with maintaining forest that is undisturbed by human extractive processes. Hence, when a forest is managed for structural attributes, a nonconvexity of the sort described in Boscolo and Vincent (2003) could arise in which there is a discrete change in amenity services once timber management activities occur. For these reasons, the opportunity cost estimates reported in Table 1 should not be interpreted as different costs of natural-processes fixed reserves for achieving the same outcome—in which case, structural management would clearly be superior—but rather as an attempt to frame the question of whether the perceived additional benefit associated with naturally developing old-growth forests warrants the additional cost.

In this study, we evaluate trade-offs and identify cost-effective strategies for achieving given goals, but we do not attempt to determine which goal is best. Addressing optimality would require valuation of the benefits of forests with old forest structure. There have been several studies that attempt to measure some aspect of value of either old-growth forest or structural attributes associated with it. For example, studies that measure recreational use value of forest attributes include Englin and Mendelsohn (1991) and Hanley and Ruffell (1993). Hagen, Vincent, and Welle (1992) used contingent valuation to measure the value of old-growth forest as habitat for the endangered northern spotted owl. Loomis and Gonzalez-Caban (1998) and Gregory (2000) used contingent valuation and conjoint analysis to measure willingness to pay to protect old-growth forest from fire. Studies that measure willingness to pay for improved visual attributes through deviating from standard commercial forest management practices include Van Rensburg et al. (2002) and Mattson and Li (1994). The studies that are most relevant to our analysis attempt to measure willingness to pay for deviations from standard commercial forest management practices that enhance biodiversity or improve ecosystem services. These include Boyle et al. (2001), who estimate compensating variation between \$900 and \$2,800 per person (1997 dollars), roughly \$54 to \$168 per year, for "more benign forest practices" on a 23,000-acre parcel, and Garrod and Willis (1997) who estimate annual willingness to pay £6 to £11 (\$9 to \$17 in 1995 dollars) for 20% of their study area to be managed to enhance biodiversity while producing timber. While the benefits measured in these studies are only very roughly comparable to the benefits provided by OFS management, these studies are suggestive of the possibility that OFS management may improve efficiency.

Some question the usefulness of monetary valuation of old-growth forest because the ultimate justification for its preservation or restoration may be ethical rather than utilitarian (Booth 1997). Nonetheless, the opportunity cost analysis demonstrated in this paper is useful for several reasons. First, it can help identify cases in which old-growth preservation or restoration may clearly be justified, without resort to ethical debate, because the cost is low. It can help policymakers compare different conservation goals on the basis of relative cost. For example, we may not know the "right" area target to aim for, but it may be possible to judge whether doubling the area target from 20% to 40% is worth tripling the cost. And, finally, it can help forest managers identify cost-effective strategies for achieving whatever target is ultimately selected. This is important because management for old forest structure reduces income for the landowners that undertake it and reduces the supply of wood products to consumers. Conservation strategies that minimize these impacts will be preferred over strategies that are perceived as ineffective and wasteful by a society that values both wood and conservation.

APPENDIX

MARKET MODEL

Let X_{nj} be the area in acres of forest stand type n assigned to management prescription j. A stand type is a combination of stand age, site conditions, and structural characteristics. A management prescription is a time series of management activities to be applied to a site over the planning time horizon, $t = 0, \ldots, T-1$. A prescription might include, for example, a set of actions designed to lead to structurally old forest. The model chooses three control variables so as to maximize the sum of discounted consumer plus producer surplus in the log market: (1) X_{nj}, for $n = 1, \ldots, N$ and $j = 1, \ldots, J$, (2) investment in capital stock, I_t, for $t = 0, \ldots, T-1$; and (3) $\overline{A}$, the average timber harvest age used in the post-projection period.

$$\max_{X_{nj}, I_t, \overline{A}} \sum_{t=0}^{T-1} \left(\frac{\int_{q=0}^{Q_t} P_t(q, K_t)dq - k_m K_t - k_u I_t - \sum_{n=1}^{N} \sum_{j=1}^{J} c_{njt} X_{nj}}{(1+r)^t} \right) + \frac{v \int_{q=0}^{Q_T} P_T(q, K_T)dq - c_T Q_T}{r(1+r)^T} \quad \text{[A1]}$$

subject to:

$$Q_t = \sum_{n=1}^{N}\sum_{j=1}^{J} f_{njt}X_{nj} + M_t \quad \text{[A2]}$$

$$K_{t+1} = K_t(1-\delta) + I_{t+1} \quad \forall t \quad \text{[A3]}$$

$$\lambda K_t \geq Q_t \quad \forall t \quad \text{[A4]}$$

$$Q_T = \sum_{n=1}^{N}\sum_{j=1}^{J} 2F_{nj}X_{nj}/\overline{A} + M_T \quad \text{[A5]}$$

$$\sum_{j=1}^{J} X_{nj} = Z_n \quad \forall n \quad \text{[A6]}$$

$$\sum_{n=1}^{N}\sum_{j=1}^{J} y_{njt}X_{nj} \geq \alpha \sum_{n=1}^{N} Z_n \quad \forall t \geq \tau \quad \text{[A7]}$$

where:

Q_t is the total volume of logs delivered to mills in time period t.

M_t is net import and public timber harvest log volume in time period t.

f_{njt} is per acre log volume produced from stand type n assigned to management prescription j in time period t.

$P_t(q,K_t)$ is derived demand for logs in time period t; in this study, derived demand price is a linear function of quantity and current capacity (and other exogenous variables not explicitly shown in the notation).

K_t is the quantity of capital stock in time period t measured as maximum log processing capacity.

I_t is quantity of capital stock, K_t, purchased in time period t.

k_m is the per unit cost of maintaining capital stock.

k_u is the per unit cost of purchasing capital stock.

λ is the maximum capital stock utilization rate.

δ is depreciation rate of capital stock.

c_{njt} is the cost per acre for stand treatments, timber harvest, and log transport for stand type n assigned to management prescription j in time period t.

r is the real discount rate.

Q_T is average annual volume of logs delivered to mills in the post-projection period.

F_{nj} is per acre volume of standing timber on stand type n assigned to management prescription j at the beginning of the post-projection period.

$\overline{A}$ is the average timber harvest age used to compute average annual harvest in the post-projection period.

M_T is average annual net imports in post-projection period.

c_T in average annual cost for harvest, silvicultural treatments and log transport in the post-projection period.

Z_n is the area of forest inventory stand type n.

y_{njt} is a binary (0,1) variable such that y_{ijt} = 1 if forest in forest inventory stand type n assigned to management prescription j meets structural criteria for old growth in time period t.

α is the target percentage area for forest area that meets structural criteria for old growth.

τ is the target time period by which percentage area targets must be met and sustained until $t = T$.

In the western Oregon application, we employed a time horizon of $T = 155$ years, beginning in 2002, with 31 five-year decision periods. The forest inventory stand types, n, were defined from forest inventory data on the basis of existing stand and site attributes. A linear derived demand equation for softwood logs, $P_t(q, K_t)$, was estimated from annual data from 1970 to 1998. Details are given in Adams et al. (2002) and Schillinger et al. (2003) along with assumptions about public timber harvest levels and net imports from other regions, M_t in equation [A5]. Projections of all exogenous demand variables (lumber price, plywood price, labor wage, and time trend) are based on the USDA Forest Service RPA Timber Assessment (Haynes 2003). Under the base case RPA scenario, these variables were roughly constant. Final harvest costs were computed as a function of average stand diameter, per acre volume, and slope based on equations developed by the Oregon Department of Forestry; thinning costs were computed in the same way but 10% higher than final harvest costs (Fight, LeDoux, and Ortman 1984; Lettman 2001). Stand treatment costs are mid-range values based on data from Oregon State University Forestry Extension (Rose and Jacobs 1999) and Oregon Department of Forestry. All market model projections assume a 6% real discount rate. This model simulates private landowner and wood processor behavior in the log market for the purpose of estimating opportunity cost of OFS for these owners. When Adams et al. (2002) performed market model simulations using a range of discount rates, they found that a 6% rate generated forest land value estimates that most closely approximated observed values. A lower discount rate might be more appropriate for social cost benefit analysis. We expect that a lower rate would lead to longer rotation ages for commercial prescriptions and, hence, a smaller difference between OFS and commercial timber management and harvest volumes.

The model as written is an optimal control problem with control variables X_{nj}, I_t and $\overline{A}$. In the discrete time form it was solved as a linear program, formulated in GAMS, using the CPLEX optimizer (Brooke et al. 2003). Although the area under the derived demand for logs curve is nonlinear, we used a piece-wise linearization approach that allowed the model to be structured as a linear program. Investment in capital stock, I_t, and average rotation age in the post-projection period, $\overline{A}$, were determined by iterating solutions in a Gauss-Seidel fashion until all endogenous variables had stabilized within a small tolerance.

Stand Management Prescriptions

Stand management prescriptions were identified using a simple random heuristic search algorithm similar to Bullard, Sherali, and Klemperer (1985) to search for the management prescription, j, that defines the sequence of activities that occur at ages a in the life of stand type n. For regenerated stands the process maximizes soil expectation value, SEV_n:

$$\max_j SEV_n = \frac{\sum_{a=0}^{A_j} (pf_{nja} - c_{nja})(1+r)^{A_j - a}}{(1+r)^{A_j} - 1} \qquad \text{[A8]}$$

and, for existing stands, land and timber value, LTV_n,

$$\max_j LTV_n = \frac{\sum_{a=a^0}^{A_j} (pf_{nja} - c_{nja})(1+r)^{A_j - a} + SEV_n}{(1+r)^{A_j - a^0}} \qquad \text{[A9]}$$

subject to:

$$y_{nja} = 1 \quad \forall a \geq A_j - 30 \qquad \text{[A10]}$$

where:

- A_j is the final clearcut harvest age.
- a^0 is the current age of the existing stand.
- p is log price.
- f_{nja} is the per acre harvest volume harvested at age a from stand type n assigned to management prescription j.
- c_{nja} is cost of harvest, transport, and treatment applied at age a for stand type n assigned to management prescription j.
- r is the annual real discount rate.
- y_{nja} is a binary (0,1) variable such that $y_{nja} = 1$ if stand type n assigned to management prescription j meets structural criteria for old growth at age a.

Equations [A8] and [A9] find optimal commercial even-age management prescriptions. To find optimal old forest management prescriptions, maximizations in [A8] and [A9] were constrained to meet OFS criteria for at least 30 years prior to clearcut harvest (constraint [A10]). For both types of management, regeneration stand regimes from equation [A8] were found first (constrained by OFS management in at least the last 30 years, if appropriate). The SEV_n thus identified was then used in equation [A9] for existing stands. In order to allow some flexibility in the timing of OFS management, we attempted to solve the models for three time limits: 35 years, 65 years, and 120 years. However, the algorithm was unable to identify prescriptions for the shorter time limits for several of the stand types.

Decision variables in the optimizations included the timing (between ages 20 and 110 years) and intensity (between 10% to 70% volume removal) of up to 3 commercial thinnings. The individual tree simulation model ORGANON (Hann, Hester, and Olsen 1997) was used in combination with a model of standing dead tree deterioration adapted from Cline (1977) and Graham (1981) to project individual tree heights, diameters, mortality, and volume of standing deadwood in order to evaluate OFS criteria and estimate harvest volumes. Timber harvest, log transport, and stand treatment costs and log prices were in 1992 dollars. Log prices, exogenous in this stand-level model, were constant at the average log price projected in a recent western Oregon timber supply study (Schillinger et al. 2003).

References

Adams, D., R. A. Schillinger, G. Latta, and A. Van Nalts. 2002. "Timber Harvest Projections for

Private Land in Western Oregon." Forest Research Laboratory Research Contribution 37. Corvallis, Ore.: Oregon State University, College of Forestry. http://fcg.cof.orst.edu/rc/rc37.pdf.

Alaouze, C. M. 2004. "The Effect of Conservation Value on the Optimal Forest Rotation." *Land Economics* 80 (May): 209–23.

Azuma, D. L., P. A. Dunham, B. A. Hiserote, and C. F. Veneklase. 2002. "Timber Resource Statistics for Western Oregon, 1999." Resource Bulletin PNW-RB-238. Portland, Ore.: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Booth, D. E. 1991. "Estimating Prelogging Old-Growth in the Pacific Northwest." *Journal of Forestry* 89 (1): 25–29.

———. 1997. "Preserving Old-Growth Forest Ecosystems: Valuation and Policy." *Environmental Values* 6 (1): 31–48.

Bordelon, M. A., D. C. McAllister, and R. Holloway. 2000. "Sustainable Forestry Oregon Style." *Journal of Forestry* 98 (1): 26–34.

Boscolo, M., and J. R. Vincent. 2003. "Nonconvexities in the Production of Timber, Biodiversity, and Carbon Sequestration." *Journal of Environmental Economics and Management* 46 (2): 251–68.

Boyle, K. J., T. P. Holmes, M. F. Teisl, and B. Roe. 2001. "A Comparison of Conjoint Analysis Response Formats." *American Journal of Agricultural Economics* 83 (2): 441–54.

Brooke, A., D. Kendrick, A. Meeraus, and R. Raman. 2003. *GAMS: A User's Guide.* Washington, D.C.: GAMS Development Corp. http://www.gams.com/docs/gams/GAMSUsersGuide.pdf.

Bullard, S. H., H. D. Sherali, and W. D. Klemperer. 1985. "Estimating Optimal Thinning and Rotation for Mixed-Species Timber Stands Using a Random Search Algorithm." *Forest Science* 31 (2): 303–15.

Buongiorno, J., S. Dahir, H. C. Lu, and C. R. Lin. 1994. "Tree Size Diversity and Economic Returns in Uneven-aged Forest Stands." *Forest Science* 40 (1): 83–103.

Carey, A. B., and R. O. Curtis. 1996. "Conservation of Biodiversity: A Useful Paradigm for Forest Ecosystem Management." *Wildlife Society Bulletin* 24 (4): 610–20.

Carey, A. B., B. R. Lippke, and J. Sessions. 1999. "Intentional Systems Management: Managing Forests for Biodiversity." *Journal of Sustainable Forestry* 9 (3/4): 83–125.

Cline, S.P. 1977. "The Characteristics and Dynamics of Snags in Douglas-fir Forests of the Oregon Coast Range." Master's thesis, Department of Forest Resources, Oregon State University.

Conrad, J., and D. Ludwig. 1994. "Forest Land Policy: The Optimal Stock of Old-Growth Forest." *Natural Resource Modeling* 8 (1): 27–45.

Davis, L. S., and K. N. Johnson. 1987. *Forest Management.* New York: McGraw Hill.

Englin, J., and R. Mendelsohn. 1991. "A Hedonic Travel Cost Analysis for Valuation of Multiple Components of Site Quality: the Recreation Value of Forest Management." *Journal of Environmental Economics and Management* 21 (3): 275–90.

Er, K. B. H., and J. L. Innes. 2003. "The Presence of Old-Growth Characteristics as a Criterion for Identifying Temperate Forests of High Conservation Value." *International Forestry Review* 5 (1): 1–8.

Fight, R. D., C. B. LeDoux, and T. L. Ortman. 1984. "Logging Costs for Management Planning for Young-growth Coast Douglas-fir." General Technical Report PNW-176. Portland, Ore.: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Franklin, J. F., K. Cromack Jr., W. Denison, C. Maser, J. Sedell, J. Swanson, and G. Juday. 1981. "Ecological Attributes of Old-Growth Douglas-fir Forests." General Technical Report PNW-GTR-118. Portland, Ore.: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Garrod, G. D., and K. G. Willis. 1997. "The Non-use Benefits of Enhancing Forest Biodiversity: a Contingent Ranking Study." *Ecological Economics* 21 (1): 45–61.

Graham, R. L. L. 1981. "Biomass Dynamics of Dead Douglas-fir and Western Hemlock Boles in Mid-Elevation Forests of the Cascade Range." Ph.D. dissertation, Oregon State University.

Gregory, R. S. 2000. "Valuing Environmental Policy Options: a Case Study Comparison of Multiattribute and Contingent Valuation Survey Methods." *Land Economics* 76 (May): 151–73.

Hagen, D. A., J. W. Vincent, and P. G. Welle. 1992. "Benefits of Preserving Old-Growth Forests and the Spotted Owl." *Contemporary Policy Issues* 10 (1): 13–25.

Hanley, N. D., and R. J. Ruffell. 1993. "The Contingent Valuation of Forest Characteristics: Two Experiments." *Journal of Agricultural Economics* 44 (2): 218–29.

Hann, D. W., A. S. Hester, and C. L. Olsen. 1997. *ORGANON User's Manual: Edition 6.0.* Corvallis, Ore.: Department of Forest Resources, Oregon State University. http://www.cof.orst.edu/cof/fr/research/organon/.

Hartman, R. 1976. "The Harvesting Decision When a Standing Forest Has Value." *Economic Inquiry* 14 (1): 52–58.

Haynes, R. W. (tech. coordinator). 2003. "An Analysis of the Timber Situation in the United States: 1952 to 2050." General Technical Report PNW-GTR-560. Portland, Ore.: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Helms, J. A. 2004. "Old-Growth: What Is It?" *Journal of Forestry* 102 (3): 8–12.

Kant, S. 2002. "The Marginal Cost of Structural Diversity of Mixed Uneven-Aged Hardwood Maple Forests." *Canadian Journal of Forest Research* 32: 616–28.

Latta, G., and C. A. Montgomery. 2004. "Minimizing the Cost of Stand Level Management for Older Forest Structure in Western Oregon." *Western Journal of Applied Forestry* 19 (4): 221–31.

Lettmann, Gary. 2001. Personal communication. Oregon Department of Forestry. February 8, 2001.

Lichtenstein, M. E., and C. A. Montgomery. 2003. "Biodiversity and Timber in the Coast Range of Oregon: Inside the Production Possibility Frontier." *Land Economics* 79 (Feb.): 56–73.

Loomis, J. B., and A. Gonzalez-Caban. 1998. "A Willingness to Pay Function for Protecting Acres of Spotted Owl Habitat from Fire." *Ecological Economics* 25 (3): 315–22.

Mattson, L., and C. Li. 1994. "How Do Different Forest Management Practices Affect the Nontimber Value of Forests? An Economic Analysis." *Journal of Environmental Management* 41 (1): 79–88.

Montgomery, C. A., and D. M. Adams. 1995. "Optimal Timber Management Policies." In *The Handbook of Environmental Economics*, ed. D. W. Bromley. 379–404. Oxford, U.K.: Basil Blackwell, Ltd.

Montreal Process Working Group. 2004. http://www.mpci.org/ (accessed in August 2004).

Nalle, D. J., C. A. Montgomery, J. L. Arthur, N. H. Schumaker, and S. Polasky. 2004. "Modeling Joint Production of Wildlife and Timber in Forests." *Journal of Environmental Economics and Management* 48 (3): 997–1017.

Öhman, K. 2000. "Creating Continuous Areas of Old Forest in Long Term Forest Planning." *Canadian Journal of Forest Research* 30: 1817–23.

Öhman, K., and L. O. Eriksson. 1998. "The Core Area Concept in Forming Contiguous Areas for Long Term Forest Planning." *Canadian Journal of Forest Research* 28 (7): 1032–39.

Önal, H. 1997. "Trade-off between Structural Diversity and Economic Objectives in Forest Management." *American Journal of Agricultural Economics* 79 (3): 1001–12.

Oregon Department of Forestry. 2001. *Northwest Oregon State Forests Management Plan*. http://oregon.gov/odf/state_forests/nwfmp.shtml.

Plantinga, A. J., and R. A. Birdsey. 1994. "Optimal Forest Stand Management When Benefits Are Derived from Carbon." *Natural Resource Modeling* 8 (4): 373–87.

Rebain, S., and M. E. McDill. 2003. "A Mixed-Integer Formulation of the Minimum Patch Size Problem" *Forest Science* 49 (4): 608–18.

Reed, W. J., and J. J. Ye. 1994. "The Role of Stochastic Monotonicity in the Decision to Conserve or Harvest Old-Growth Forest." *Natural Resource Modeling* 8 (1): 47–79.

Rose, R., and D. Jacobs. 1999. *Guide to the Pacific Northwest Reforestation Cost Analysis Spreadsheet*. Corvallis, Ore.: Oregon State University Extension Service.

Schilllinger, R. R., D. M. Adams, G. S. Latta, and A. K. Van Nalts. 2003. "An Analysis of Future Private Timber Supply Potential in Western Oregon." *Western Journal of Applied Forestry* 18 (3): 166–74.

Sessions, J., D. Johnson, J. Ross, and B. Sharer. 2000. "The Blodgett Plan: An Active-Management Approach to Developing Mature Forest Habitat." *Journal of Forestry* 98 (12): 29–33.

Snyder, D. L., and R. N. Bhattacharyya. 1990. "A More General Dynamic Economic Model of the Optimal Rotation of Multiple-use Forests." *Journal of Environmental Economics and Management* 18 (2, part 1): 168–75.

Spies, T. A., and J. F. Franklin. 1991. "The Structure of Natural Young, Mature, and Old-Growth Douglas-fir Forests in Oregon and Washington." In *Wildlife and Vegetation of Unmanaged Douglas-Fir Forests*, ed. L. F. Ruggerio, 91–109. General Technical Report PNW-GTR-285. Portland, Ore.: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Strang, W. J. 1983. "On the Optimal Forest Harvesting Decision." *Economic Inquiry* 21 (4): 576–83.

Swallow, S. K., P. J. Parks, and D. N. Wear. 1990. "Policy-Relevant Nonconvexities in the Production of Multiple Forest Benefits." *Journal of Environmental Economics and Management* 19 (3): 264–80.

Swallow, S. K., P. Talukdar, and D. N. Wear. 1997. "Spatial and Temporal Specialization in Forest Ecosystem Management under Sole Ownership." *American Journal of Agricultural Economics* 79 (2): 311–26.

Tappeiner, J. C., D. Huffman, D. Marshall, T. A. Spies, and J. D. Bailey. 1997. "Density, Ages, and Growth Rates in Old-Growth and Young-Growth Forests in Coastal Oregon." *Canadian Journal of Forest Research* 27 (5): 638–48.

Thomas, J. W. (team leader). 1993. *Forest Ecosystem Management: an Ecological, Economic, and Social Assessment*. Document 1993-793-071. Washington, D.C: U.S. Government Printing Office.

U.S. Department of the Interior. 2005. *Overview of the Healthy Forest Initiative*. http://www.healthyforests.gov/initiative/index.html (accessed June 2005).

Van Rensburg, T. M., G. A. Mill, M. Common, and J. Lovett. 2002. "Preferences and Multiple Use Forest Management." *Ecological Economics* 43 (2–3): 231–44.

World Resource Institute. 2004. *Earth Trends*. http://earthtrends.wri.org/ (accessed June 2004).