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A hierarchical spatial framework for forest landscape planning

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Abstract

A hierarchical spatial framework for large-scale, long-term forest landscape planning is presented along with example policy analyses for a 560,000 ha area of the Oregon Coast Range. The modeling framework suggests utilizing the detail provided by satellite imagery to track forest vegetation condition and for representation of fine-scale features, such as riparian areas. Spatial data are then aggregated up to management units, where forest management decisions are simulated. Management units may also be aggregated into harvest blocks to closer emulate management behavior. Land allocations, subdivisions of landowner groups, can be used to represent different levels of management. A management unit may contain multiple land allocations, such as riparian management emphases that vary based on distance from the stream system. The management emphasis required by each land allocation is retained in the simulation of policies. When applied within a large-scale forest landscape planning context, the implications of policies that suggest clearcut size restrictions, minimum harvest ages, or the development of interior habitat areas can be assessed. Simulations indicated that the minimum harvest age constraint has a stronger influence on even-flow harvest levels than do maximum clearcut size or interior habitat area constraints. Even-flow timber harvest level objectives, however, also have an effect on the results: time periods beyond the constraining time period show a build-up of timber inventory, which suggests a possible relaxation or modification of the objective in order to achieve average harvest ages that are closer to the minimum harvest age.

Keywords: Forest management; Forest planning; Simulation; Operations research; Policy analysis; Geographic information systems

1. Introduction

The development of forest policies that both sustain social and economic values of forests and watersheds is a major challenge for policy-makers and managers. In Oregon's Coast Range (USA), for example, the mixed ownership pattern of the region and the major policies recently introduced have suggested a need for broad-scale forest landscape policy simulations. The policies

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now in effect, though, were enacted without examining simulations of likely landscape conditions and associated effects. Rather, they were based on stand-level analyses of forest management policies on individual ownerships. Policy-makers rarely examine the long-term effects of specific policies or compare policies in both a spatial and temporal context because they have historically lacked the information to do so (Gustafson and Crow, 1994). Spatial forest landscape planning models can assist policy analyses through their ability to evaluate policies at spatial and temporal scales that are otherwise difficult or impossible to accomplish (Gustafson et al., 2000).

Forest landscape planning involves the examination of forest management alternatives or policies across large areas and long time frames. What sets forest landscape planning apart from traditional forest planning, or harvest scheduling, is an emphasis on the modeling of management behavior of all landowners within a large geographic area (500,000 ha or more). The suite of planning tools available for scheduling or simulating management activities on landscapes varies from the traditional exact techniques (i.e., linear and integer programming) to the non-traditional, inexact techniques (i.e., heuristic programming and simulation). The non-traditional techniques, however, are often the only alternative for modeling very large systems, with simulation modeling frequently seen as the most appropriate method. Simulation models for forest landscapes can be developed to provide a spatial and temporal context in which policy-makers can evaluate alternatives. Simulation models, in general, are developed to capture relevant features of the dynamic nature of some "target system" under study (Birta and Özmizrak, 1996), and their reliability depends highly on how well the models reflect reality (Li et al., 1993).

A number of simulation models have been developed in the last two decades to model events or behaviors across forested landscapes. Franklin and Forman (1987) were one of the first to simulate the ecological effects of forest management activities on a landscape. Others (Flamm and Turner, 1994; Gustafson and Crow, 1994, 1996; Wallin et al., 1994; Johnson et al., 1998; Gustafson et al., 2000) have since developed simulation models for management activities or disturbances at various spatial and temporal scales within forested landscapes.

A number of limitations characterize the current suite of forest management simulation models. First, the models generally lack the integration of activities within a spatial hierarchical structure. The allocation of management activities is thus applied either to raster database pixels or to management units, with limited recognition of higher (aggregation of harvest units) or lower (heterogeneity within a management unit) scales of the system. In addition, only a few variables, such as transition probabilities or stand ages, are used to influence the allocation of management activities. Other aspects of the system, such as management intensities, or the spatial position of landscape features, may allow a model to more closely emulate actual land management processes. Further, in a number of simulation models, the spatial allocation of harvest activities utilizes random processes that are unrelated to landowner objectives. And, key landscape features, such as topography and stream networks, may be ignored.

Many natural resource information management systems contain a hierarchy of spatial data (MacMillan et al., 2004), and as with many large-scale planning efforts, the analysis process is also hierarchical, ranging from large regions with broad goals to small areas with specific operational aspects (Church et al., 2000). The smaller areas, or lower levels in the hierarchy, are generally used to provide forest structural conditions, and the larger regions are used to provide constraining conditions (Burnett and Blaschke, 2003). Each component of a hierarchy should be structured to reflect their real-world analog (Harris and Gorley, 2003). Focusing on a single scale, such pixels in a GIS database, may limit the usefulness of a model to represent complex multi-scale systems (Burnett and Blaschke, 2003). Most planning processes center on a basic unit of analysis, which can either be disaggregated into smaller components or aggregated into larger ones. Bragg et al. (2004) describe a hierarchical system for managing individual forest stands using tree-level data and stand-level goals. Burnett and Blaschke (2003) describe a landscape analysis system that utilizes patches (stands) and their topological relationships to accommodate higher-level landscape goals.

Levels of organization in a hierarchy of spatial information are typically definitional, and defined by the observer (Burnett and Blaschke, 2003) or planning team. Freemark (1995), for example, describes a biologically driven hierarchy for application in assessments of ecosystem processes on agricultural land, and Harris and Gorley (2003) describe a ecologically driven hierarchy for modeling hydrologic systems. Our model is a by-product of the need to adequately represent both the ecology of a landscape and the behavior of landowners. Our intent is not to review the basis for ecological (or socio-economical) driven hierarchies, as Wu and David (2002) have previously provided a detailed discussion of how complex systems can be hierarchically organized using hierarchy theory, and discussed the need to identify the spatial patterns that are relevant to the processes of interest. Our model involves the use of both top-down (where broad scale constraints are important) and bottom-up (where local interactions are important) approaches described in Wu and David (2002) in defining the hierarchy that is important for landscape planning in western Oregon.

In the work presented here, we try to overcome many of these problems, to facilitate a close simulation of an actual land management system and evaluate changes to management policies. Toward that end, the LAndscape Management Policy Simulator (LAMPS) (Bettinger and Lennette, 2003) was developed. Our objective here is to detail the mathematical approaches taken in LAMPS to simulate the management of private industrial and public (state governed) forest areas across a broad, heterogeneous landscape. These processes are not described in Bettinger and Lennette (2003) nor elsewhere. The mathematical approaches require a hierarchy of spatial information to represent the heterogeneous landscape as well as management behavior. We also present the results of a number of policy simulations applied to the north coastal region of the Oregon Coast Range (USA), to illustrate the utility of the model.

This research presents two advancements in the use of simulation techniques for forest landscape planning. First, it illustrates the usefulness of a large-scale spatial hierarchy for forest landscape planning. The difference between this approach and the approach described in Bettinger et al. (2003) is the emphasis here on multiple landowners and the ability to model a flexible (i.e., not delineated a priori) spatial arrangement of harvest and habitat blocks. Second, the spatial hierarchy presented here allows the modeling of over 5 million Model I variables (Johnson and Scheurman, 1977), a problem size perhaps intractable for integer programming approaches. The simulation process utilizes a forest landscape planning model that can be categorized as both models 5(b) (management models: management of natural resources), and 8(a) (models of terrestrial ecosystems: forests) of the delineation of models provided by Jørgensen (1997).

2. Methods

The major stakeholders involved in the management of public and private land in the Oregon Coast Range include the Oregon Board of Forestry (1995), Oregon Department of Forestry, U.S. Forest Service, Bureau of Land Management, several industrial timber organizations, and a small woodland owners organization. Each has the power to affect land-use decisions at a broad (e.g., Oregon Board of Forestry) or local scale. Each also, through numerous meetings, has provided input and feedback regarding the model structure described here, and the utility of the model results in informing the policy debate. The framework described below addresses the strategic and tactical objectives of the industrial and state-managed land in the Coast Range. For example, as a whole the industrial group behavior has been to produce an even-flow of timber harvest volume from the landscape, yet each industrial organization may have different tactical goals (e.g., green-up policies, leave tree retention policies). On state-managed land, we have determined that the objective is to also produce an even-flow of timber harvest volume, yet while striving to develop a landscape with certain forest structural conditions.

In modeling the behavior of these landowners, two distinct areas of concern relevant to forest landscape planning efforts are the design of the spatial framework around which the modeling occurs, and the development of the problem formulation.

2.1. Hierarchical spatial framework

Most forest planning efforts assume that the spatial framework is relatively simple: a single ownership is examined, and management units (or vegetation strata) are designed to accommodate decision variables. All forest conditions and management decisions related to the management units (or strata) are considered homogenous. The next few sections describe a hierarchical framework that builds from a small, yet recognizable land unit to the larger landscape, allowing the recognition and maintenance of vegetation conditions at a fine scale, yet facilitating the simulation of decisions at larger scales.

2.1.1. *Basic simulation units*

The decision regarding the smallest unit recognized in a modeling effort is usually made with two considerations in mind: the need to use units that adequately represent the heterogeneity of the landscape, and the need to develop a set of units that does not tax the available computer systems. In many university- or agency-sponsored large-scale landscape modeling efforts, raster databases developed from satellite imagery are the primary data structure around which logic and simulation are based. These basic simulation units generally range from 30 m (e.g., Landsat imagery) to 1.1 km (e.g., AVHRR imagery) square pixels. Most North American forestry companies, on the other hand, use a basic simulation unit consisting of irregularly shaped vector polygons, where the minimum size is 2–4 ha. Each of these structures assumes that the forest conditions in each unit are homogeneous. In the industrial case, the potential to ignore fine-scale vegetation heterogeneity is relatively high. Alternatively, if one were to use 30 m pixels as the basic simulation units for a 500,000 ha landscape, one would need to recognize over 5.5 million units, since each is approximately 0.09 ha in size. If the number of attributes that need to be tracked for each unit is large, computer memory could be taxed.

We assume here that classified Landsat satellite imagery is available for subsequent forest landscape planning and analysis. The vegetation database developed by Ohmann and Gregory (2002), as an example, might be considered a crucial part of a landscape planning process. This raster database consists of pixels that have associated with them fine-scale vegetation detail (tree lists) that describe the underlying vegetative structure. Given the potential limitations noted above of using satellite imagery, aggregating contiguous pixels of similar slope class, vegetative condition, and distance from streams can reduce the number of units recognized (Fig. 1) to a more manageable size. This process was performed using the Ohmann and Gregory (2002) database for the Coast Range of Oregon, and the resulting size of basic simulation units was 0.12 ha, reducing the number of units to be recognized to about 4.2 million in a 500,000 ha area. These basic simulation units can be viewed as Model I decision variables (Johnson and Scheurman, 1977), where the vegetation condition of each is recognized and maintained through time.

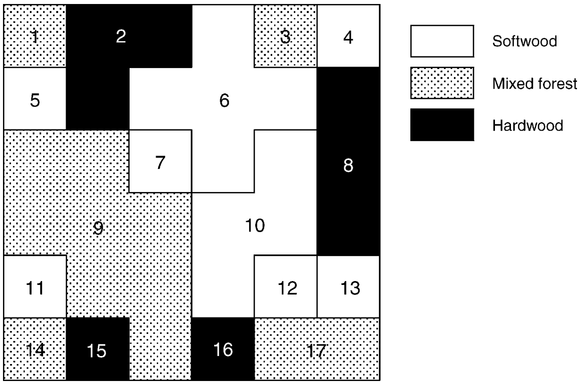

Fig. 1. Basic simulation units: aggregations of similar, contiguous raster grid cells.

2.1.2. *Management units*

While forest structural attributes may be assigned and tracked at the basic simulation unit scale, decisions regarding forest management activities are generally made at larger scales. Management units consist of areas that encompass terrain and vegetation characteristics of a size appropriate for logging systems typical of a region. Therefore, basic simulation units can be aggregated up to management units, where the resulting size is about 10–20 ha (Fig. 2). The vegetation condition of a management unit is therefore either the sum (e.g., for timber volume) or weighted average (e.g., for age) of the conditions of basic simulation units.

2.1.3. *Aggregations of management units*

In many cases, management units are aggregated for temporally simultaneous treatment. In the western U.S., contiguous management units of similar characteristics (Fig. 3) are commonly scheduled for simultaneous treatment (e.g., clearcut, thinning, etc.) due to the economy of scale of the cumulative management activities. Thus, to emulate landowner behavior, management units may need to be aggregated using a blocking process described in Bettinger and Johnson (2003) or Nelson (2001). In addition, the development of interior habitat blocks on public land requires the development of contiguous areas of certain types

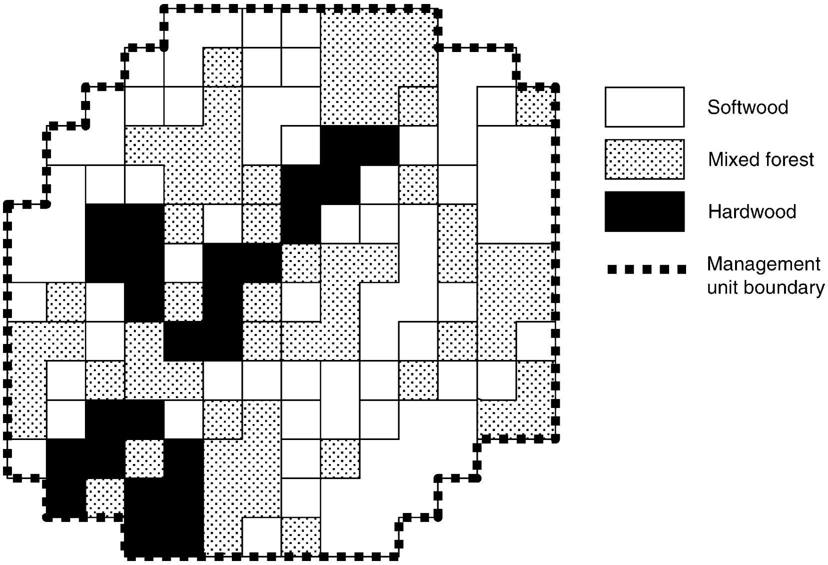

Fig. 2. Management unit: an aggregation of basic simulation units, defined by topography and dominant vegetation.

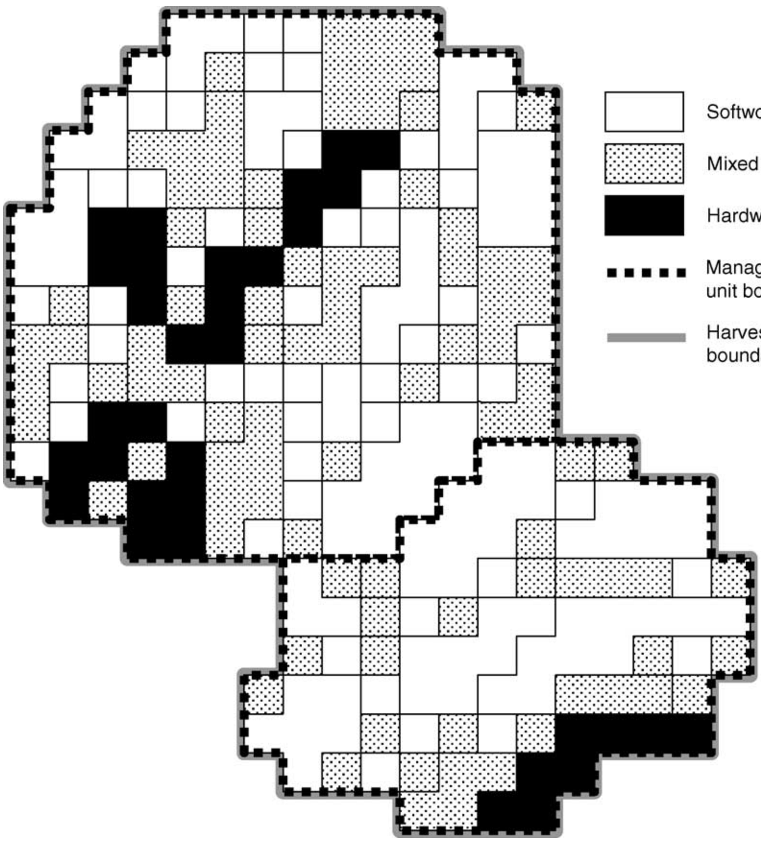

Fig. 3. Harvest blocks: aggregations of management units for simultaneous treatment.

of vegetation. Since contiguous management units may be aggregated for harvest or habitat goals, knowledge of the adjacency relationships of management units is needed.

2.1.4. Land allocations

In some cases, land ownerships are further subdivided and placed into allocations with differing emphases of management. For example, wilderness areas are generally separated from general forest management areas. Since basic simulation units are small, they have assigned to them a single land allocation in this spatial hierarchical structure. Management units, on the other hand, may include multiple land allocations. For example, areas closer to streams may require the retention of more residual leave trees than areas further away from streams, thus two (or more) land allocations may be present in a single management unit. In these cases, when a forest management activity is simulated in a management unit, the level of activity simulated may differ based on the land allocation assigned to each basic simulation unit.

2.2. Management prescriptions

The level of detail contained in management prescriptions within a forest planning effort varies from the rather general (e.g., clearcut or thin entire management units), to the complex (e.g., clearcut and leave some residual leave trees, leave undisturbed areas near the stream, etc.). To illustrate the hierarchical nature of the forest landscape planning process suggested in this research, we describe a complex system of management that closely emulates management behavior. Here, with regard to clearcutting decisions, the following aspects are incorporated into the simulation process: riparian policies, transition probabilities, future stand management intensities, and residual leave tree policies. In addition, a short discussion of the stand-level forest structure projections is provided to further illustrate the multi-scale nature of the modeling system.

2.2.1. Riparian policies

In the modeling effort described here, three general policies can be used to describe the behavior of forest landowners with respect to riparian areas: (1) management activities are prohibited within a certain distance of the stream system (Fig. 4), (2) limited management activities are allowed within a certain distance of the stream system (Fig. 5); (3) limited management activities are allowed within a certain distance of the stream system, yet only within certain vegetation types (e.g., conifer) (Fig. 6). To enable these policies to be modeled within management units that encompass areas that extend well beyond the boundaries of typical riparian management areas (30–100 m), these decisions are made at the basic simulation unit scale, and are based on the type of activity assigned to a land allocation. Our example simulations use the second case noted above.

2.2.2. Residual leave tree policies

Residual leave tree policies can be modeled at the management unit scale, where the number of residual leave trees within a simulated clearcut is constant. However, since more than one land allocation might be present within a management unit, and since forest structural conditions are tracked at the basic simulation unit scale, the leave tree policy may also be modeled at the basic simulation unit scale. For example, within a single management unit, simulating clearcuts near the stream system may require retention of a large number of residual leave trees under certain policies, whereas clearcuts further away from the stream system may require retention of a smaller number of residual leave trees. These two policies can be modeled simultaneously if performed at the basic simulation unit scale. The level of residual leave trees that we model in our example simulations is consistent with those required by the Oregon Forest Practices Act (Oregon State Legislature, 2001) and guidance provided by public land managers.

2.2.3. Management intensities

The intensity of forest management, which may range from "very low" (e.g., natural regeneration, no thinning, final harvest) to "very high" (e.g., plant, pre-commercial thin, fertilize, commercial thin, final harvest), is inherent in the management prescriptions applied to units modeled within forest planning efforts. Since, in the hierarchical spatial structure presented here, forest structural information is tracked at the basic simulation unit scale, management intensity can be tailored to this scale. In a typical forest management plan, however, management intensity decisions are made at the management unit scale, and when viewed from a

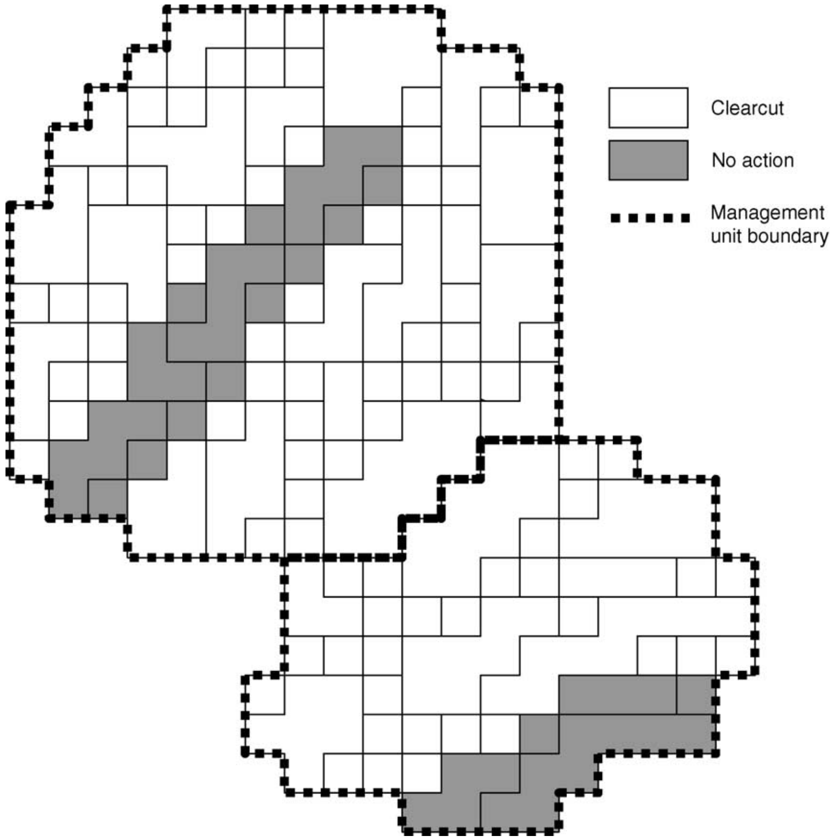

Fig. 4. Riparian policy where no activity is allowed within a certain distance of the stream system.

larger landscape (or ownership) perspective, the range of intensity may vary by management unit. For example, a private forest company may manage 25% of their land at a high intensity, 25% at a low intensity, and 50% somewhere between the two levels, depending on silvicultural budgets. A public agency may manage most of their land at a medium management intensity (e.g., plant, final harvest). Therefore, it may seem reasonable to be able to model a range of intensity of management for forest plantations, and choose a level of intensity to model for an entire management unit when clearcut activities are scheduled. With a distribution of management intensities, a simulation model can be designed to randomly assign the level of intensity modeled as clearcuts are scheduled. All basic simulation units within the management unit are then assigned prescriptions of similar management intensity, to the extent possible. For example, all conifer basic simulation units may be modeled at a high management intensity, yet hardwood basic simulation units would be modeled as simply regenerated areas, if intensive hardwood management is not common to a region.

2.2.4. Transition probabilities

Deciding how clearcut areas, hence regenerated stands, are to be simulated in periods of time after clearcutting has been scheduled is a key issue when evaluating long-term projected conditions of large landscapes. Many forest growth and yield models lack the ability to adequately represent the type of trees regenerating after harvest without some input from the modeler. Most often in modeling processes, a single, or limited transition is assumed to occur after harvest. Assuming a single transition of forested areas, however, may mis-represent the heterogeneity of management and ecological processes inherent across

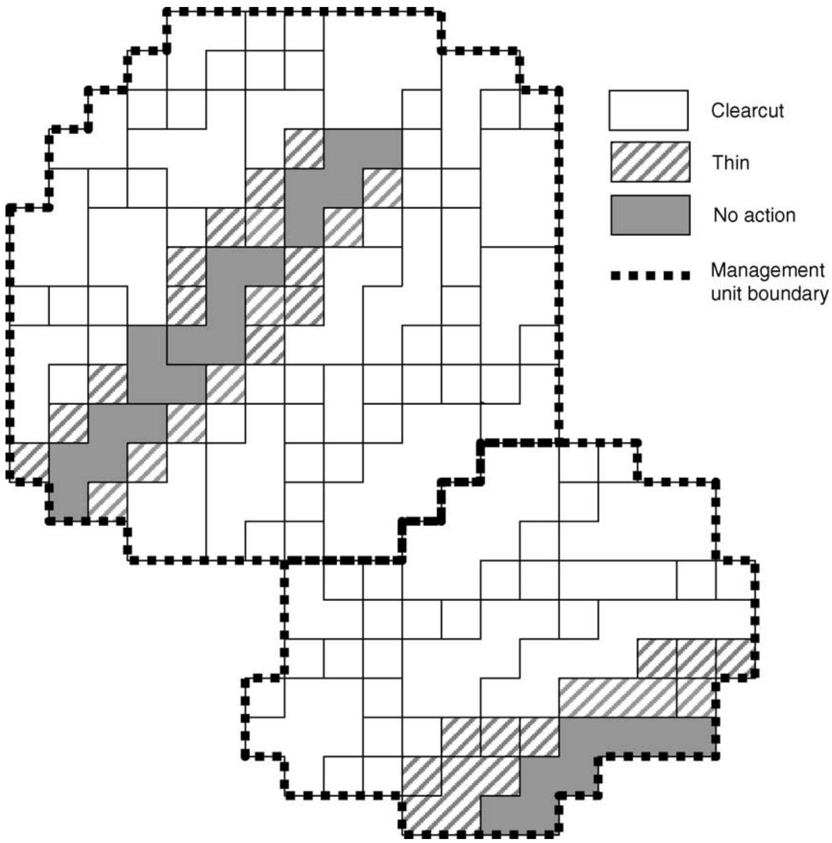

Fig. 5. Riparian policy where limited activity is allowed within a certain distance of the stream system.

a landscape after disturbance. For example, to assume that all clearcut areas will return as conifer plantations on private industrial areas is overly optimistic, and assumes one disregards the problems associated with failed planting efforts, competition from residual hardwood species, and other processes that act to suppress the regeneration success of planted conifers. To more adequately model the type of forest that regenerates after harvest, it would seem reasonable to use a set of transition probabilities that emulate historical progression of forested areas, and subsequently infer that the transition is probabilistic. The probabilities might be a function of the regeneration management intensity assumed, but perhaps also a function of the distance to the stream system and the type of vegetation that resided in the harvested area prior to activity. Within the spatial hierarchy described here, transition probabilities are applied at the basic simulation unit scale, where the management intensity of the management unit can be considered along with the distance each basic simulation unit is from the stream system, and the type of vegetation that was present within the basic simulation unit prior to harvest. By doing so, the simulations can retain some of the landscape heterogeneity that was present at the initiation of the planning process (as reflected in the initial vegetation database).

2.2.5. Stand-level projections of forest structure

Individual tree forest growth and yield models are used to facilitate the estimation of forest structure within each basic simulation unit. Two growth and yield models were utilized: (1) ORGANON (Hann et al., 1997), a distance independent, individual tree model based on empirical relationships and validated for conifer and some mixed stands up to 100 years of age, and (2) ZELIG (Urban and Shugart, 1992, Garman

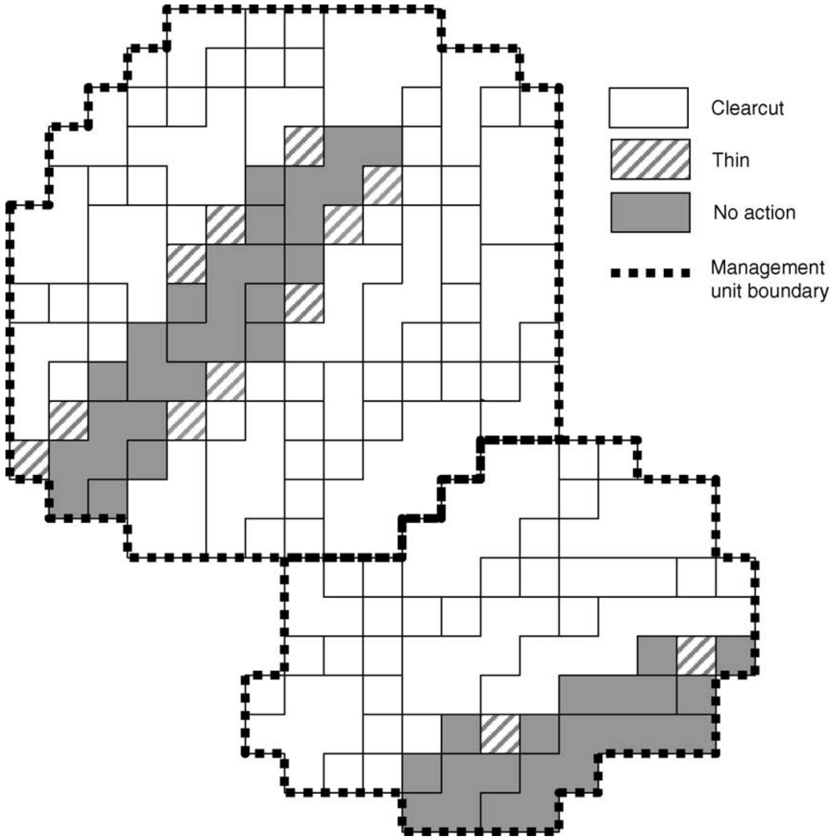

Fig. 6. Riparian policy where limited activity is allowed within a certain distance of the stream system, yet only in certain forest types.

et al., 2003), a distance independent, individual tree model based on theoretical ecological (gap) relationships for use for any stand age and stand composition, but with relatively little empirical validation for any particular age and stand condition. Since ORGANON is used by many industrial forestry organizations in western Oregon, and thus has credibility with industrial landowners, ORGANON has been employed for management prescriptions that involve regeneration harvest of stands younger than 100 years of age. We also wanted to use a growth and yield model that could simulate ecological succession in older forests representative of public reserves. Since ORGANON only models mortality with inter-tree competition relationships (rather than with natural gap disturbances) ZELIG is employed for management prescriptions on public land where regeneration harvests often occur in stands with ages in excess of 100 years, or where a regeneration harvest is not considered. ZELIG was calibrated to ORGANON timber volume projections for simulations of young, intensively managed stands on public lands. Both models produce similar projections of basal area, quadratic mean diameter, and tree density for the first 80 years of a forest rotation. For the projections of landscape condition described here, we utilize the CLAMS ORGANON data to represent the forest structural conditions of private industrial lands, and the ZELIG data to represent forest structural conditions on public lands. In the next generation of landscape simulations, and with further calibration of ZELIG projections to ORGANON projections, we plan to use ZELIG to describe the forest structural conditions of all landowners. With proper manipulation, of course, any growth and yield model can be used to represent the forest conditions of all landowners. The trouble with ORGANON would be to determine how to represent gap disturbances typical of older forests, which currently can only be represented by thinning prescriptions.

2.3. Problem formulation

Two general types of management behavior are next described. One relates to the behavior of a large group of private industrial landowners, where the goal of management may be to maximize individual organizational objectives, usually involving wealth. The other relates to a large public (state) ownership of land, where the goals of management may be two-fold: to produce commodities, and to provide forest structural conditions that might facilitate the achievement of ecological goals.

2.3.1. Modeling of private industrial forest management behavior

The behavior of individual industrial landowners can generally be described as one that seeks to maximize the value of the asset (land and timber) to the owners of the company, whether they be stock holders, families, or individuals. However, when viewed as a whole, across a broad landscape and through time, the behavior of the landowner group might be characterized differently due to variations in management objectives, inventory levels, and other economic, political, and regulatory circumstances. For example, in one study (Lettman and Campbell, 1997), the industrial group as a whole tended to harvest a relatively stable amount of timber volume over time, even though the individual landowners each sought to maximize value. Given the propensity of the private industrial landowner group, as a whole, to harvest a relatively stable amount of timber volume over time, the objective function for this group was developed to provide simulations that maximized an even-flow of timber harvest volume.

Objective function

Maximize

$$\sum_{b=1}^{B}\sum_{t=1}^{T} v_b x_{b,t} a_b \tag{1}$$

where b is a basic simulation unit; B is the total number of basic simulation units; t is a time period; T is the total number of time periods; v_b is the harvestable volume per unit area in basic simulation unit b; $x_{b,t}$ is a binary (0,1) variable indicating whether or not basic simulation unit b was harvested in time period t; a_b is the area represented by basic simulation unit b.

To understand the constraints influencing the behavior of the private industrial landowner group in the Coast Range of Oregon, a number of meetings were arranged over the 1998–2002 time period to discuss modeling approaches and assumptions. The group, as a whole, must manage their forest land within the guidelines specified in the Oregon Forest Practices Act (Oregon State Legislature, 2001), which limits the maximum size of clearcut areas, requires a green-up time period of about 5 years between adjacent clearcut areas that might result in a clearcut area greater than the maximum area prescribed, and limits the activity allowed in riparian areas. Although there was some variation in the management behavior derived from discussions with the industrial landowners, a number of significant aspects were deemed important. First, the landowners stressed that any modeling effort should closely emulate the Forest Practices Act. Second, the act of blocking harvest areas for simultaneous treatment was thought important, given their propensity to do so in practice. Third, modeling prescriptions that included intensive management of future forests was identified as important, to the extent identified in surveys of management behavior (Lettman, 1998). Finally, providing an indication of the impact of policies that might further restrict current management behavior was, while contentiously debated, thought important. These policies included, among others, reducing the maximum clearcut size and implementing a minimum harvest age. The general flow of information across spatial scales, and related to the objective and constraints of the industry modeling process, is described conceptually in Fig. 7.

The achievement of an even-flow of timber volume is accomplished with a modified version of binary search. Leuschner (1990) describes the basic binary search process. Here, a target timber volume is set for each time period, and harvests are accumulated by blocking together management units for treatment using a dynamic, deterministic blocking process described in Bettinger and Johnson (2003), a process much different than scheduling harvests by forest strata. The scheduling process starts with the first time period, and once enough harvests have been scheduled to exceed the volume target, harvests in subsequent

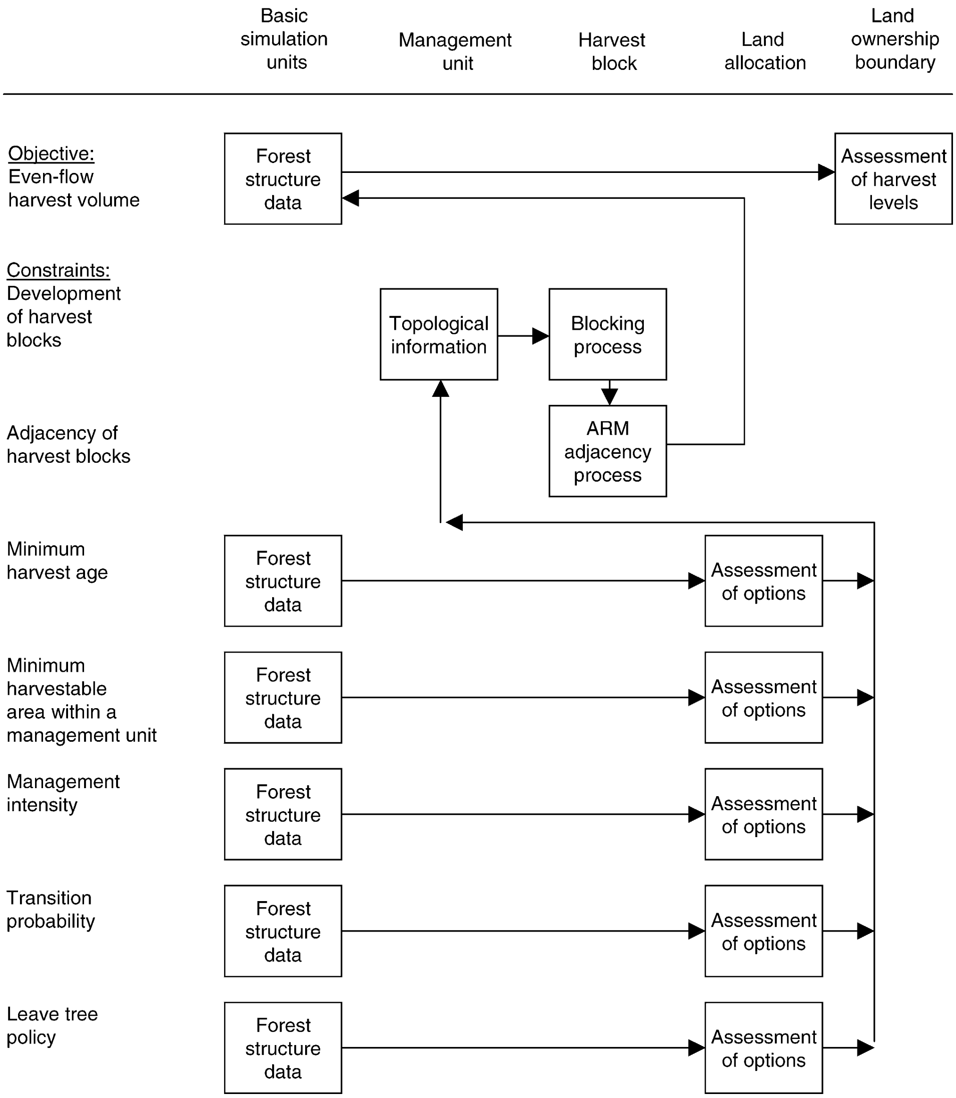

Fig. 7. Conceptual model of the flow of information across spatial scales, and in association with the objective and constraints, for the industrial landowner behavior modeling process.

time period(s) are scheduled. If enough volume can be scheduled in all time periods, the target is increased, and the process begins anew. If there is not enough volume available in one or more time periods, the target is reduced, and the process begins anew. The even-flow constraint can be described as:

$$\sum_{b=1}^{B} v_b x_{b,t} a_b \geq \mathrm{VT}_t \qquad \forall t \tag{2}$$

where VT_t is the target volume to be harvested in time period t.

While the summation of timber volume scheduled for harvest occurs at the basic simulation unit scale, adjacency restrictions are modeled at the management unit scale. There are two general approaches to applying adjacency restrictions in forest planning. The first is the application of a technique called the “Unit Restriction Model” (URM), which makes it possible to restrict harvest activity in management units that neighbor other management units already scheduled for clearcutting, disallowing neighboring management units from being treated in the same time period (or near-time periods). Constraints such as the one that follows can be used to control URM problems (Murray, 1999).

$$X_{i,t} + X_{j,t} \leq 1 \qquad \forall i, t, j \in N_i \tag{3}$$

where i is the management unit; $X_{i,t}$ is a binary (0,1) variable indicating whether or not management unit i is clearcut during time period t; N_i is a set of all management units adjacent to management unit i.

Management units (10–20 ha) in our spatial hierarchy are typically smaller than maximum clearcut size restrictions (50 ha), and thus it may be important to schedule adjacent units for harvest to produce a feasible management plan containing "harvest blocks." In such cases, a second technique, called the "Area Restriction Model" (ARM), can be used to assign simultaneous treatments to adjacent management units, as long as the total contiguous area does not exceed the maximum area limit (Murray, 1999). Recursive functions are generally used to evaluate the resulting spatially sprawling harvest block of management units. To assess ARM problems, constraints such as the one noted below are used.

$$X_{i,t}\mathrm{CA}_{i,t} + \sum_{j \in N_i \cup S_i} X_{j,t}\mathrm{CA}_{j,t} \leq \mathrm{MCA} \tag{4}$$

where $\mathrm{CA}_{i,t}$ is the area of management unit i that is clearcut during time period t; S_i is the subset of the total number of harvested management units that contains all units adjacent to the neighbors of management unit i plus all units adjacent to the neighbors of the neighbors, etc.; MCA is maximum permissible area of the harvest block.

The blocking process used in this research is described in Bettinger and Johnson (2003). It includes an ARM technique to evaluate the size of harvest blocks, and a URM technique to prevent two clearcut harvest blocks from merging together if they are being simulated for clearcut harvests during the same time period.

In addition to adjacency restrictions, a minimum harvest age (MHA) constraint allows basic simulation units within a management unit to be considered for clearcut harvest in a particular time period only if the age of the vegetation within the basic simulation unit is greater than a minimum age.

$$\begin{aligned} &\text{If } \mathrm{Age}_{b,t} \geq \mathrm{MHA} \qquad x_{b,t} \in \{0, 1\} \\ &\text{Else } x_{b,t} = 0 \end{aligned} \tag{5}$$

where $\mathrm{Age}_{b,t}$ is average age of the trees in basic simulation unit b during time period t.

Obviously when using satellite imagery as the database describing the vegetation across a landscape, a considerable amount of heterogeneity in forest structure (i.e., age) can be present within management units. A constraint and some logic is used to control the scheduling of small portions of management units for harvest in any particular time period, if only a small percentage of basic simulation units have vegetation ages greater than the MHA. First, a cursory examination of the potential harvest opportunities of basic simulation units is performed by evaluating the percentage area of each management unit that could be clearcut harvested in each time period:

$$\begin{aligned} &\text{If } \mathrm{Age}_{b,t} \geq \mathrm{MHA} \text{ and } r_b = 0 \text{ then } y_{b,t} = 1 \\ &\text{Else } y_{b,t} = 0 \end{aligned} \tag{6}$$

where r_b is a binary variable indicating whether (1) or not (0) a riparian restriction has been placed on the clearcutting of basic simulation unit b; $y_{b,t}$ is a binary (0,1) variable indicating whether or not basic simulation unit b could potentially be clearcut harvested during time period t.

Here, if the age of the vegetation describing a basic simulation unit is greater than the MHA and there are no riparian restrictions, the basic simulation unit can potentially be clearcut. The percentage of each management unit that potentially could be clearcut in each time period is then examined.

$$\left[\frac{\sum_{b=1}^{B_i} y_{b,t} a_b}{\sum_{b=1}^{B_i} a_b}\right] = \gamma_{i,t} \qquad \forall i, t \tag{7}$$

where B_i is the subset of basic simulation units b that are contained within management unit i; $\gamma_{i,t}$ is the percentage of management unit i that could be clearcut during time period t.

With this determination of the percentage of each management unit that could be clearcut in each time period, the possible set of values for decision variables $X_{i,t}$ and $x_{b,t}$ are known.

$$\begin{aligned}&\text{IF } \gamma_{i,t} \geq \text{MHP then } X_{i,t} \in \{0, 1\}; x_{b,t} \in \{0, 1\}\\&\text{Else } X_{i,t} = 0;\ x_{b,t} = 0 \qquad \forall b \cup B_i\end{aligned} \tag{8}$$

where MHP is the minimum percentage area required prior to simulating a management unit for a clearcut activity.

Three pieces of information are tracked with each basic simulation unit, allowing one to understand the structural characteristics contained within: the vegetation conditions (tree list or other information allowing one to compute age and volume), the management prescription assumed (should it include intermediate treatments such as thinnings), and the time of the last regeneration harvest. The assignment of management intensity to a management unit is made at the time of clearcutting, and with this information, the vegetative condition and prescription assigned to the regenerated basic simulation units can be defined. The transition probabilities key off of the management intensity assigned to the management unit, the distance each basic simulation is from the stream system, and the pre-clearcut vegetation conditions. In addition, the leave tree policy for each land allocation indicates the type of structural legacy remains in the regenerated basic simulation units. This process allows both basic simulation units and management units to be simulated for more than one clearcut activity during the planning horizon.

$$\sum_{t=1}^{T} x_{b,t} \geq 0 \qquad \forall b \tag{9}$$

$$\sum_{t=1}^{T} X_{i,t} \geq 0 \qquad \forall i \tag{10}$$

2.3.2. Modeling of public forest management behavior

Public forest management varies according to the agency charged with managing forest land. Here, we refer to “public” as state (non-federal) land management agencies. The management behavior of public agencies in North America in the past two decades, when viewed from the landscape level, has emphasized ecological objectives along with economic objectives. There is a strong belief that public agency management activities should be self-sustaining, from economic, ecological, and social perspectives, thus the emphasis on multiple-use of forest resources. To model the behavior of the public forest management group in the Coast Range of Oregon, a number of meetings were arranged over the 1998–2002 time period to discuss modeling approaches and assumptions with state forest managers. The group, as a whole, must manage their forestland within the guidelines specified in their respective forest management plans as well as the State Forest Practices Act (Oregon State Legislature, 2001). These guidelines limit the maximum size of clearcut areas, require a green-up time period of about 5 years between adjacent clearcut areas that might result in a clearcut area greater than the maximum area prescribed, limit the activity allowed in riparian areas, suggest the development of a diverse forest structure, and suggest the development of interior habitat (older forest) management areas. As with the private industrial landowner group, the state forest managers stressed that any modeling effort should closely emulate the Forest Practices Act. In addition, modeling prescriptions that reflected a medium level of management intensity for future forests (e.g., plant, commercial thin, final harvest) was identified as important. Finally, the managers indicated that the simulations should seek to emulate the development of a diverse forest structure and the development and maintenance of interior habitat areas, while providing a stable timber harvest volume.

In our public forest management example, the same objective function used in the modeling of private industrial forest management behavior is assumed: maximize an even-flow of timber harvest volume. The implementation of this objective is achieved, as noted earlier, using a binary search criteria. The constraints of the analysis include a unit restriction model of adjacency, where neighboring individual management units are prohibited from being scheduled for clearcut during the same time period. In addition, a MHA constraint is applied, as noted above, and a minimum percentage of area within management units must be available for clearcut prior to scheduling a clearcut activity. There are two aspects of this modeling process that differentiate it from the private industrial process: (1) the scheduling process seeks to achieve a distribution of structural conditions in five structural classes (older forest, layered canopy development, understory development, closed canopy, and regeneration), and (2) a distribution of sizes of blocks of interior habitat need to be simulated. The general flow of information across spatial scales, and related to the objective and constraints of the public land (state) modeling process, is described conceptually in Fig. 8.

To enable the achievement of a distribution of structural conditions through space and time, the amount of area in each class is assessed each time period. Since management decisions are made the management unit scale, an assessment of forest structural class condition (Table 1) needs to be made at the management unit scale. The structural class of each basic simulation unit is used to determine the class of the management unit. First, the dominant structural condition within each management unit is assessed.

$$\sum_{c=1}^{C}\sum_{b=1}^{B_i} a_b h_{b,c,t} = S_{i,c,t} \qquad \forall i \tag{11}$$

$$\sum_{c=1}^{C} h_{b,c,t} = 1 \qquad \forall b, t \tag{12}$$

where c is a forest structural condition class; C is the set of forest structural condition classes; $h_{b,c,t}$ is a binary variable indicating whether (1) or not (0) habitat class c describes the forest structural condition of basic simulation unit b during time period t; $S_{i,c,t}$ is the area of forest structural condition class c within management unit i during time period t.

Each $S_{i,c,t}$ is then examined, and the one that represents the highest proportion of area of management unit i as assumed to represent the structural condition of the management unit. A binary (0,1) value is then assigned to variable $\mathrm{SC}_{i,c,t}$ where

$$\sum_{c=1}^{C} \mathrm{SC}_{i,c,t} = 1 \qquad \forall i, t \tag{13}$$

where $\mathrm{SC}_{i,c,t}$ is a binary (0,1) variable indicating whether (1) or not (0) management unit i is assumed to represent forest structural class c during time period t.

The percentage of the landscape area in each structural class is then assessed.

$$\left[\frac{\sum_{i=1}^{I} A_i \mathrm{SC}_{i,c,t}}{\mathrm{LSA}}\right] = H_{c,t} \qquad \forall c, t \tag{14}$$

where A_i is the total area of management unit i; LSA is the area of the landscape under consideration; $H_{c,t}$ is the proportion of the landscape in forest structural class c during time period t.

Constraints are then imposed on four of the five structural classes using sets of logic. First, since the regeneration structural class condition increases with each clearcut activity scheduled, some control must be placed on the maximum amount of the landscape in this condition. The percentage area in the regeneration class is assessed with the simulation of each clearcut activity.

$$\begin{array}{l}\text{If } H_{r,t} \leq \mathrm{SG}_r \text{ then } X_{i,t} \in \{0, 1\} \\ \text{Else } X_{i,t} = 0\end{array} \tag{15}$$

where $H_{r,t}$ is the proportion of the landscape in structural class r (regeneration) during time period t; SG_r is the goal (percentage of the landscape desired for structural class r).

Second, if the older forest structural condition goal is not met during a time period, harvest activities from management units that have this condition are prohibited.

$$\begin{array}{ll}\text{If } H_{o,t} \geq \mathrm{SG}_o \text{ then } X_{i,t} \in \{0, 1\} & \forall i : \mathrm{SC}_{i,o,t} = 1 \\ \text{Else } X_{i,t} = 0 \quad \forall i : \mathrm{SC}_{i,o,t} = 1 & \end{array} \tag{16}$$

Table 1
Characteristics of forest structural condition classes for public management behavior in the Oregon Coast Range

<65% hardwood basal area		≥65% hardwood basal area	
Age	Class	Age	Class
≤15	Regeneration	≤15	Regeneration
>15 and ≤30	Closed canopy	>15	Closed canopy
>30 and ≤60			
RD > 45	Closed canopy		
RD ≤ 45	Understory		
>60 and ≤80			
RD > 55	Closed canopy		
RD ≤ 55 and RD > 40	Understory		
RD ≤ 40	Layered		
>80 and ≤120			
Thinned	Layered		
Not thinned	Older forest		
>120	Older forest		

RD: relative density (total basal area/quadratic mean diameter$^{0.5}$).

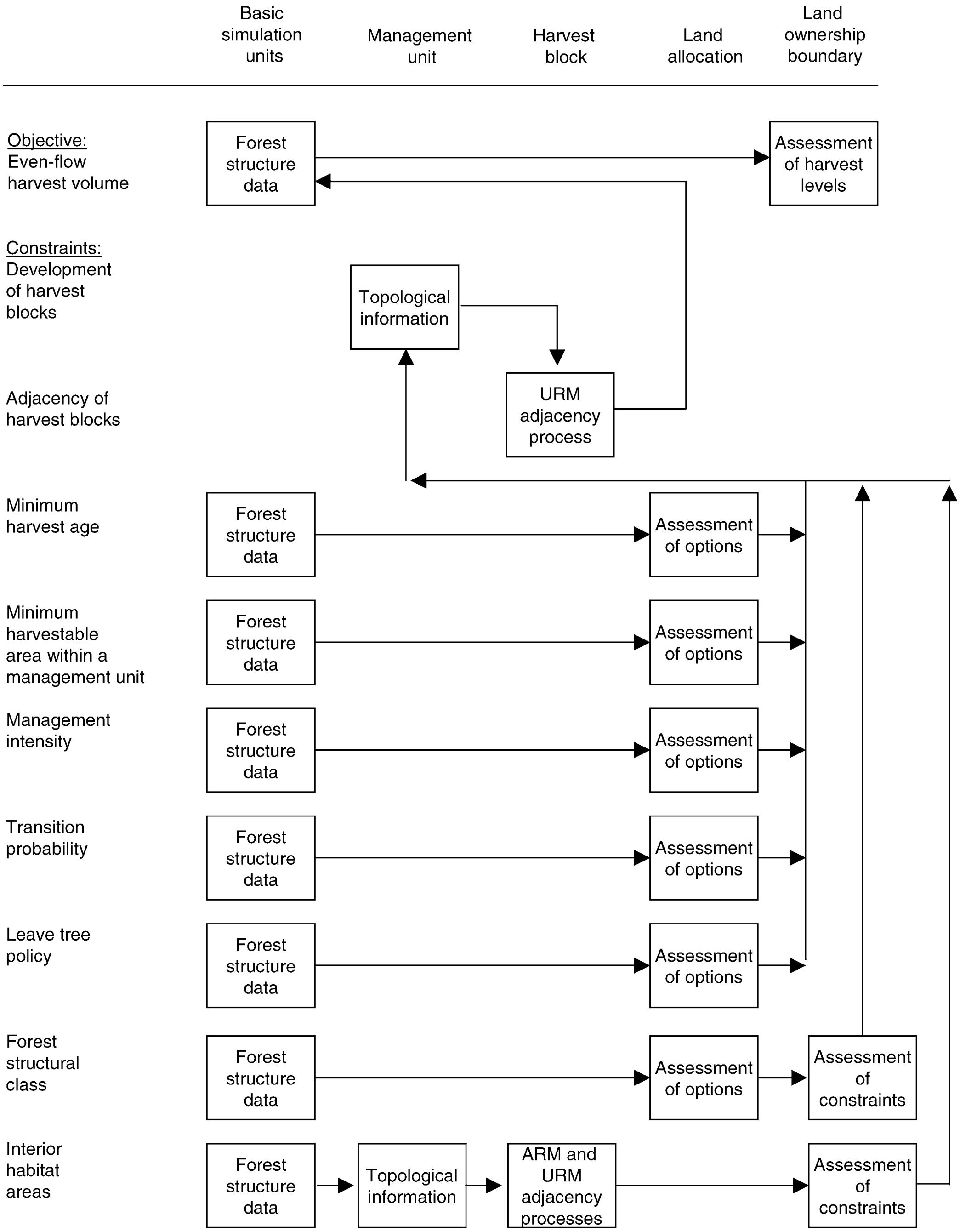

Fig. 8. Conceptual model of the flow of information across spatial scales, and in association with the objective and constraints, for the state land modeling process.

where $H_{o,t}$ is the proportion of the landscape in structural class o (older forest) during time period t; SG_o is the goal (percentage of the landscape desired for structural class o).

Third, if the layered forest structural condition class goal is not met during a time period, harvest activities from management units that have this condition are prohibited.

$$\begin{aligned}&\text{If } H_{l,t} \geq SG_l \text{ then } X_{i,t} \in \{0, 1\} \qquad \forall i : SC_{i,l,t} = 1\\&\text{Else } X_{i,t} = 0 \qquad \forall i : SC_{i,l,t} = 1\end{aligned} \tag{17}$$

where $H_{l,t}$ is the proportion of the landscape in structural class l (layered forest) during time period t; SG_l is the goal (percentage of the landscape desired for structural class l).

Fourth, and finally, if the understory forest structural condition class goal is not met during a time period, harvest activities from management units that have this condition are prohibited.

$$\begin{aligned}&\text{If } H_{u,t} \geq SG_u \text{ then } X_{i,t} \in \{0, 1\} \qquad \forall i : SC_{i,u,t} = 1\\&\text{Else } X_{i,t} = 0 \qquad \forall i : SC_{i,u,t} = 1\end{aligned} \tag{18}$$

where $H_{u,t}$ is the proportion of the landscape in structural class u (understory forest) during time period t; SG_u is the goal (percentage of the landscape desired for structural class u).

These last three structural class conditions are at their maximum levels prior to the simulation of management activities in each time period, thus they may decrease with each clearcut activity simulated, and need to be reassessed with each simulated clearcut.

To enable the development of interior habitat areas, a process of building habitat blocks is utilized, one that is similar of the process of building clearcut harvest blocks. Here, the ARM technique (Murray, 1999) is used to build interior habitat blocks of certain sizes. Recursive functions are used to evaluate the resulting spatially sprawling interior habitat block of management units, and constraints such as the one noted below are used.

$$\sum_{i \in N_i \cup S_i} A_i \geq \text{IHA} \tag{19}$$

where S_i is a subset of the total number of management units that contains all units adjacent to the neighbors of management unit i plus all units adjacent to the neighbors of the neighbors, etc. Only management units where $SC_{i,o,t} = 1$, $SC_{i,l,t} = 1$ and $SC_{i,u,t} = 1$ are available for inclusion into the habitat block; IHA is the minimum area of the interior habitat block desired.

The process utilizes an ARM technique to develop each block. The blocking process stops once the minimum habitat block size has been exceeded. A URM technique is then used to prevent two interior habitat blocks from merging together, forming a larger, single block. If management units are included in an interior habitat block during time period t, $X_{i,t} = 0$.

3. Case study

To illustrate how the spatial hierarchical modeling framework might be applied, we provide several examples of modeling both private industrial management behavior and public management behavior on a 560,000 ha area of land in the Oregon Coast Range. The area is composed of a mixture of land ownerships (Fig. 9), the main groups being private industrial and public (state). The private industrial areas are modeled according the methods presented earlier. A number of management scenarios were simulated to provide an indication of the sensitivity of timber harvest levels to changes in forest policies (Table 2). The MHA modeled varies from 35 to 50 years, and the maximum clearcut size ranges from 24.3 to 48.6 ha. In total, 16 simulations are performed using the private industrial management behavior process. The riparian policies gathered through surveys of industrial forest management behavior indicated that on one-half of the land area within riparian areas, partial cutting is implemented to the extent possible under state law, with harvests reducing basal area to certain minimum levels depending on stream type and riparian emphasis.

Table 2
Scenarios modeled for the private industrial management areas in the north coast of coastal Oregon

Minimum harvest ages	Maximum clearcut sizes
35	24.3 ha (60 acres)
40	32.4 ha (80 acres)
45	40.5 ha (100 acres)
50	48.6 ha (120 acres)

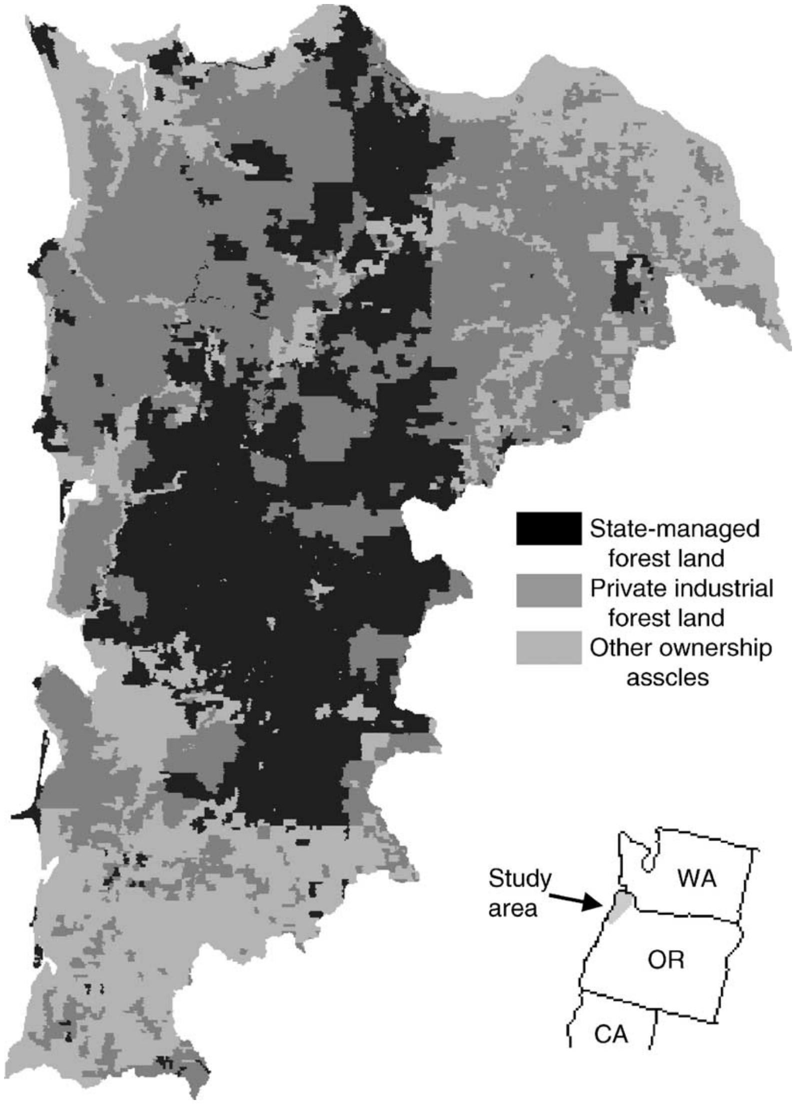

Fig. 9. Land ownership pattern for a 560,000 ha area of the north coastal region of Oregon (USA).

On the other half of the riparian area, harvests are precluded. In our modeling effort, the location of these areas is randomly defined at the basic simulation unit scale. After clearcut harvest, management prescriptions are assigned to basic simulation units based on the management intensity assigned to each management unit. We assume here that 20% of all clearcut management units will be assigned a high management intensity (plant, pre-commercial thin, fertilize), 60% will be assigned a medium-high management intensity (plant, pre-commercial thin), and 20% are assigned a medium management intensity (plant). These are hypothetical assumptions of future management behavior; any arrangement of management intensities can be used. Commercial thinnings are simulated in regenerated management units if over one-half of each management unit returns as a conifer forest type. Transition probabilities (Table 3) are used to determine the type of forest that returns after clearcutting. These probabilities are applied at the basic simulation unit scale, and

Table 3
Transition probabilities for forest industry land in the coastal ecoregion of Oregon, when land is managed under a medium management intensity

	Distance from stream (m)			
	0–50	51–100	101–150	>151
Previous vegetation class: hardwood[a]				
To open/semi-closed	0.10	0.05	0.04	0.02
To predominantly hardwood	0.20	0.15	0.15	0.12
To predominantly mixed	0.30	0.27	0.21	0.18
To predominantly conifer	0.40	0.53	0.60	0.68
Previous vegetation class: mixed[b]				
To open/semi-closed	0.07	0.05	0.03	0.02
To predominantly hardwood	0.15	0.12	0.07	0.05
To predominantly mixed	0.28	0.25	0.20	0.13
To predominantly conifer	0.50	0.58	0.70	0.80
Previous vegetation class: conifer[c]				
To open/semi-closed	0.05	0.02	0.02	0.01
To predominantly hardwood	0.10	0.06	0.06	0.04
To predominantly mixed	0.22	0.19	0.13	0.10
To predominantly conifer	0.63	0.73	0.79	0.85

[a] Areas where hardwood tree species occupy 65% or more of the basal area of trees.
[b] Areas where hardwood tree species occupy less than 65% and greater than or equal to 20% of the basal area of trees.
[c] Areas where hardwood tree species occupy less than 20% of the basal area of trees.

are developed from empirical analyses associated with the CLAMS project (Spies et al., 2002). A different set of probabilities is assumed for each level of management intensity, with higher conversion to conifer assumed with higher management intensities.

The state lands within the north coastal region of the Oregon Coast Range are simulated as noted earlier in the public forest management methods section. Here, a number of policies are modeled to evaluate the sustainability and economic goals on public land. The MHA is assumed to vary from 40 to 55 years, and the structural condition classes are assumed to be constant, at 20% for each of the five classes. A number of sets of interior habitat blocks (Table 4) are modeled. Therefore, 16 simulations are performed using the public management behavior process. The riparian policies were gathered through examinations of state forest plans. In some land allocations, such as reserved or special forest management areas, either no activity is allowed in the riparian areas or only thinning activities can be implemented. In other land allocations, as suggested by state management plans, five residual leave trees are retained in clearcuts. After clearcut harvest, management prescriptions are assigned to basic simulation units based on the management intensity assigned to each management unit. We assume here that all clearcut management units will be assigned a medium management intensity (plant). Commercial thinnings are simulated in regenerated stands if over one-half of each management unit returns as a conifer forest type. Transition probabilities similar to those shown in Table 3 are used to determine the type of forest that returns after clearcutting. These probabilities are applied at the basic simulation unit scale, and are developed from empirical analyses associated with the CLAMS project (Spies et al., 2002).

The hierarchical spatial simulation process for both ownership behavior groups requires about 1 hour on a computer equipped with a 2.4 GHz central processing unit and 2 Gb of RAM. The simulation model was developed with the C programming language, and includes a Visual Basic interface to allow the specification of simulation parameters. Depending on the amount of output data desired, up to 1 Gb can be generated to describe the forest structural conditions of the landscape over the 100-year time horizon.

4. Results

There is considerable debate about the appropriate rotation age for industrial land in the Oregon Coast Range, with various groups suggesting ages anywhere from 30 to 60 years. When evaluating forest policies with variations in MHAs, it is not surprising that the policy with the lowest MHA would result in the highest even-flow timber volumes (Fig. 10). As the MHA is increased from 35 to 40 years, the maximum even-flow volume decreases about 26%. The 45-year MHA results in less than one-half of the volume levels produced with the 35-year MHA, and the 50-year MHA results

Table 4
Number and size of interior habitat blocks modeled for the public management areas in the north coast of coastal Oregon

Interior habitat block size	Number of habitat blocks			
	A	B	C	D
1–100 ha	0	9	27	81
101–200 ha	0	6	18	54
201–400 ha	0	3	9	27

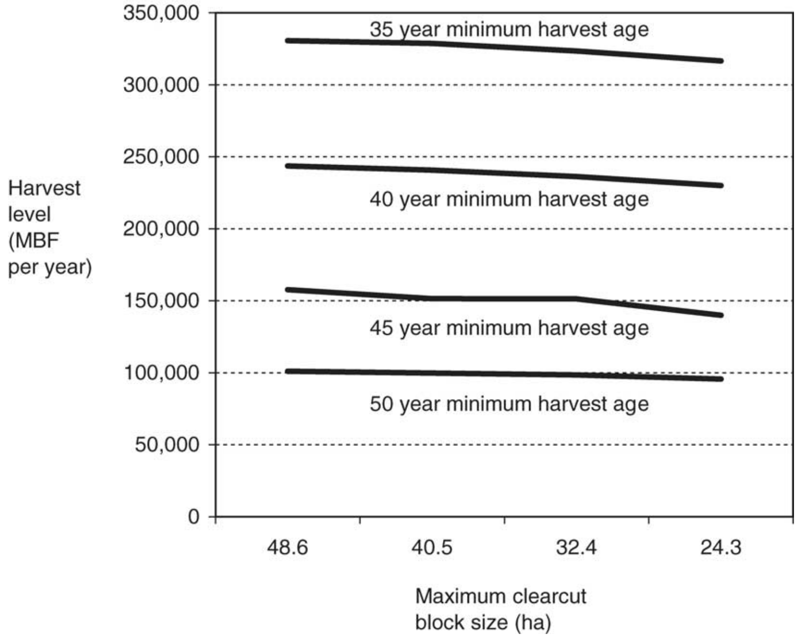

Fig. 10. Projected annual harvest levels from a simulation requiring an even-flow timber harvest volume with minimum harvest age and maximum clearcut size constraints on private industrial land in the north coastal region of Oregon (USA).

in about a 70% decrease in harvest levels. This all assumes, of course, that as policies change, private industrial landowners will continue to operate, as a group, to produce even levels of timber volume. As the maximum clearcut size decreases from 48.6 ha to 24.3 ha, maximum even-flow timber harvest volume levels decline by 4% with the 35-year MHA to about 10% with the 45-year and 50-year MHAs.

What we find with these results is the complex interaction of the objective and the constraints. For the most part, the reduction in timber harvest with the increase in MHA is the sequential effect of removing (or adjusting) the constraint. These results, however, may be an artifact of a simulation process. The even-flow harvest method we have demonstrated, for example, is notorious for becoming encumbered by bottlenecks (periods of low available volume), which heavily influence the resulting solutions. These bottlenecks are time periods where the harvest volume does not reach the desired target, which may be influenced by the desire to harvests levels in previous time periods, the initial description (i.e., age class distribution and forest structural conditions) of the landscape, or the constraints. The bottlenecks may occur when the simulation process is completing the harvest of current (initial) stands and beginning the harvest of regenerated stands (those harvested and regenerated by the simulation process). In some cases, however, they occur earlier, suggesting that one or more of the constraints may be limiting the placement of activities across the landscape. More than likely the combination of the even-flow objective and the minimum harvest age constraint limits possibilities in the first few time periods, given the resulting *average* harvest ages of clearcut blocks (Fig. 11).

The blocking process described in Bettinger and Johnson (2003) combines lower valued management units (based on net revenue divided by stand age) around higher valued management units to form harvest blocks. This is consistent with the direction we received in discussions with forest industry landowners. Thus, while the MHA has a large effect on even-flow volumes regardless of maximum clearcut size, the net effect (4–10% reduction of even-flow harvest levels) of smaller maximum clearcut sizes is the delay of the conversion of low valued management units of the initial landscape to regenerated units, since fewer of the lower-valued units would be combined with higher values units. Smaller harvest blocks thus favor harvesting

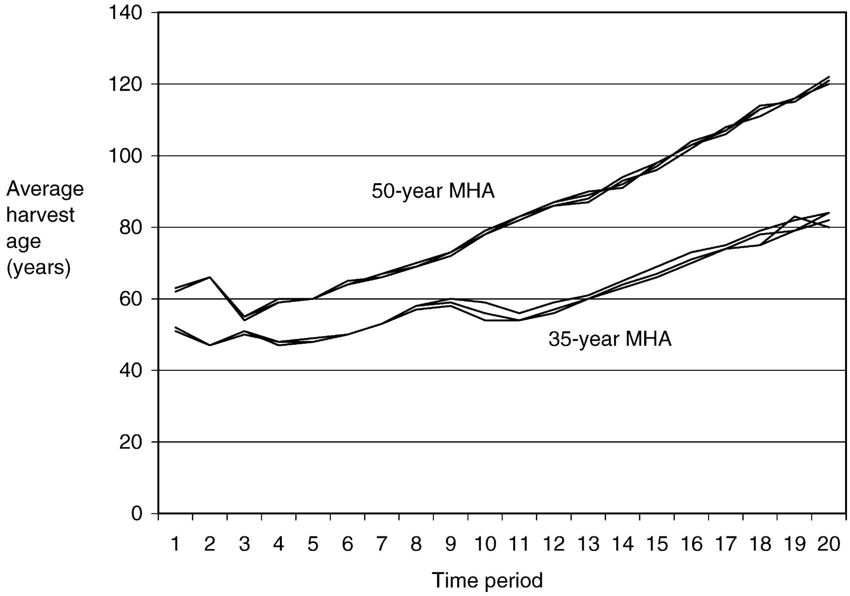

Fig. 11. Average harvest ages for the four simulations allowing a 35-year minimum harvest age, and the four simulations allowing a 50-year minimum harvest age, on private industrial land in the north coastal region of Oregon (USA).

more higher-valued management units early in the simulation process.

The MHA constraint also plays the largest role in the public management behavior simulation process. Here, as the MHA is increased from 40 years to 45 years, the even-flow volume levels decline about 7% (Fig. 12). This assumes, as in the private industrial case, that public forest managers continue to operate as otherwise assumed once the minimum harvest age policy changes. As the MHA is increased to 50 and 55 years, respectively, even-flow volume levels decline about 13% and 31%.

The influence of increasing levels of interior habitat areas has little effect on the achievement of even-flow harvest volumes, mainly because this constraint is complementary to the structural stage constraints: both require the reservation of older forest areas. While older forest areas are required for the interior habitat blocks, they are allowed to move around the landscape through time, thus the initial older forest areas are not specifically reserved during all time periods. It is, however, the initial condition of the public forest land that is important, as very little of it is considered older or layered forests, thus much of is it off-limit for harvest for some time, until the area in each of these classes exceeds 20% of the public forest land. Thus, a heavy reliance is placed on the clearcut harvest of younger stands in the closed canopy condition, stands which have ages in the 30–50-year range generally. A separate analysis of marginal differences in the percentages of structural stages required showed similar small influence on the even-flow harvest levels, except when the maximum percentage allowed in the regeneration class was decreased to 10% or less.

5. Discussion

The hierarchical spatial framework we have described for modeling large-scale, long-term forest policies allows the recognition of fine-scale spatial detail as well as decisions typical of forest landowners in the Oregon Coast Range. The framework is, of course, a simplification and synthesis of a more complex system of land management. Recognition of current and future management behavior of all landowners increases the credibility and realism of simulations. However, achieving reliability in a simulation model is not a trivial task. For example, ecological consequences can differ dramatically, depending on the pattern of land

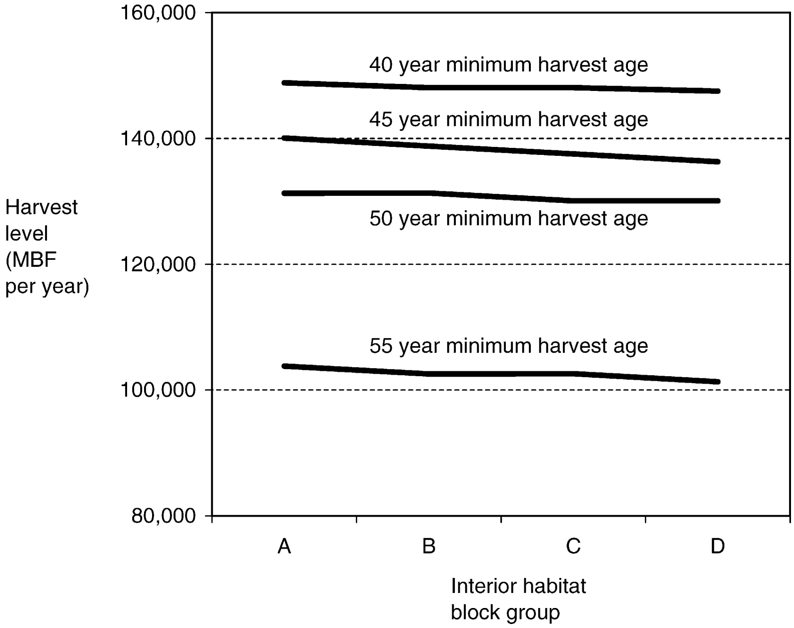

Fig. 12. Annual harvest levels from a simulation of even-flow timber harvest volume with minimum harvest age and interior habitat block constraints on public (state) land in the north coastal region of Oregon (USA).

use activities imposed on a landscape (Franklin and Forman, 1987). Thus, modeling land use activities appropriately is quite important. This may require a major collaboration between scientists, planners, managers, and policy-makers to develop the kind of model that has widespread application and acceptance at the spatial and temporal scales at which it is used. With the hierarchical spatial framework introduced here, fine-scale forest structural conditions are recognized while achieving management goals measured at coarser scales. The recognition of basic simulation units allows one to track the development of forest structural conditions as they may vary with riparian management emphasis, leave tree policy, and management intensity. This also facilitates further analysis of biological effects of forest management alternatives at a fine scale. For example, riparian conditions are retained, rather than lost as a result of assumptions requiring homogeneity of conditions within management units.

We want to make clear that neither the even-flow timber volume objective nor the minimum harvest age constraint are required by law for either the industry or public management behavior processes. These were assumptions we made based, in one case (even-flow), on guidance from the landowners and evidence from recent behavior, and in the other case (MHA), on concerns about potential future constraints on management activity. In the past, the industry has harvested a fairly even level of timber volume in western Oregon because they had the ability to utilize federal timber harvests to buffer changes in timber markets. Federal timber sales have declined dramatically in the past decade, and thus the ability of industrial landowners to continue to harvest a relatively even amount of timber each year in the future is uncertain.

Results of the simulations also indicate that a higher amount of timber volume can be simulated for harvest in the future if the even-flow constraint is relaxed. After the constraining time period (the bottleneck where even-flow is constrained) has passed, standing inventory volumes build up because regenerated stand growth exceeds harvest. Relaxing the even-flow constraint by allowing variable harvest levels could result in solutions with higher total harvest levels and average harvest ages that are closer to the minimum harvest age assumed. We are currently experimented with several approaches in this area: (1) if a target harvest is not obtained in a time period, reduce the target for that time period only; (2) rather than an even-flow goal, use binary search to obtain a target harvest level pattern set by the user, where the harvest levels can vary from one time period to the next, and the entire pattern is shifted upward or downward depending on whether the targets are met.

An infinite number of scenarios can be modeled with the spatial framework, given the continuous nature of some of the constraint values (e.g., MHA, maximum clearcut size), and variations in the transition probabilities. Our next goal is to formulate reasonable assumptions into a "base case" scenario that will be used to compare against realistic alternatives. The results of the base case, specifically timber volume levels and spatial pattern of activities, will be compared against historical data. We plan to model a number of significant alternative scenarios for the entire Oregon Coast Range to help inform stakeholders and policy makers. These scenarios include additional variations on management intensities, minimum harvest ages, riparian restrictions, and tree retention policies.

One of the main limitations of this modeling effort relates to the validation of the simulation process, which is inherently problematic. While projected harvest levels and spatial patterns of activities can be compared against recent activity, forest landscape planning does not lend itself well to validation processes. In forest landscape planning, we project into the future a representation of the current condition of the landscape. When projecting scenarios into the future, a number of real system dynamics are contingent on factors that may have unknown or uncertain distributions, such as climate change and human population growth (Carpenter, 2002). Therefore, the uncertainty surrounding the projections presented here cannot be computed. Some have suggested developing landscape conditions of 20–50 years ago, then projecting those to the present to determine whether current patterns and levels of activity can be simulated well. The crux of the problem with this type of analysis is in developing historical databases containing the detail required for large areas such as those modeled here.

Evaluating alternative future scenarios with forest landscape planning models has value, however, by allowing one to think through decisions when accurate predictions are not possible, by broadening people's perspectives, and by challenging conventional thinking (Carpenter, 2002). Scenarios make it possible to compare alternative policies in light of other uncontrollable aspects of the future. Scenarios provide a range of possibilities, and integrate science with policy, rather than waiting for results of further research (Carpenter, 2002). Individual scenarios are therefore not subject to rigorous statistical validation. Rather, they are tested for robustness against a set of other alternative scenarios, and allow policy makers and managers to understand possible futures, and how they might be influenced by past or present management decisions.

As we have previously noted, with many modeling efforts that address complex behavioral systems and broad mixed-ownership landscapes, there is considerable room for improvement of the simulation process. The public forest management behavior process, for example is quite complex. Through a thorough analysis of the influence of the various constraints on the achievement of management goals, alternative modeling processes, including both the processes to schedule activities and to evaluate constraints, may be developed. In addition, while it appears that the minimum harvest age constraint has the largest impact in both the public and private modeling processes, a further exploration of the interaction among goals and constraints will improve our understanding of the results, and facilitate better communication of the results to stakeholders and policy makers.

Finally, one of the main limitations of the approach described here is that only the behavior of two of the four major landowner groups in the region have been described. We feel confident in our interpretation of their behavior, and have thus presented processes here to modeling it in a spatial and temporal manner. While the area we analyzed was dominated by state and industrial ownership, federal and non-industrial landowners also have a large presence in other portions of the Oregon Coast Range. We have developed preliminary modeling processes for these ownerships as well, in an effort to fully model the behavior of all landowners. However, federal management policies are in a state of flux, thus our understanding of their current behavior continues to be refined (as does the modeling of their behavior). In addition, our understanding of the behavior of the thousands of non-industrial landowners is limited, and currently we use a Monte Carlo process along with gross probabilities of harvest to project the activities of this landowner. We continue to refine these two processes.

6. Conclusions

The hierarchical spatial framework for forest landscape planning presented here allows one to examine alternative forest management policies across large land areas while recognizing fine-scale forest structural conditions as well as decisions typical of forest landowners, which operate at larger scales. This framework allows a more reasonable portrayal of management behavior at the fine-scale while also facilitating broad-scale analyses of forest policies. Sustainability policies encourage maintaining the capacity of a landscape to provide a wide range of values, services, and products desired by society. Landscape planning models that integrate ecological and socio-economic concerns, while adequately modeling the behavior of landowners, can help policy-makers, managers, and other stakeholders think through the implications of potential sustainability policies from both economic and ecological perspectives. Our simulations, for example, indicate that a minimum harvest age constraint has a stronger influence on even-flow harvest levels than do maximum clearcut size or interior habitat area constraints. Even-flow timber harvest level objectives, however, also have an effect on the results, suggesting that a possible relaxation or modification of the objective may be necessary to achieve average harvest ages that are closer to the desired minimum harvest age.

Modeling alternative landscape policies may require recognizing and utilizing multiple spatial scales, thus closely emulating both natural processes and human behavior. We have demonstrated here a spatial framework to facilitate these types of analyses. The resulting forest structural conditions of each policy are recognized, maintained, and reported at a fine scale, accommodating further analyses. The set of additional potential analyses (e.g., wildlife habitat suitability) is therefore broadened, encouraging a more complete picture of the economic-ecological trade-offs of policies.

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