AN ABSTRACT OF THE DISSERTATION OF

Pete Bettinger for the degree of Doctor of Philosophy in Forest Resources presented on April 2, 1996. Title: Spatial Analysis Techniques for Ensuring the Compatibility of Land Management Activities and Aquatic Habitat Goals in Eastern Oregon.

Abstract approved: ______________________________

K. Norman Johnson

A land management scheduling model is developed that uses a Tabu search procedure to schedule timber harvests and road management activities, while simultaneously meeting (over time and space) two aquatic goals, and also providing for an even-flow of timber harvest volume. Decision variables include land units and roads, and they are considered to take on integer (0-1) solutions. Decision choices include those that involve land allocation issues (harvest and road obliteration), and those that involve changes in management practices (using lower tire pressures on certain roads to reduce the amount of sediment produced). The scheduling model included provisions for estimating stream sediment and temperature impacts as a result of the spatial location of management activities, and provisions for projecting the growth and yield of timber stands over time using growth rates derived from yield tables.

The model uses Tabu search procedures to guide the selection of land management activities, and was applied to a 14,643 acre case study watershed

in eastern Oregon. Twenty independent solutions were generated, of which 80 percent were within 10 percent of an estimated global optimum net present value, and all were within 15 percent. Although the limitation to using Tabu search is that one is not assured of obtaining the global optimum solution to a particular problem, the model developed here is an important contribution to forest planning for problems which have 100,000+ integer variables and spatial goals.

An analysis of model results showed significant negative correlation between equivalent clearcut acres (ECA), a commonly used measure of cumulative watershed effects, and a stream temperature index. No correlation was observed between ECA, a stream sediment index, and timber harvest volume levels. These results suggest that sediment and temperature index levels may not be good proxies for ECA (or vice versa).

Finally, the sensitivity of model results was examined using three different representations of the landscape: (a) vegetation units, (b) soils units, and (c) a combination of vegetation and soils units. Results show significant differences exist in terms of net present value, length of road assigned to central tire inflation use per period, stream sediment and temperature indices, ECA, and timber harvest volume levels.

Spatial Analysis Techniques for Ensuring the Compatibility of Land Management Activities and Aquatic Habitat Quality in Eastern Oregon

by

Pete Bettinger

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APPROVED:

Major Professor, representing Forest Resources

Head of Department of Forest Resources

Dean of Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Pete Bettinger, Author

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For his guidance, and for providing me with an opportunity to pursue an integrated doctorate in forest management, planning, and geographic information systems, I would like to first thank the chair of my committee, Dr. K. Norman Johnson. I am honored to have been one of his students. Dr. John Sessions provided constant guidance and encouragement in the pursuit of this dissertation. I owe much of my success to Dr. Sessions.

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There is more to life than graduate school, and my wife Kelly A. Bettinger made sure that I was constantly aware of this. Her patience, support, and love were priceless.

CONTRIBUTION OF AUTHORS

Dr. K. Norman Johnson was involved in the design and writing of two manuscripts. Dr. John Sessions was involved in the design and analysis of the Tabu search algorithm developed in this research, and the writing of two manuscripts.

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DEDICATION

This dissertation is dedicated to my parents,

Janet R. and Lewis F. Bettinger

Spatial Analysis Techniques for Ensuring the Compatibility of Land Management Activities and Aquatic Habitat Quality in Eastern Oregon

Chapter 1

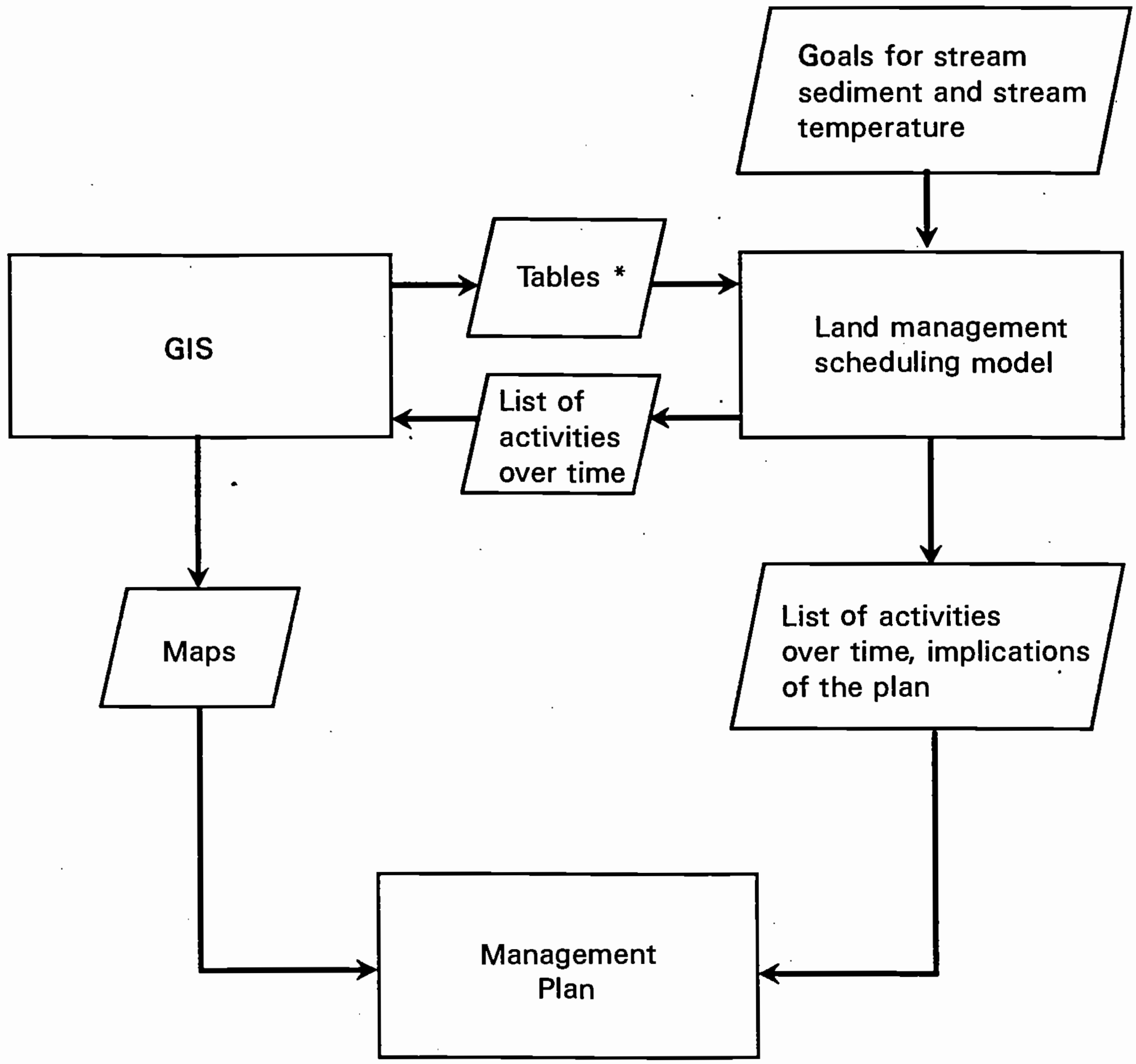
Introduction

The cumulative effects of seemingly insignificant habitat alterations by humans or natural processes may dramatically change the productivity and diversity of fish populations (Meehan 1991) and other resources. In the Columbia River basin of the Pacific Northwest, the central issue in resource management is the protection of certain stocks of anadromous fish designated as threatened or endangered under the federal Endangered Species Act. The more fundamental problem is the real or potential loss of naturally spawning, wild Columbia River salmon stocks, and the declining populations of fish in these stocks (Cornelius 1993). Other resource goals also receive considerable support from the public. Thus goals for National Forest management in eastern Oregon have recently begun to emphasize resources other than wood production, and are becoming "restrictive" to timber sales. Therefore, the development of a land management scheduling model that would ensure the compatibility of a least some of these goals (in this case aquatic habitat goals) with land management activities seemed to be an important undertaking.

Given the legal and societal priorities and management goals for various species and their habitats, management planning has become arduous. The current planning process consists of piecemeal efforts in which forest plans are developed and the effects on various goals subsequently evaluated. These plans area generally developed using linear programming techniques, and thus the effects of management actions on resources of interest are based solely on the area affects (e.g., the number of acres affected). The measurement of goals for certain species of interest may require the use of models which take into account more information than just the amount of area affected, perhaps even spatial information. For planning goals that are dependent on landscape features, spatial analysis (analysis which utilizes variables that identify where entities are in relation to each other) can be used to provide spatial information. Optimizing management actions with spatial analysis requires the use of techniques other than linear programming. Thus developing a spatial-analysis technique for predicting the effect of management activities on measurable resources appeared to be useful.

In the course of this research, I have developed a mathematical programming technique that can be integrated with a geographic information system (Figure 1.1) to produce feasible and efficient solutions to problems with aquatic habitat goals (stream sediment and temperature) and land management activities (timber harvests and road management). This technique attempts to develop feasible solutions (with respect to the aquatic habitat goals) and locates the one with the highest net present value (NPV). Stream sediment and stream temperature estimation models, both of which were previously developed, are used to model the functional relationships between land management and aquatic habitat. The types of management activities that I consider in this model include:

Figure 1.1. Flow of information in the development of a land management plan, utilizing a geographic information system (GIS) and an independent land management scheduling model.



*GIS Tables: Units (Volume per unit area, age, soil type, distance to stream, etc.), Roads (road length, road standard, distance to stream, etc.), Streams (stream length, stream class, adjacent units, etc.), and Entry nodes (unit, entry point into road system for each logging system).

Harvesting systems:

- Partial cutting on a 30-year return interval, all tree species, no cutting before age 50 or after age 150.
- Partial cutting on a 50-year return interval, all tree species, no cutting before age 50 or after age 150.
- Clearcutting and thinning. If thinning is the first harvesting activity, it can occur between the ages of 50 and 100. Clearcutting follows 20 years later. If clearcutting is the first harvesting activity, it can occur between the ages of 101 and 150. After a clearcut has occurred, thinning occurs at subsequent age 50, and clearcut at age 70. Lodgepole pine stands only.
- Not harvesting

Logging systems:

- Ground-based
- Skyline
- Helicopter

Road standard changes:

- Standard rock to central tire inflation
- Standard rock to obliterated
- No change in road standard

The decision variables that I use include those that involve land allocation issues (timber harvesting and road management), and those that involve changes in management practices (requiring lower tire pressures for log trucks on certain roads, to reduce the amount of sediment produced). The second type of decision variable is considered a temporary action, it does not change the state of the decision variable, and is used to perhaps help us meet the aquatic habitat goals.

The land management scheduling model that I have developed is applied to a 14,643 acre watershed on the Wallowa-Whitman National Forest in eastern Oregon. The primary hypothesis is that the mathematical programming technique will produce feasible and efficient forest management plans. This hypothesis is tested by estimating a global optimum NPV from an asymptotic distribution of model solution NPVs, and then comparing these solutions to the estimated optimum. Extreme value theory is used to estimate the global optimum.

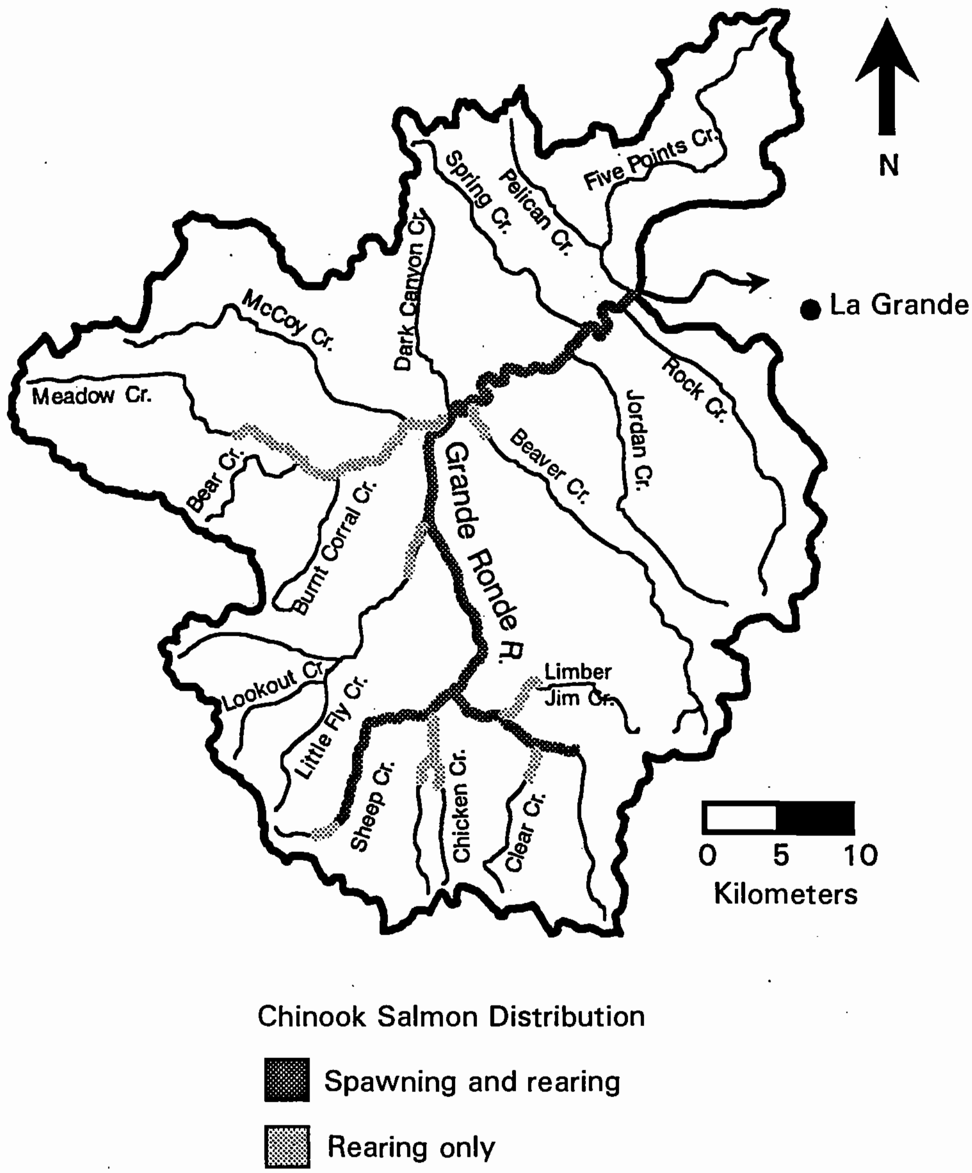
A second hypothesis that I test is whether equivalent clearcut acres (ECA), a measure of landscape use, captures the variation in other measurable goals (stream sediment, stream temperature, timber harvest volume levels). ECA is a measure of landscape use, and is used by National Forests to describe in aggregate the level of management use in a landscape. My three sub-hypotheses are: 1) that there is no correlation between ECA and the other goals; 2) that there is no correlation between timber harvest levels and aquatic habitat goals; and 3) that there is no correlation between stream sediment and stream temperature levels. These sub-hypotheses are tested with a correlation analysis and a bootstrapping technique.

Two types of decision variables are used in the land management scheduling model, land units and roads. There has been some debate recently concerning the appropriate definition of land units, therefore a third hypothesis I test is that the definition of land unit decision variables does not significantly affect the results (net present value, ECA, stream sediment and temperature levels, etc.). I utilize three types of land units to test this hypothesis: 1) vegetation units, 2) soils units, and 3) a combination of vegetation and soils units. For each type of land unit, a number of solutions (the best feasible solutions from independent runs of the mathematical programming technique) are produced. This hypothesis is tested using a non-parametric technique (the Kolmogorov-Smirnov test).

The expected results of this research will contribute to the broader theoretical framework of forest planning by allowing estimation of aquatic habitat goals to occur simultaneously with decision variable choices, thus potentially controlling the scheduling of land management activities. Rather than relying on a posterior measurement of aquatic habitat suitability, sediment and temperature levels may then be used as goals to achieve within the development process of a land management plan.

Below I briefly describe the setting for this research (the Upper Grande Ronde River basin [Figure 1.2] on the Wallowa-Whitman National Forest in eastern Oregon), discuss some recent legal and administrative actions that have affected forest planning in eastern Oregon, and attempt to put this research into context by comparing the traditional forest management philosophy (multiple-use management) with a more recent adaptation of this philosophy (ecosystem management). Finally, I provide an overview of mathematical programming approaches which can be used to attempt to meet goals set under either philosophy. The result of these discussions provides the reasoning behind the

Figure 1.2. The Upper Grande Ronde River basin, with current range of spawning and rearing habitat for spring Chinook salmon (Oncorhynchus tschawytscha).



development of a spatial-analysis technique to ensure the compatibility of land management activities and aquatic habitat quality in eastern Oregon.

The Upper Grande Ronde River Basin

From the several resource goals that guide National Forest management in the upper Grande Ronde River Basin, a subset of five (Table 1.1) was developed from a search of the literature and from discussions with resource specialists and hydrology and fisheries experts familiar with the basin. Because careful identification of this subset was important to the study, I involved U.S. Forest Service personnel and researchers who were knowledgeable about current scientific research related to the goals. The five broad goals identified were: 1) to produce high quality fish habitat, 2) to maintain high quality elk habitat, 3) to produce high quality habitat for other wildlife, 4) to restore and maintain forest conditions within natural variability, and 5) to contribute to community stability.

Produce High Quality Fish Habitat

Spring chinook salmon (Oncorhynchus tschawytscha) and steelhead trout (O. mykiss) comprise the bulk of anadromous fish species spawned on the Wallowa-Whitman National Forest. Populations of spring chinook have been reduced substantially since 1960, partly because of passage problems further downstream from the Grande Ronde River. Splash damming and associated log drives (from the late 1880's to about 1919) are believed to have had a devastating effect on aquatic life and stream channels (McIntosh 1992, TWG

Table 1.1. Forest resource goals and measures of attainment for National Forests in eastern Oregon.

Goals and quantifiable factors	Measure	Recommended level
I. Produce high-quality fish habitat		
Reduce sedimentation	Fines	<15-25% fines
Reduce stream temperatures	Temperature	<58°F stream temperature
Increase number of pools	Pools per mile	Number based on stream wetted width
II. Maintain elk habitat		
Manage distances between forage and cover	Distance	Meet distance requirements between cover and forage areas of minimum size (wildlife/timber allocation areas)
Maintain minimum cover levels	Cover and open road density	>30% marginal or satisfactory cover (timber production allocation areas) <2.5 mi/mi^2 open roads (timber allocation areas) <1.5 mi/mi^2 open roads (wildlife / timber allocation areas)
Maintain HEI[a]	HEI[a]	>62% HEI (timber allocation areas) >74% HEI (wildlife / timber allocation areas)
III. Produce high-quality habitat for other wildlife		
Provide habitat corridors	Habitat corridors	None

Table 1.1 (cont.). Forest resource goals and measures of attainment for National Forests in eastern Oregon. Recommended levels from the Wallowa Whitman National Forest Plan (USDA Forest Service 1990), a timber sale screening process, and a Conservation Strategy for the Upper Grande Ronde River basin (USDA Forest Service 1994).

Goals and quantifiable factors	Measure	Recommended level
III. Produce High-Quality Habitat for Other Wildlife		
Provide habitat corridors	Habitat corridors	None
Provide snags and down logs	snags and down logs	Snags: 100% potential population for primary cavity nesting birds. Down logs: varies by plant assoc.
IV. Restore and Maintain Range of Natural Variability		
Maintain land in late and old seral stages	Seral stage distribution	10-25% in late or old seral stages
Prescribed fire	None	None
Selectively harvest undesirable tree species	None	None
V. Contribute to Community Stability		
Contribute to economic health of the community	Employment and personal income produced as a result direct or indirect jobs	None
Produce a non-declining even-flow of timber harvest volume	Harvest levels from period to period	Non-declining timber yield
Efficiency	Net present value	Highest net present value

[a]HEI = Habitat Effectiveness Index

1992). Stream habitat has also been degraded from riparian timber harvests, stream channelization, livestock grazing, and mining. Since 1941, the level of livestock grazing has declined in the Upper Grande Ronde River basin, and timber harvests and road densities have increased (McIntosh 1992). Measurable goals that may be used to improve the quality and quantity of aquatic habitat, include reducing summer stream temperatures, reducing stream sediment levels, and increasing the number of pools.

The loss of riparian vegetation (and resultant decrease in stream shading) has significantly increased summer stream temperature levels in the Grande Ronde River (TWG 1992). Stream temperatures frequently exceed State standards and are considered lethal for spring chinook salmon. Altered levels of temperature and dissolved oxygen and changed rates of sedimentation and nutrient delivery to streams are the principal aquatic consequences of timber harvesting (Meehan 1991). Transportation systems affect fish populations and aquatic habitat as a result of sediment delivery to streams from surface erosion and mass movement of destabilized soil (Meehan 1991). Draw-bottom and unimproved roads are major contributors to sedimentation (USDA Forest Service 1994). Paved roads contribute less sediment than gravel-surfaced roads (Reid and Dunne 1984), and road-cut slopes more than road treads (Megahan and others 1983).

Pools provide rearing habitat for juvenile fish and resting habitat for adult fish before spawning, as well as refugia during catastrophic events. Pools are a function of riparian management and channel morphology, however, the causal mechanisms of disturbance are not clear.

Stream temperature is primarily a function of activities that increase sunlight reaching the stream surface: harvesting in riparian zones, openings created by roads, fire, and livestock grazing. Effects on stream temperature are spatial in that only activities within approximately one mature tree height affect the amount of light reaching the stream surface, assuming no topographic shading. The standards set in the Conservation Strategy (USDA Forest Service 1994) for meeting this objective are given in Table 1.2. Stream sediment is a function of several factors (e.g., soil type, type of activity or natural event) including the distance from a sediment-producing activity to the stream system. So both of these goals theoretically have a spatial component in their estimation.

In this research I estimate the impacts of land management activities on stream sediment and temperature using established models. I do not evaluate the number of pools because I have not identified a model for predicting pool frequency as a function of land management activities or natural processes.

Table 1.2. Conservation Strategy requirements for stream temperatures in the Upper Grande Ronde River basin (USDA Forest Service 1994).

Stream temperature	≤ 6th order stream	> 6th order stream
Maximum daily (summer)	61°F	68°F
Maximum 7-day	58°F	65°F
Minimum daily	32°F	32°F

Maintain High Quality Elk Habitat

Elk are probably present in greater numbers now than in any recorded time. Goals that I identified for elk habitat include: managing the distance between forage and cover, maintaining minimum cover levels, and maintaining a habitat effectiveness index (Table 1.3). The desired distribution of mature conifer stands (which provide optimal cover) and forage areas vary with the objectives of each forest land-allocation area (specific areas to which prescriptions have been assigned for achieving specific objectives). These distributions are a function of the size and location of regeneration harvests with respect to mature timber and natural forage areas such as meadows. Previous research has been performed to ensure that this goal can be met in the development of a land management plan (Bettinger et al. 1996). Maintaining minimum cover can be achieved with an area-based goal in which stratums are developed to include all areas considered to have acceptable cover for elk. Minimum area levels of each stratum can then be achieved using many techniques, including linear programming.

The habitat effectiveness index (HEI) is a quantitative measure of habitat quality for elk (Thomas and others 1988, Hitchcock and Ager 1992). It is affected by adjustments of the ratio between cover and forage, cover quality, forage quality, and open road density. Several variations of HEI account for habitat use by geographic region. Standards for HEI are available for almost all National Forests in the Pacific Northwest, although validation of the model has not been completed (Hitchcock and Ager 1992). I do not incorporate an HEI model into the land management scheduling model developed here.

Table 1.3. Example of National Forest standards and guidelines for big game resources on the Wallowa-Whitman National Forest (USDA Forest Service 1990).

Timber production allocation areas (Forest Plan, Management Area 1)	
Open road density	Generally not to exceed 2.5 miles/mi^2; within elk winter range, not to exceed 1.5 miles/mi^2
Forest cover	At least 30% land in an analysis area maintained as marginal or satisfactory cover. (Marginal cover $\geq$40% $\geq$10 ft tall; satisfactory cover $\geq$70%, multistoried, $\geq$40 ft tall)
Habitat effectiveness index	62% on average
Wildlife/timber allocation areas (Forest Plan, Management Area 3)	
Open road density	Generally not to exceed 1.5 miles/mi^2
Elk summer range	At least 80% of treated area to be within 600 feet of a hiding or thermal cover patch (at least 6 acres), and within 900 feet of a thermal cover patch (at least 40 acres)
Elk winter range	At least 80% of treated area to be within 600 feet of a thermal cover patch (at least 6 acres)
Regeneration	10 feet tall or greater before adjacent units are cut
Local roads	Closed to meet the needs of big game and the 1.5 mi/mi^2 standard
Habitat effectiveness index	74% on average

Produce High Quality Habitat for Other Wildlife

Habitat corridors were identified as a goal to achieve in producing high quality habitat for other wildlife. However, specific quantitative measures to achieve habitat corridors are undefined, site-specific, and species-specific. Corridors are viewed as major links of otherwise fragmented and isolated patches (Morrison and others 1992); however, they function at different scales for different species (Morrison and others 1992). The type and juxtaposition of patches across the landscape may be modeled as a network of patches that meet species-specific criteria. Sessions (1992) has solved the habitat corridor problem as a network problem, and this technique is available in SNAP II+ (Sessions and Sessions 1993), a harvest scheduling model which also uses spatial analysis to achieve goals.

Most wildlife species associated with late-successional forests rely on moderate to high levels of snags and down logs for nesting, denning, roosting, and feeding. Past management practices have greatly reduced the number of large snags and down logs in managed stands. According to the timber sale screening process, enough snags ($\geq$15 inches diameter at breast height) must be left on-site (after harvesting) to meet 100% potential population levels of primary cavity nesting birds. Twenty down logs per acre should be left on-site in mixed conifer stands, and all down logs should be left on-site in ponderosa pine stands. Since data concerning the initial levels of snags and down logs are unavailable, I have chosen not to model these goals here. However, adjustments to yield tables can be made to recognize reduced harvest levels as a result of leaving trees on-site for wildlife habitat purposes.

Restore and Maintain Forest Conditions within Natural Variability

Sizeable amounts of forestland area in eastern Oregon, composed of Douglas-fir and true fir species, have died as a result of overcrowding on drier sites, drought, and insects (Johnson et al. 1995). Large stand-replacing fires have also recently occurred, due to a resulting build-up in fuels. And, a major portion of the live forest is under stress because stands are too dense, increasing the likelihood of future mortality in both understory and overstory. Finally, the distribution of late-successional stands is lower than the range estimated for pre-settlement forests. Historical forest management practices have contributed to these problems, and have increased the uniformity of forests in eastern Oregon (Johnson et al. 1995).

Removing undesirable tree species from pine and larch sites, and utilizing prescribed fire, may reduce stress in overstory trees, reducing the susceptibility of the forest to insect attack and crown fires. These efforts may help lead to the restoration of ecosystems in eastern Oregon and move them back toward historical conditions. Guidelines like those from the timber sale screening process, which emphasize the diversity of pre-settlement conditions, may help ensure that future forests are more heterogenous. Active forest management can help achieve this type of landscape (Johnson et al. 1995).

Historic percentages of land in various structural stages are available to help guide the development of more heterogenous forests (Umatilla National Forest 1994). Although data is lacking to describe the statistical distribution of the natural range of variability, these percentages can be used as a template for ecosystem sustainability. However, the published ranges of natural variability are broad (USDA Forest Service 1993), making a firm goal elusive. In any event, area-based constraints (maintaining a minimum or maximum amount of land area in a given seral stage) can be used to meet these goals. I did not identify a range of natural variability to use as a goal to meet in this research, although I do acknowledge the shortage of late-successional forests and hope to meet this goal by not harvesting any stand where the dominant trees become ≥150 years of age. Finally, modeling stochastic natural processes (drought, insect attack, wildfire) that affect forest health is not within the scope of this study.

Contribute to Community Stability

In rural areas of Oregon, some component of community stability can be related to timber harvest levels and associated employment. About 50% of the timber processed locally comes from the Wallowa-Whitman National Forest, and about 7-12% of local employment is in the timber sector. Historically, timber harvest levels on the Wallowa-Whitman National Forest were higher than the non-declining even flow calculated for the forest plan in 1990 — a result of failure to fully recognize unit plan direction, accelerated harvest of lodgepole pine, losses due to insects, and more precise estimation of standing timber volume. During the last 5 years, harvest levels have declined precipitously, and timber sales appear to be increasingly designed for achieving other ecosystem goals, a trend possibly begun in response to the forest health problem and the resultant timber salvage program (McKetta and Associates 1994). Further reductions in timber harvests will result in more displaced workers and lost income, with impacts being greatest in rural areas where workers must either leave, accept less desirable work in the immediate area, or commute to jobs in other communities (Carlson 1994). Timber harvesting can contribute to economic stability by providing jobs and an even-flow of timber sales. The number of jobs generated directly and indirectly by a timber sale is rather difficult to quantify, but a non-declining flow of timber is a goal achievable by smoothing out sustainable harvests over a projection period.

I used net present value (NPV) to rank the solutions developed by my land management scheduling model, believing it to be useful for the following reason: the activities implemented should maximize net social welfare and minimize federal cost to taxpayers.

Summary of Forest Management Goals used in this Research

From the five broad sets of goals previously discussed, I will attempt to ensure the compatibility of aquatic habitat goals with land management activities. Two measures of aquatic habitat (stream sediment and temperature) will be utilized, which generally require spatial and temporal information regarding the placement of land management activities. Two measures of community stability (even-flow of timber harvest volume and efficiency) will also be considered. Several types of land management activities (timber harvesting and road management) will be assessed in relation to these goals.

Recent Legal and Administrative Activities Affecting National Forest Management in Eastern Oregon

In the early 1980's it was noted that virtually every study concerning Columbia and Snake River anadromous fish runs concluded that the principal cause of the depleted runs was the development and operation of federal and non-federal dams (Natural Resources Law Institute 1982). By the late 1980's attention spread to the effects of land management on fish habitat quality, as experts agreed that both the National Environmental Policy Act (NEPA) and the National Forest Management Act (NFMA) require the Forest Service to embrace an ecosystem approach to land management, noting the increased concern of the effects of timber harvesting and logging road siltation on anadromous fish habitat (Natural Resources Law Institute 1987). Since the development of the Wallowa-Whitman National Forest Plan in 1990, four major actions have influenced forest planning in the Upper Grande Ronde River basin: 1) the listing of salmon stocks as endangered under the Endangered Species Act (ESA) and subsequent consultation with the National Marine Fisheries Service (NMFS); 2) the development of a timber sale screening process for eastside National Forests; 3) recommendations by the Technical Working Group (TWG) of the Upper Grande Ronde River, and 4) the adoption of PACFISH guidelines (USDA Forest Service and USDI Bureau of Land Management 1995) for the protection of aquatic habitat. In addition, recent legal opinions regarding the consideration of cumulative effects by the Forest Service have influenced the need to evaluate the effects of land management activities on a watershed scale.

An injunction was filed on 10 October 1993 against future activities on the Wallowa-Whitman and Umatilla National Forests (Pacific Rivers Council v. Robertson, Civil No. 92-1322-MA, 9th Cir. 1993) seeking declaratory and injunctive relief on the grounds that the Forest Service violated the ESA, by failing to engage in Section 7 consultations with NMFS regarding the effects of the two Forest Plans on spring chinook salmon. The goal of the Pacific Rivers Council was to seek an injunction against the continuation of all activities which have been identified by the Forest Service as activities which "may affect" listed salmon species. Although the Forest Plans themselves should have no direct impact on listed salmon, actions authorized under the Plans may adversely affect the species. The Ninth Circuit Court found that the Forest Service did violate the ESA by failing to initiate the Section 7(a)(2) consultation process in Forest Plan development. The scope of the injunctive relief covers any proposed future actions which may cause an irreversible or irretrievable commitment of a resource. Timber sales are such Section 7(d) commitments. Therefore all future projects involving timber sales cannot proceed without consultation.

The Forest Service has since conducted consultations regarding land management activities on a site-specific basis with NMFS. During the consultation process, only those activities which can be classified as "beneficially affecting" or "not likely to adversely affect" listed species under Section 7 of the ESA have been permitted to continue.

The timber sale screening process was developed for eastside National Forests as a result of a need to be consistent with NFMA viability requirements for old-growth species. Timber sale projects are subsequently screened with respect to riparian area guidelines, ecosystem guidelines concerning the historical range of variability of late and old seral stages, and wildlife guidelines primarily concerned with maintaining habitat connectivity and reducing habitat fragmentation of late and old seral stages. The wildlife screens are considered the most restrictive step in the process (P. Boehne, USDA Fisheries Biologist, Wallowa-Whitman National Forest, La Grande, OR, pers. comm.).

The TWG (1992) developed an anadromous fish habitat protection, restoration, and monitoring plan for the Upper Grande Ronde River. The plan is recommended for inclusion in the policies and management guidance for agencies planning activities in the Upper Grande Ronde River basin. The plan is based on an interpretation of existing scientific information, with the goal of optimizing the freshwater survival of anadromous fish. The Wallowa-Whitman National Forest administers about 80 percent of the land in the Upper Grande Ronde River basin, and was a cooperator in the development of the plan (TWG 1992). A subsequent Conservation Strategy (USDA Forest Service 1994) was developed to incorporate the recommendations of this group. The PACFISH guidelines for the protection of aquatic habitat are a recent addition to Standards and Guidelines for Forest Plans, in an attempt by the Forest Service to avoid appeal and litigation.

In summary, all future activities on the Wallowa-Whitman National Forest which may affect listed fish stocks cannot proceed without project planning consultation with NMFS. Timber sales are included in these activities. Project planning is also guided by the development of a timber sale screening process and by guidelines concerning anadromous fish habitat protection, which are formalized in the PACFISH report.

Legal suits brought against the Forest Service based on NEPA have also affirmed a duty on the Forest Service to consider the cumulative impacts of land management activities on fish habitat and water quality (Craig 1987). Over the years, the courts have made it clear that the Forest Service must consider the cumulative effects of its actions from an ecological perspective. Cumulative actions include incremental impacts on the environment when added to other future, present, or past activities, regardless of who conducts the action (Craig 1987). Instead of analyzing one activity in isolation from other activities, NEPA requires the Forest Service to develop environmental impact statements that use ecological (spatial) boundaries in analyzing the interrelationships between resource components (Craig 1987). Thus, a cumulative impact analysis of all reasonably foreseeable actions within an ecological boundary must be completed in the hopes of attaining more ecologically sensitive long-term planning (Craig 1987). Watershed-level planning on federal land may help the Forest Service meet some of these requirements.

Forest Management Philosophies

As discussed above, many current forest management problems involve goals which require a landscape- or watershed-level perspective. For example, the cumulative effects on water quality and fish habitat, resulting from land management activities require a landscape perspective (National Research Council 1990). Thus there is a need to investigate the consequences of land management activities applied over time and space (National Research Council 1990). Two forest management philosophies are currently under debate: 1) multiple-use management, the philosophy under which many National Forest plans in the Columbia River basin were developed, and during which timber production was a primary focus, and 2) ecosystem management, a slightly different philosophy which treats commodity production goals as secondary to the maintenance of system processes, and gains much of its theory from the field of landscape ecology.

Multiple-Use Management

The philosophical basis for multiple-use management is utilitarian. The premise behind multiple-use management is that there are a number of outputs expected from the landscape, each with explicit objective levels (Sedjo 1995). For example, timber and grazing activities typically have objectives stated in terms of annual harvest volume or level of animal unit months, respectively. With this in mind, explicit decisions are made to manage the landscape for these outputs. Multiple-use management has historically been driven by socially defined goals and objectives. The need to address the trade-offs among the various resources is a necessity, so that the social value to society can be optimized. However, the variables which must be weighed in making land management decisions generally do not include environmental quality, endangered species, and other goals (Dana and Fairfax 1980).

Multiple-use management does not meet the criteria outlined by the Society of American Foresters task force on sustaining long-term forest health and productivity (SAF 1993) for maintaining long-term productivity of all forest values. Specifically, multiple-use management: 1) does not ensure the integrity of the system is maintained (by focusing on too small of a scale), 2) does not meet the desires of people for non-commodity values, and 3) is difficult to implement given the more recent emphasis on non-commodity values (SAF 1993). Multiple-use management has been long perceived as a balancing process, but the problem has become compounded by the acknowledgement of diverse goals and the increasingly complicated political process, hence the compromises produced under multiple-use management never satisfy everyone (Dana and Fairfax 1980). Furthermore, multiple-use management occurred during a period when we thought that natural forests could easily and simply be transformed into highly regulated and much more productive forests.

Ecosystem Management

In a response to changing societal expectations and management challenges, and an increasing body of knowledge indicating "forests" are indeed more complicated than tree farms, many public agencies are attempting to embrace what they consider a new management paradigm, ecosystem management. Within the context of ecosystem management, forested ecosystems must be diverse, healthy, productive and sustainable (Guldin 1996). Ecosystem management thus encompasses the need to protect and restore ecological structure, function, and processes in order to sustain natural resources over the long-term (Czech 1995). Further, it is a concept wherein activities are evaluated within the context of economic, ecological, and social interactions in a defined area or ecoregion, and over time (Thomas 1995), and embodies the principles and practices of ecological paradigms such as hierarchy theory to reach the goals of healthy and sustainable systems, but also recognizes people as the dominant part of the ecosystem. Therefore human influences, values, and desires must be considered.

Successful ecosystem management requires matching land management practices to the achievement of a desired future condition of goals across various spatial and temporal scales (Thomas 1995). As a result, a sustainable extraction of commodities may be allowed if the forest ecosystem can be maintained in a healthy state. Ecosystem management offers a way to view ideas, management, and agricultural activities in context, over time and space. The recognition of how each component nests within larger components is the foundation of the ecological approach to management.

Landscape ecology and conservation biology can provide ecological paradigms as alternatives to the traditional views of forest management, and allow a more spatially and temporally integrated process to direct management of the ecosystem. Hierarchy theory is one of these principles, and is concerned with systems that can be decomposed into discrete functional components at different scales, and thus have an organized complexity (Urban et al. 1987). An understanding of the hierarchical nature of ecosystems is critical to the development of management strategies for ecosystem sustainability (Everett et al. 1994). This approach assumes that if similar landscape patterns and processes are maintained, reflecting those that governed historical species evolution and survival, a full complement of species will persist, and biodiversity will be preserved (Everett et al. 1994). Using a hierarchical framework will also help decision-makers frame resource management issues within an ecological context (Carpenter et al. 1995).

At the patch level, measurements are confined to identifying and characterizing the spatial properties of individual patches, where the boundaries of patches are meaningful only when referenced to a particular phenomenon at an appropriate scale (Baskent and Jordan 1995). At this scale, fairly close estimates can be made for many goals, thus the problem formulation can be a reasonable representation of forest conditions. At a landscape level, spatial representation of the entire forest landscape is represented by a single value. Distinctions between small and large scales are conceptual more than procedural (Kirby et al. 1980). At this scale, the quantity of data required may make precision impossible (Kirby et al. 1980). Information on environmental potential provided by these two classifications can be integrated with information related to existing social, economic, and environmental conditions in order to implement ecosystem management through planning, analysis, and decision-making (Carpenter et al. 1995).

Science can become a part of the implementation and refinement of ecosystem management, and provide the framework for monitoring and analyzing results to determine progress towards meeting ecosystem goals. Science can therefore provide the knowledge for at least a portion of the basis behind management decisions (Norris 1995).

Mathematical Programming Techniques

Several mathematical programming techniques can be utilized to meet the goals of multiple-use or ecosystem management. The specific techniques to use to solve problems which will take into account stream sediment and temperature goals will depend on the specific type of problem being solved. Many mathematical programming techniques have been used for forest planning, including linear programming, integer programming, dynamic programming, binary search, and heuristic programming. Some of these techniques arrive at globally optimal solutions, and others produce feasible solutions which are near-optimal.

Linear Programming

Linear programming (LP) is a mathematical programming technique which utilizes linear representations of the constraints to search all feasible solutions and find the one that is optimum, according to the objective function (Davis and Johnson 1987). The decision variables are those things which can be controlled in the short-run to influence the total value of the final solution, or the things about which decisions are made (Dykstra 1984). All of the decision variables can assume any real number, joint interactions between variables are not allowed, and none of the variables can assume a negative value. In addition, all coefficients and right-hand-side elements in the LP model are known constants (Dykstra 1984). There is no limitation on the units used in the objective function, as long as they are quantitative and consistent, and the objective function and all constraints must be strictly linear over the entire range of permissible levels of activity (Dykstra 1984).

LP models always provide optimal solutions within the constraints of the problem, otherwise the problem is infeasible and no solution is found (Leuschner 1990). Sensitivity analyses are easy to evaluate with LP techniques, since a rich amount of data is provided (e.g. reduced costs, dual prices) whose interpretation is well documented (Leuschner 1990). LP has the potential to include thousands of decision variables, and the greater the number, the more focused the decision guidelines. However, with more decision variables, more detail is required by the program, and the cost of obtaining a solution increases (Leuschner 1990). Most forest applications require extensive aggregation to meet these dimensionality restrictions, thus decision variables may require disaggregation before they can actually be implemented; in addition, the optimal value from LP can be infeasible, inferior, or both, when compared to disaggregated approaches (Yoshimoto 1990). LP has been used in forestry applications to model adjacency constraints, yet the resulting nonintegral solutions are difficult to interpret and may be impossible to implement (Lockwood and Moore 1993).

Most forest planning models utilize area-based linear programming algorithms, and determine forest output levels in the presence of forest-wide constraints (Jamnick and Walters 1993). These models are area-based in the sense that the relationships (e.g., timber production, grazing production) embedded in the models generally are a function of the amount of area of decision variable (e.g., land unit) that is scheduled for use. Area-based algorithms can use aggregated land units (stratums) and averaged cost and yield estimates, yet they cannot explicitly recognize site-specific and operational considerations that actually guide forest management activities. And, area-based forest management scheduling models may overestimate the spatial feasibility of allowable cuts (Clements et al. 1990). Operational constraints found in forest management problems include rules and regulations affecting the implementation of forest practices, and are usually the most difficult to incorporate into long-term forest planning analyses due to the spatial relationships they entail (Jamnick and Walters 1993). Operational forest planning is very difficult due to the size of a typical model formulation and the relatively large number of decision variables which may have to be considered binary (0-1) or integer (Murray and Church 1993). Since spatial constraints quickly become unwieldy in a linear program, an alternative often must be used (Jamnick and Walters 1993).

Integer Programming

Integer programming (IP) is similar to LP in that it deals with the maximization or minimization of a function of many decision variables subject to inequality or equality constraints, yet there are integer restrictions on some or all of the decision variables (Yoshimoto 1990). In order to obtain more precise solutions in forest management scheduling, particularly those with spatial concerns, many decision variables are required to be 0-1 integer (Yoshimoto 1990). Thus integer solutions are required of mathematical programming problems that involve quantities which are considered indivisible (Dykstra 1984).

The decision variables used in IP are similar to those used in LP, with the exception that some (or all) are restricted to being integer values. In addition, the objective function and constraints are similar to LP, with the exception of those constraints which may force a value to become an integer. Several algorithms can be used to locate IP solutions, but most first determine the optimal LP solution and subdivide the solution space from there. Two algorithms are commonly used in IP; the branch and bound algorithm and the cutting plane algorithm. The branch and bound algorithm evaluates only a small fraction of the total number of possible IP solutions, yet locates the optimal IP solution. The cutting plane algorithm cuts the solution space into several planes, and terminates when it isolates the optimal integer solution. When the number of decision variables is large, the optimal solution should ideally be located in the earliest stages of the IP algorithm, or some other technique used, such as heuristic programming (Yoshimoto 1990). With either method, the number of decision variables can be large (100,000+), yet the solution time may range from only a few minutes to never, depending on the problem formulation (R. Guy, CPLEX Optimization, Inc., Incline Village, NV, pers. comm.).

Monte Carlo IP (MCIP) algorithms have been used in forestry applications to generate solutions to mixed IP (MIP) formulations (Clements et al. 1990), since IP or MIP formulations have severe limitations in handling combinatorial problems (Lockwood and Moore 1993). In an MCIP application, random solutions to MIP problems are generated, tested for spatial and temporal feasibility, and subsequently evaluated against an objective function. MCIP algorithms can handle problems that are too large or complex to solve with a traditional MIP or IP approach (Clements et al. 1990). Nelson and Brodie (1990) used MCIP, and Jones et al. (1991) used MIP to incorporate road work decisions into a planning context. Hof et al. (1994) and Hof and Joyce (1992) used an IP approach to solve small wildlife problems that involve the distribution of forest classes.

Dynamic Programming

Dynamic programming (DP) is a sequence of interrelated decisions that are made in such a way that the overall effectiveness of a management plan is maximized (Dykstra 1984). Most applications of DP have been at the stand-level, optimizing the management of individual stands, rather than the simultaneous management of an entire forest (Leuschner 1990). Three types of variables make DP different than LP and IP; stage variables, state variables, and control variables. Stage variables define the sequence in which decisions are made, and usually are described in terms of time (Leuschner 1990). State variables describe the system's behavior over all stage variables, and control variables (decision variables) are those decisions that are chosen directly, and affect the state variables in a definable manner (Leuschner 1990). The constraints used in DP are generally described as the boundaries within which the state and control variables lie, defining whether a state is admissible to the problem or not (Leuschner 1990).

The objective of DP is to optimize some function of the state variables, and a true global optimum is located during the search (Leuschner 1990). An interesting facet of DP is that whenever one is determining the optimal solution, the optimal policy for the remaining stages in the analysis is independent of any policy adopted in previous stages (Dykstra 1984). DP is also different than LP and IP in that the equations used in DP can be non-linear (Leuschner 1990).

One disadvantage of using DP is that no single algorithm can be developed to solve all of the problems satisfying the requirements of the DP structure (Dykstra 1984). Another disadvantage is that the number of calculations required to solve DP problems tends to explode as new decision variables are added to the problem (Leuschner 1990).

Binary Search

Binary search is a search routine in the sense that the algorithm starts with a bounded solution space and reduces the range of bounds repeatedly, dividing the solution space into two parts, determining at each step which of the two parts has the optimal value. There is no objective function which is optimized subject to constraints. The whole objective variable is programmed into the routine, and the routine iterates until it converges on a solution. The ending condition is usually stated as a solution which lies within a tolerance range of improvements over the previous iteration (Leuschner 1990).

Decision variables used in forestry applications of binary search are usually the annual harvest volumes, and it is difficult to include budget and wood flow constraints in a net present value optimizing binary search routine (Leuschner 1990). Binary search does not allow for varying rotation ages, requires a growth and yield function to be included in the program, and requires inventory data to be calculated at each iteration of the program (Leuschner 1990). Binary search does not necessarily provide an optimal solution to a problem. It only enters the neighborhood of an optimal solution. In addition, sensitivity analyses are usually cumbersome, and provide limited information (Leuschner 1990).

Heuristic Programming

Heuristic programming (HP) includes many techniques that use procedures which reduce the amount of search in problem-solving activities, may obtain solutions to problems within a limited computing time, and may provide good (but not necessarily optimal) solutions to difficult problems easily and quickly (Zanakis and Evans 1981). In many optimization techniques (LP, IP, etc.) the degree of spatial resolution is insufficient to deal with many important relationships, therefore solutions may not be implemented directly (Elwood and Rose 1990). HP may overcome many of the limitations of mathematical techniques in solving forest management scheduling problems (Elwood and Rose 1990). For example, Yoshimoto and Brodie (1994) developed a HP algorithm which can provide solutions to larger problems that cannot be formulated or solved using IP or MIP methods.

Zanakis and Evans (1981) list several instances where the use of heuristics is desirable, including:

1. Inexact or limited data used to estimate model parameters may inherently contain errors much larger than the "suboptimality" of a good heuristic.
2. A simplified model is used, which is a inaccurate representation of the real problem, thus making the "optimal" solution only academic.
3. A reliable exact method is not available.
4. An exact method is available, but computationally unattractive due to excessive time and/or storage requirements.

5. A repeated need to solve the same problem on a real-time basis, or frequently.

HP techniques should be able to obtain solutions in reasonable amounts of time, for a wide variety of problems, and not be sensitive to changes in parameters (Zanakis and Evans (1981). HP techniques should also be able to accept multiple starting points (which are not necessarily feasible), produce multiple solutions, and utilize stopping criteria which take advantage of search "learning" and avoid stagnation in the search routine (Zanakis and Evans 1981). The utilization of HP techniques rather than traditional mathematical programming techniques may allow the integration of complex, and perhaps non-linear, relationships between goals (such as sedimentation and temperature) with scheduling algorithms.

Many HP techniques have been developed for forestry problems (O'Hara et al. 1989, Nelson and Brodie 1990, Nelson and Finn 1991, Murray and Church 1993, Yoshimoto et al. 1994). Two HP techniques have been used in forestry applications with moderate success: simulated annealing and Tabu search. Simulated annealing is a stochastic optimization technique that allow nonlinear and discontinuous constraints and objectives to be used (Lockwood and Moore 1993). Simulated annealing techniques tentatively alter the arrangement of a system, evaluate the change in the system's objective function value, then conditionally accept or reject the new arrangement, depending on the outcome of an acceptance criterion. The acceptance criterion prevents the objective function from "greedily" converging on a local minima (Lockwood and Moore 1993).

Tabu search is a strategy for solving combinatorial optimization problems whose applications range from graph theory to MIP problems (Glover 1989). The chief limitation of using an IP formulation is that an optimal solution reported may only be local minima, and not a global optimum. Tabu search provides for a continual exploration of the solution space without becoming confounded by an absence of improving moves (Glover 1989). A move is a transition from a feasible solution to a transformed feasible solution, and may represent the best possible improvement in a solution, or the least deterioration of the objective function value (Voß 1993). A Tabu list restricts the search to a subset of the admissible moves, which may lead to feasible moves at each iteration without cycling between a set of solutions (Voß 1993). Tabu search can employ search intensification or diversification routines. Search intensification routines keep track of the attributes of all moves that have been performed, and eliminates from further consideration those attributes which have not been a part of any solution during a given number of iterations (Voß 1993). Search diversification utilizes long-term memory to penalize often-selected assignments, which may allow the algorithm to search into unexplored regions of the solution space (Voß 1993). Within forestry, Tabu search has been applied to such problems as scheduling timber harvests subject to simple adjacency requirements (Murray and Church 1993, Thompson et al. 1994), and meeting spatial goals for elk (Bettinger et al. 1996).

Summary of Mathematical Programming Techniques

Most traditional mathematical programming techniques utilize area-based algorithms to determine output levels in the presence of forest-wide constraints. Area-based algorithms can utilize aggregated decision variables (stratums), yet cannot easily recognize spatial and operational considerations. The importance of spatial information in making forest management decisions is in part due to the need to consider spatially dependent factors (i.e. road construction, transportation distances, and other operational constraints), and in part due to governmental regulations which control the spatial and temporal distribution of activities on a landscape (Clements et al. 1990).

To know the extent to which the spatial and temporal distributions of activities occur within decision variables, disaggregate, integer decision variables are required. With this approach, planners will know exactly when and where activities occur. Therefore, IP or HP techniques are the only plausible techniques available when considering this approach. IP, however, becomes unwieldy as the number of decision variables grows. So HP techniques seem to be the only plausible techniques for scheduling activities on a watershed scale, where stream sediment and temperature are dependent on spatial information, and estimated for each land management activity.

Summary

The Columbia River system is symptomatic of the conflicts that arise from multiple uses of publicly owned natural resources. The salmon issue is a crucial test of the public's ability to manage natural resources in the Columbia River system in a responsible, sustainable manner (Cornelius 1993). Traditional forest management planning has emphasized individual resources and has provided only limited consideration of the spatial and temporal relationships between land management activities and those resources (Everett et al. 1994). Whether ecosystem management is a new paradigm shift or simply an expansion of multiple-use management, the forest condition is the preeminent output (Sedjo 1995).

Without the assurance of protection of wild fish stocks, through the maintenance or restoration of forest conditions which affect aquatic habitat, land management activities on National Forests in northeastern Oregon cannot go forward. Stream sediment and temperature have been identified as two major aquatic habitat measures for the Upper Grande Ronde River basin. Land management plans, generally speaking, must be developed so that a decrease in both sediment and summer stream temperature levels occurs over time. Timber harvests and road management activities must be spatially and temporally arranged in such a way to meet these goals.

Area-based planning is relatively ineffective in allowing the measurement of the effect of land management activities on achievement of aquatic habitat goals. Therefore, the development of a process for evaluating the impact of each decision choice on aquatic habitat goals during plan formulation seems to be needed. This simultaneous evaluation of aquatic habitat goals with each decision choice is more efficient than relying on a posterior evaluation of plan suitability to the goals. Therefore a major gap to be filled with this research is the development and testing of a mathematical programming technique, which uses spatial information, to ensure the compatibility of aquatic habitat goals and land management activities. Successfully meeting this challenge would represent an original contribution to forest science.

This research will focus on the effects of land management activities on ecosystem health, specifically activities related to timber production and road management. We are ultimately interested in the development and sustainability of healthy forest ecosystems, and a sustainable flow of resources from this ecosystem (Figure 1.3). Many activities can be used to influence the health of the forest ecosystem, including timber harvesting, ecosystem management across ownerships, and stream restoration. Viable salmonid populations partly define ecosystem health in the Upper Grande Ronde basin (Figure 1.4), and are influenced by many activities. This research will attempt to evaluate ecosystem health using surrogate goals (stream sediment and temperature) that can provide a measure of the state of the aquatic habitat (Figure 1.5). We can then imply that the response of these surrogates to land management activities is a reflection of the effect of activities on ecosystem health (this assumes a positive relationship between ecosystem health and aquatic habitat quality). While the reference scale of measuring stream sediment and temperature may be a small patch (e.g., 10 ha), or a road segment, the significance of the effects of land management activities can be accumulated through a stream network to a watershed scale, where from there the effects on ecosystem health can be implied by a corresponding increase or decrease in fish habitat quality.

Figure 1.3. Influencing factors on healthy forests and sustainable flows of resources.

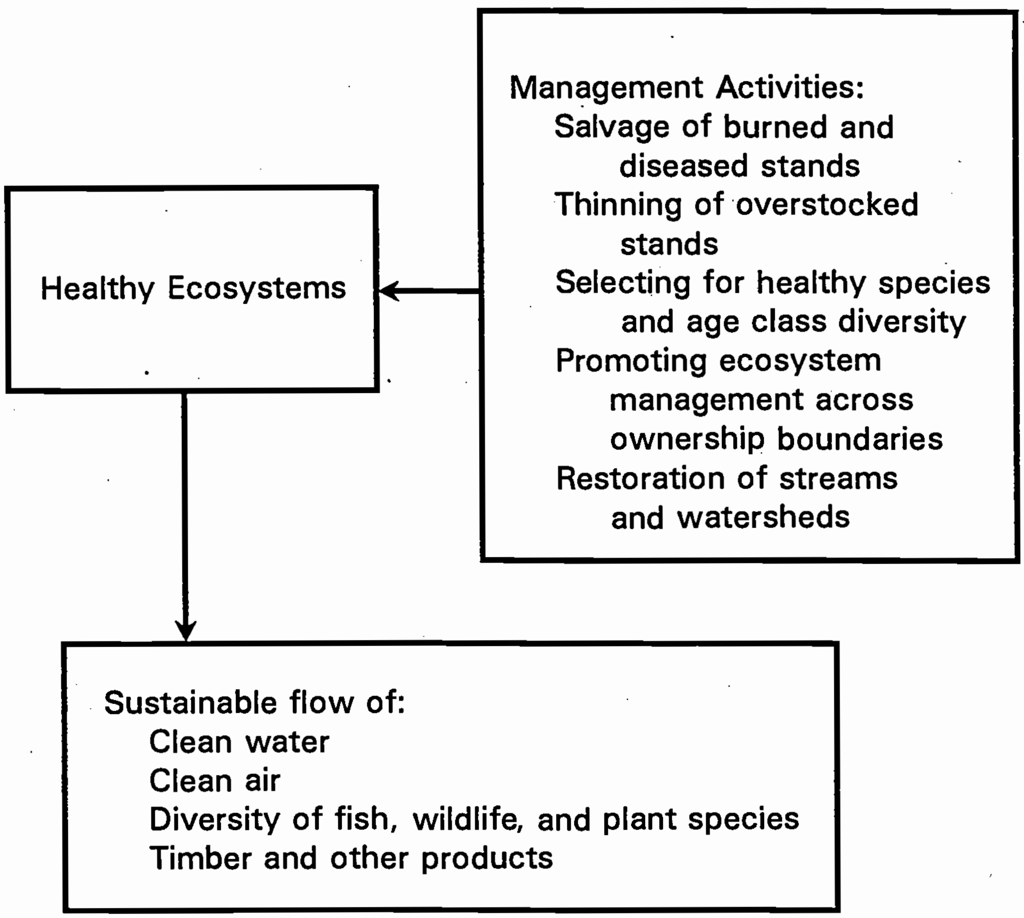


Figure 1.4. Activities which can influence ecosystem health in eastern Oregon, as represented by viable salmonid habitat.

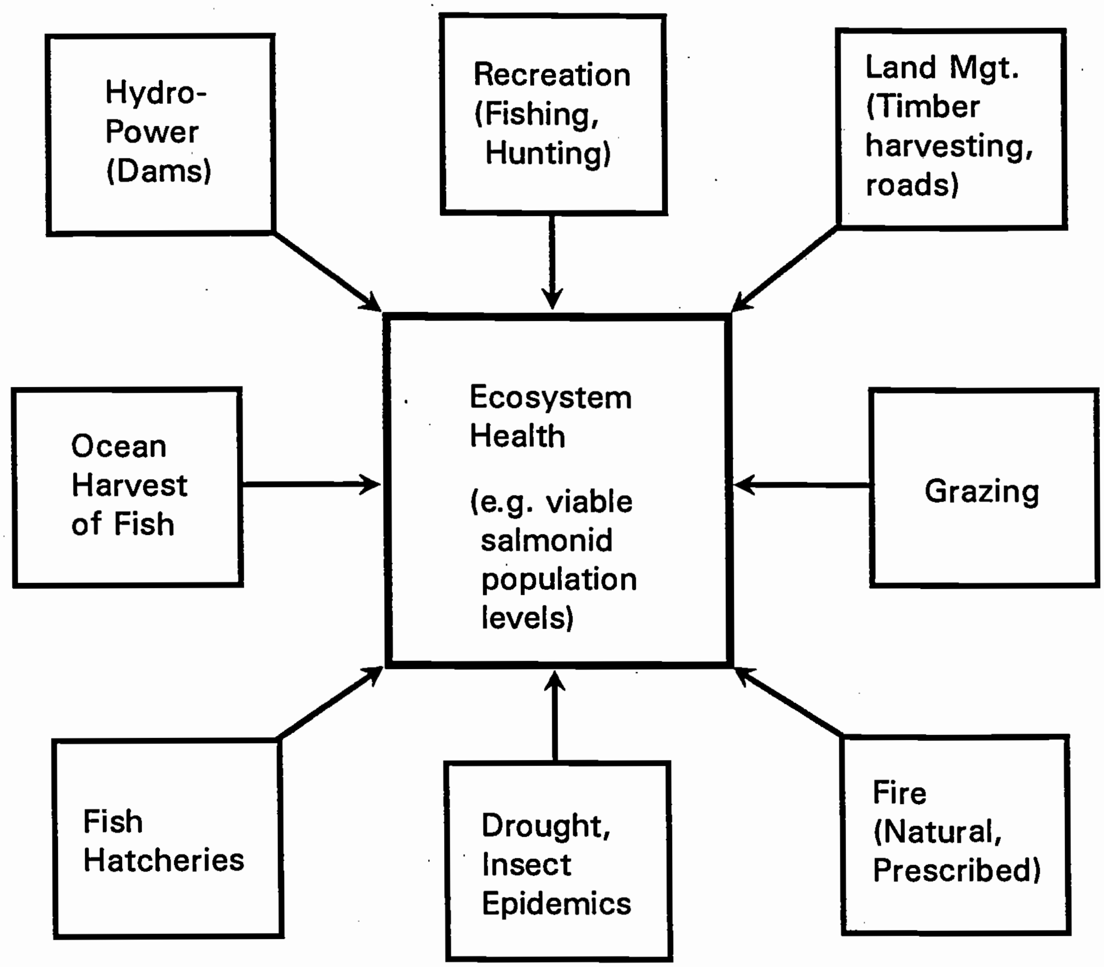
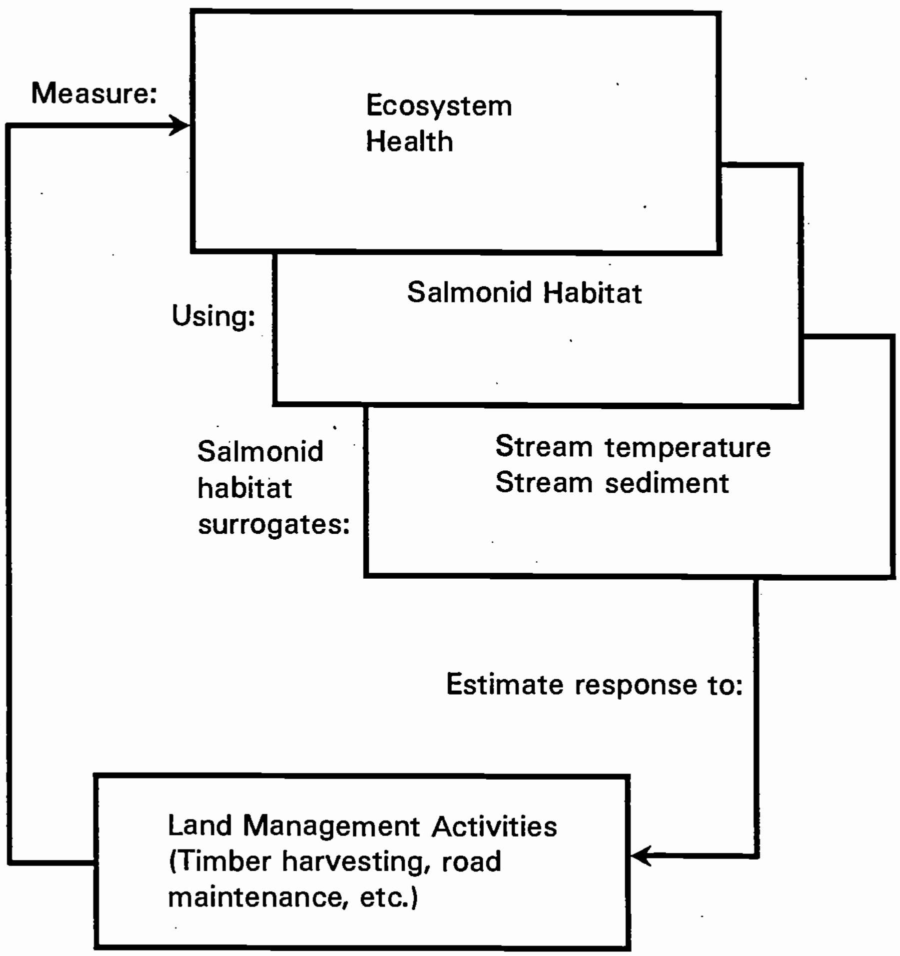


Figure 1.5. Hierarchical structure where ecosystem health is measured in response to land management activities. Salmonid habitat, and hence two surrogates of salmonid habitat, is used to represent the health of the ecosystem.



With this research I will attempt to accomplish several goals. First, I present a new land management scheduling model to evaluate the compatibility of land management activities and aquatic habitat quality (Chapter 2). Both the theoretical complexity and a validation of the effectiveness of the model are examined. In Chapter 3, I describe detailed results of the application of the land management scheduling model to a 14,643 acre watershed in eastern Oregon. In Chapter 4, I evaluate the correlation between a commonly-used (by National Forests) measure of watershed use (ECA) and two measures of aquatic habitat quality (stream sediment and temperature indices), using the results obtained from the results described in Chapter 3. I then go on to evaluate whether different definitions of land units decision variables affect the results (Chapter 5). Finally, the contribution of the research to ecosystem management is discussed (Chapter 6), as are future directions for ensuring the compatibility of land management activities and aquatic habitat quality in eastern Oregon.

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Chapter 2

Ensuring the Compatibility of Aquatic Habitat and Commodity Production Goals in Eastern Oregon with a Tabu Search Procedure

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Abstract

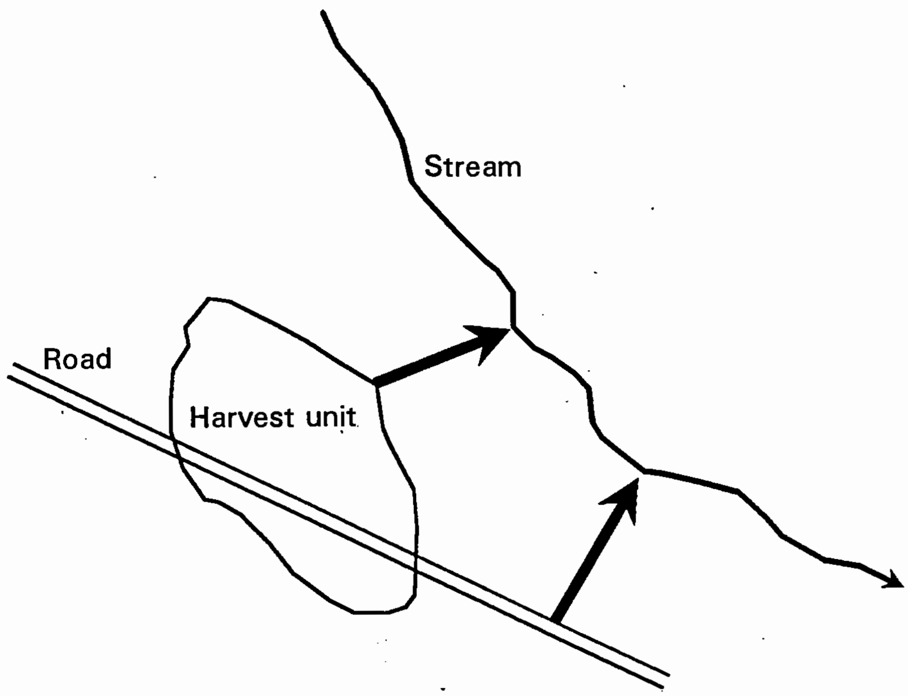
We present a model for ensuring the compatibility aquatic habitat quality and commodity production goals in forest management. This model uses Tabu search procedures to select feasible land management activities (timber harvesting and road system management) subject to an even-flow constraint and aquatic habitat quality goals, as represented by stream sediment and temperature indices. The methodology for evaluating the effects of land management activities on aquatic habitat goals utilizes established procedures, yet makes evaluations with each incremental decision choice. We establish the theoretical complexity of the model and then apply the procedures to a 14,643 acre case study watershed in eastern Oregon to evaluate the performance. For comparison, a global optimum solution is estimated using extreme value theory techniques. Results show that all solutions are spatially and temporally feasible with respect to stream sediment and temperature index goals. Eighty percent of solutions had net present values within 10 percent of an estimated optimal solution. Further, out of 20 independent runs, one was within 2 percent of an estimated global optimum, and all 20 were within 15 percent of the estimated global optimum. While improvements to the model can be made, we have demonstrated that moderately complex aquatic habitat quality evaluation techniques, with spatial elements, can be nested inside a land management scheduling model.

Introduction

Protection for spotted owls (Strix occidentalis) and wild fish stocks in the Pacific Northwest has become important in the past decade, as these species have become listed as threatened or endangered by the federal government. In the Columbia River basin, the central issue in resource management is the designation of certain stocks of anadromous fish as threatened or endangered under the federal Endangered Species Act. The more fundamental problem is the real or potential loss of naturally spawning, wild Columbia River salmon stocks, and declining populations of fish in these stocks (Cornelius 1993). Other natural resource issues, including big game management and forest health goals, also receive considerable support from the public, and are increasingly influencing timber sale planning on National Forests. The interrelationships of faunal and floral species and their habitats are complex, and the cumulative effects of seemingly insignificant alterations of habitat, whether caused by humans or natural processes, can possibly change the productivity and diversity of many resources (Meehan 1991).

The spatial and temporal arrangement of land management activities is important in the estimation of aquatic habitat goals, as represented here by stream sediment and temperature levels. Stream sediment levels, in general, are a function of soil type, harvest system (for example clearcut or partial cut), logging system, and the distance from a harvest site to the stream system (Figure 2.1). Similarly, sediment produced from roads would also be a function of the distance from a road to the stream system. Stream temperature levels, in general, are primarily a function of stream flow and the amount of solar radiation

Figure 2.1. Influence of spatial location of land management activities on stream sediment estimation.



Stream sediment impact from harvesting = f(soil type, harvest system, logging system, distance to stream, etc.)

Stream sediment impact from roads = f(road standard, road slope, road traffic, distance to stream, etc.)

reaching the stream system. Thus management activities in land units adjacent to the stream system may affect the amount of solar radiation reaching the water (Figure 2.2), while management activities upslope (more than one mature tree height) from the stream system generally do not affect solar radiation levels. Over time, the distribution of land management activities may provide fluxes in stream sediment and temperature levels based on their spatial location. Therefore, if aquatic habitat goals are important, it also becomes important to identify a set of activities, defined by their spatial and temporal arrangement, that provide for the maintenance or restoration of aquatic habitat quality.

Methods

The problem we attempt to solve with this research can be formulated as such:

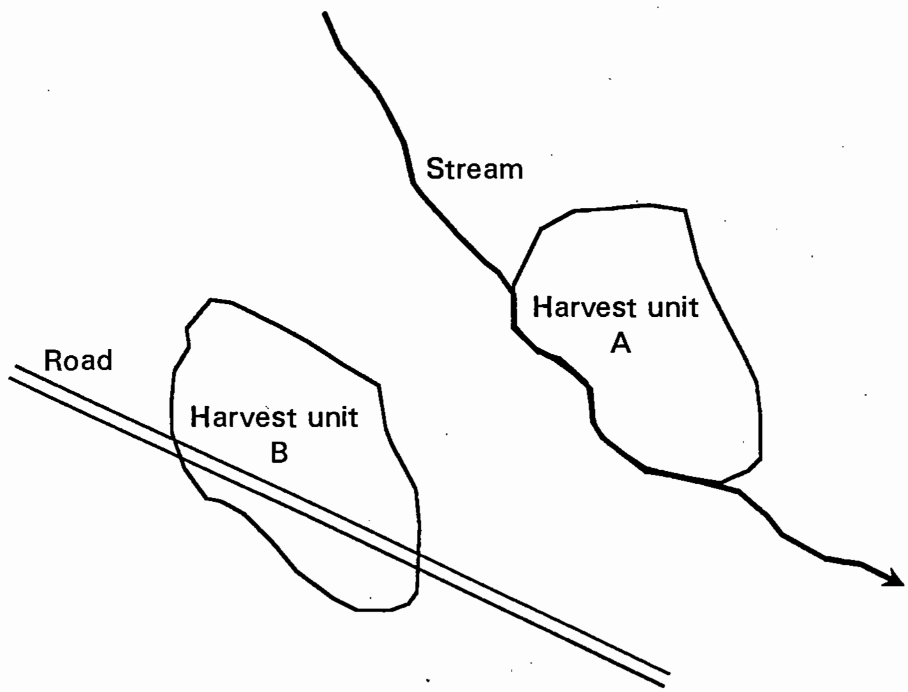
maximize:	net present value (NPV)
subject to:	an even-flow of timber harvest volume
	an upper limit on stream sediment levels
	an upper limit on stream temperature levels

The decision choices we will use consist of:

Harvesting systems:

- Partial cutting on a 30-year return interval, all tree species, no cutting before age 50 or after age 150.

Figure 2.2. Influence of spatial location of land management activities on stream temperature estimation.



Stream temperature impact from harvesting = f(stream length, stream width, stream orientation, latitude, declination, harvest system, adjacency to stream, etc.)

- Partial cutting on a 50-year return interval, all tree species, no cutting before age 50 or after age 150.
- Clearcutting and thinning. If thinning is the first harvesting activity, it can occur between the ages of 50 and 100. Clearcutting follows 20 years later. If clearcutting is the first harvesting activity, it can occur between the ages of 101 and 150. After a clearcut has occurred, thinning occurs at subsequent age 50, and clearcut at age 70. Lodgepole pine stands only.
- Not harvesting a unit.

Logging systems:

- Ground-based
- Skyline
- Helicopter

Road standard changes:

- Standard rock to central tire inflation (CTI) use
- Standard rock to obliterated
- No change in road standard

It is important to note that some of these decision choices involve land allocation issues (e.g., timber harvesting, road obliteration), while one of the choices (requiring lower log-truck tire pressures on certain roads, via CTI) involves changes in management practices. Here, the state of the road is not changed when CTI use is assigned to the road.

Review of Possible Approaches

Traditional timber harvest scheduling techniques such as linear programming (LP) and goal programming can easily deal with the requirements to maintain proportions of an area in some combination of vegetative state. Examples of linear programming (e.g., Leuschner et al. 1975, Benninghoff and Ohlander 1978, Kent 1980) and goal programming (e.g., Bottoms and Bartlett 1975, Bell 1976, Dane et al. 1977) are numerous.

A typical LP formulation for harvest scheduling is:

$$\text{maximize:} \quad NPV_1X_1 + NPV_2X_2 + \dots NPV_nX_n$$

$$\text{subject to:} \quad a_{11}X_1 + a_{12}X_2 + \dots a_{1n}X_n \leq b_1$$

$$a_{21}X_1 + a_{22}X_2 + \dots a_{2n}X_n \leq b_2$$

$$\text{"} \qquad \text{"}$$

$$\text{"} \qquad \text{"}$$

$$a_{m1}X_1 + a_{m2}X_2 + \dots a_{mn}X_n \leq b_m$$

$$X_1, X_2, \dots, X_n \geq 0$$

The coefficients NPV_1, NPV_2, ... NPV_n in the objective function are coefficients representing the net present value associated with harvesting decisions, and X_1, X_2, ... X_n are the decision variables. The inequality

$$\sum_{j=1}^{n} a_{ij} X_j \geq b_i$$

denotes the i^{th} area constraint, and the coefficients a_{ij} for $i = 1,2, \ldots m$, $j = 1,2, \ldots n$ are the area coefficients. The set of decision variables satisfying all of the constraints is called a feasible point; the set of all such feasible points defines the feasible region (Bazaraa and Jarvis 1977).

These types of techniques can utilize constraints which require maintaining minimum acreages in specific age classes, may attempt the protection of habitat for some species within a planning area, and can handle the representation of coefficients by habitat zones (e.g., riparian areas). In an LP formulation, decision variables are allowed to vary from 0 (omitted) to 100 percent (fully implemented across geographical range of land unit or road segment), based on the extent to which a variable is included in the solution after meeting all constraints (Kirby et al. 1980). However, a major drawback is, that since decision choices are represented by continuous decision variables, the exact spatial location of an activity within a decision variable is not known unless the areal extent is 0 or 100 percent.

We are interested here in modeling decision choices as discrete solutions, to assure that the spatial elements of each decision choice are accurate (to the degree of accuracy that they are measured). Integer programming (IP) can provide the mathematical structure to control the exact spatial and temporal distribution of activities (Jones and Schuster 1985). In an IP formulation decision variables must be omitted or fully implemented. However, the size of an IP problem rapidly becomes unmanageable, and the solution time grows exponentially with linear increases in integer variables. Mixed integer programming can provide some relief to these types of problems by allowing some decision variables to take on continuous solutions, and some to take on integer solutions.

Non-linear programming has shown promise for problems where the spatial allocation of harvests is important (Roise 1990, Hof and Joyce 1992). Heuristic programming (Hoganson and Rose 1984, Weintraub et al. 1995, Yoshimoto et al. 1994) also has shown promise in the development of spatially constrained harvest scheduling problems. Other harvest scheduling methods which use heuristic methods, such as binary search, include TREES (Tedder et al. 1980), HARVEST and EASYPLAN (Barber 1989). Binary search, however, has the same limitations as IP and other methods.

At the present time, an assessment of the quality of a land management plan with respect to most aquatic habitat or wildlife goals generally relies on a posterior measurement of suitability using a set of spatial statistics operating upon a spatial database (i.e., FRAGSTATS [McGarigal and Marks 1993]); with few exceptions (e.g., Bettinger et al. 1996)). In a few cases, specialized algorithms have been developed to measure the quality of a spatial solution for particular wildlife models such as elk (Cervus elaphus) (i.e., HEICALC [Hitchcock and Ager 1992], HEIWEST [Ager and Hitchcock 1992], SNAP II [Sessions and Sessions 1993]). These posterior analyses do not assure that a management plan will be feasible with respect to a particular species, they simply measure the effectiveness of the plan once it has been developed.

We discuss the use of a heuristic algorithm, Tabu search, for ensuring the compatibility of commodity production goals (timber harvesting and road management) and aquatic habitat goals (stream sediment and temperature). The technique keeps sediment and temperature levels within limits set for each goal, provides and even-flow of timber harvest volume over time, and seeks to obtain the set of activities within these constraints which achieves the highest NPV. Decision choices in the model are represented by integer (0-1) variables, that is, either an activity is assumed implemented to its full areal extent, or not at all. In addition, the model is structured as a Model I formulation (Johnson and Scheurman 1977), where each decision variable tracks a unique geographic area of the forest through time.

Although our discussion considers the aquatic habitat goals as constraints in the sense that a maximum level cannot be exceeded, timber harvest goals and aquatic habitat goals could easily be interchanged. We first present the theoretical complexity of the Tabu search model, and then report the performance of the model when applied to a watershed in eastern Oregon. We make no comparisons of this model to other algorithms, since none of the other published algorithms have provisions for using the specific aquatic habitat models used in this study, and because we did not develop a matrix generator which would allow the formulation of an IP problem. The large number of integer variables required for our case study watershed makes locating an optimal solution with an IP technique a computationally difficult process in locating the optimal solution. In fact, depending on the complexity of the model formulation and the problem size, one might never locate the optimal solution with an IP technique.

Model Formulation

Objective Function

The land management scheduling model uses an objective function that maximizes the net present value of all harvesting and road management-related activities. The objective function is formulated as:

maximize:

$$\sum_{m=1}^{n}\left(\frac{\sum_{k=1}^{u}((P_m - H_m) * V_{km}\phi_{km}) - \sum_{k=1}^{u}(FC_{km}\phi_{km} + (VC_{km} * V_{km}\phi_{km}))}{(1+i)^{(m-1)+5}}\right)$$

$$-\sum_{m=1}^{n}\left(\frac{\sum_{s=1}^{q}(RC_{sm}\omega_{sm})}{(1+i)^{(m-1)+5}}\right)$$

Where: m = Period

n = Total number of periods

k = Unit

u = Total number of units

ϕ_{km} = Variable indicating the extent to which unit k is harvested in period m

P_m = Stumpage price ($/MBF) in period m

H_m = Harvesting cost ($/MBF) in period m

V_{km} = Total volume (MBF) within unit k during period m

FC_{km} = Fixed road maintenance cost ($/mile) for the path associated with unit k in period m

VC_{km} = Variable road maintenance cost ($/MBF) for the path associated with unit k in period m

s = Individual road segment

q = Total number of individual road segments

RC_{sm} = Road standard change cost ($/mile) for road segment s in period m

ω_{km} = Variable indicating the extent to which a road standard has changed in period m

i = discount rate (percent)

In formulating the objective function for a linear programming (LP) problem, one would assume $1 \geq \phi_{km} \geq 0$ and $1 \geq \omega_{km} \geq 0$. For integer programming (IP) problems, ϕ_{km} and ω_{km} equal 0 or 1. Our approach utilizes the IP formulation of the objective function.

Even-Flow Constraint

There are various methods for ensuring an even-flow of timber harvest volume over time for a forest management problem. Classical timber management scheduling techniques address how many acres (area control) or how much volume to harvest (volume control). Area control can achieve a regulated forest in one timber rotation, yet often at the expense of near-term harvest level stability; volume control ensures near-term harvest level stability, yet may not achieve a regulated forest after one rotation (Davis and Johnson 1987). We are attempting to achieve a non-declining even-flow of timber harvest volume:

$$\sum (V_{km}\phi_{km}) \leq \sum (V_{km+1}\phi_{km+1})$$

Our approach to ensuring an even-flow of timber harvest volume, however, is not as strict as the constraint above. Our process adds incremental silvicultural management regimes, defined by a series of harvests over time, to the solution, by only considering those management regimes that can start with a harvest in the period that has the lowest harvest volume. So during the operation of our model, we examine the harvest rates over time, select the period with the lowest harvest volume, and select a management regime that can start in that period. We then are assured that the period with the lowest harvest volume will have volume added to it. It is a constraint in the sense that the set of potential decision choices is confined to those that can start with a harvest in the period with the lowest harvest volume.

Stream Sediment Goal

A formal declaration of our sediment goal is:

$$\textit{sediment goal for period } m \geq \sum_{k=1}^{u}(natu_{km}\phi_{km}) + \sum_{k=1}^{u}(sedu_{km}\phi_{km}) + \sum_{s=1}^{q}(sedr_{sm}\omega_{sm}) + \sum_{s=1}^{q}(traffic_{sm}\omega_{sm})$$

Where: $natu_{km}$ = f (area, erosion hazard rating for unit k in period m)

$sedu_{km}$ = f (harvesting system, logging system, geologic erosion factor, natural sediment rate, ground slope, slope shape, surface roughness, ground cover, texture of erodible material, water availability, distance to the stream system for unit k in period m)

$sedr_{sm}$ = f (road standard, road width, road length, slope shape, surface roughness, slope gradient, ground cover, texture of erodible material, water availability, distance to the stream system for road segment s in period m)

$traffic_{sm}$ = f (volume transported across road, possible reduction factor for using CTI for road segment s in period m)

In formulating this constraint for an LP problem, $1 \geq \phi_{km} \geq 0$ and $1 \geq \omega_{sm} \geq 0$. For IP problems, ϕ_{km} and ω_{sm} equal 0 or 1. Our implementation of the sediment constraint follows the IP formulation. Since road construction is not an option in our problem, typical road trigger constraints (see Kirby et al. 1982) are not utilized.

The procedures that we use to evaluate stream sediment levels are derived from the "Guide to predicting sediment yields from forested watersheds" (USDA Forest Service 1981), known here as the Region 1 / Region 4 (R1/R4) sediment model. We selected this model because it is an established model, and because it provided the best documentation of the models we considered. The R1/R4 model separates erosional and delivery processes and considers them individually for each land unit and road. There are four major parts to the R1/R4 model: natural sediment yield, sediment from surface erosion, sediment from mass erosion, and routing of sediment to a critical reach.

The R1/R4 model was altered to evaluate surface erosion from road traffic resulting from logging activities, and to reduce sediment from road traffic by assigning CTI use to particular road segments. A factor of 0.0338 tons of sediment / thousand board feet (MBF) - mile was developed using the extreme case from Reid and Dunne (1984), and is applied to all roads which are scheduled to be used to haul timber volume. Although Reid and Dunne's research was from western Washington, we felt that it presented the most complete information (sediment produced per MBF transported across road segments) available for use in our study. In addition, a reduction of 60% in surface erosion from road traffic is assumed when CTI is assigned to a road, based on conservative results obtained from Foltz (1994).

The estimation of sediment from mass erosion (landslides) is highly variable, and since it is not currently a major problem in our case study watershed (R. Beschta, Department of Forest Engineering, Oregon State University, Corvallis, OR, pers. comm.), it is not included in our estimation of stream sediment impacts from land management activities. Finally, stream sediment index levels are only measured at the downstream reach in the watershed. Sediment from all sources is routed to the downstream reach using a coefficient developed by Roehl (1962) that is based on watershed size. The amount of sediment routed to the downstream reach is considered here an index of sediment levels because the R1/R4 model has not been validated in eastern Oregon using empirical data. In fact, no sediment estimation models have been validated for forested watersheds in eastern Oregon.

Stream Temperature Goal

The stream temperature goal is a function of timber harvesting activities, and can be formulated as follows:

$$\textit{temperature goal for period } m \geq \sum_{k=1}^{u} (temp_{km})$$

for all {k | k is a unit adjacent to the stream}

Where: $temp_{km}$ = f (stream length, stream width, low flow (cfs), latitude of watershed, declination of watershed, ground slope, shade density, tree overhang percent, tree height, number of skyroads, percent canopy removed during harvest, stream orientation, distance from trees to channel, heat rate (BTU/square foot-minute), ground water temperature for unit k in period m)

The procedures to evaluate stream temperature levels were derived from the SHADOW model (USDA Forest Service 1993). This model calculates the area of unshaded streams, using stream orientation, solar angles, and other reach-specific data. Reach-specific data are spatial in nature in that they include only data (e.g., average tree height, terrain slope) associated with land units which are adjacent to a U.S. Forest Service class 1-3 stream reach. An equation developed by Brown (1969) is used with SHADOW to predict the increase in stream temperature (as a result of solar heating) over groundwater temperature levels. The resulting estimated temperature is considered here as an index because SHADOW has not been validated in eastern Oregon using empirical data. Only one stream temperature model has been validated for use in eastern Oregon (Bohle 1994), and then only for small stream reaches. SHADOW, however, has been applied to large watersheds, and is supported by Region 6 of the U.S. Forest Service.

Tabu Search

Tabu search is a recently-developed solution strategy for combinatorial optimization problems (Glover 1989), and has evolved from gradient search techniques. Gradient search techniques can guarantee an optimal solution when the solution space is convex. Some wildlife habitat goals do not have a convex solution space, and others are also discrete. Tabu search can systematically look for feasible solutions to both discrete and non-convex problems. The key to Tabu search is that it remembers the choices it makes, thereby avoiding becoming trapped in local minimum solutions, a feature not common to traditional gradient search algorithms. This forces the Tabu search to explore other areas of the solution space, thus increasing the chance of locating a good solution. While Tabu search cannot guarantee an optimal solution, it should provide a number of good, feasible solutions to an adequately formulated problem.

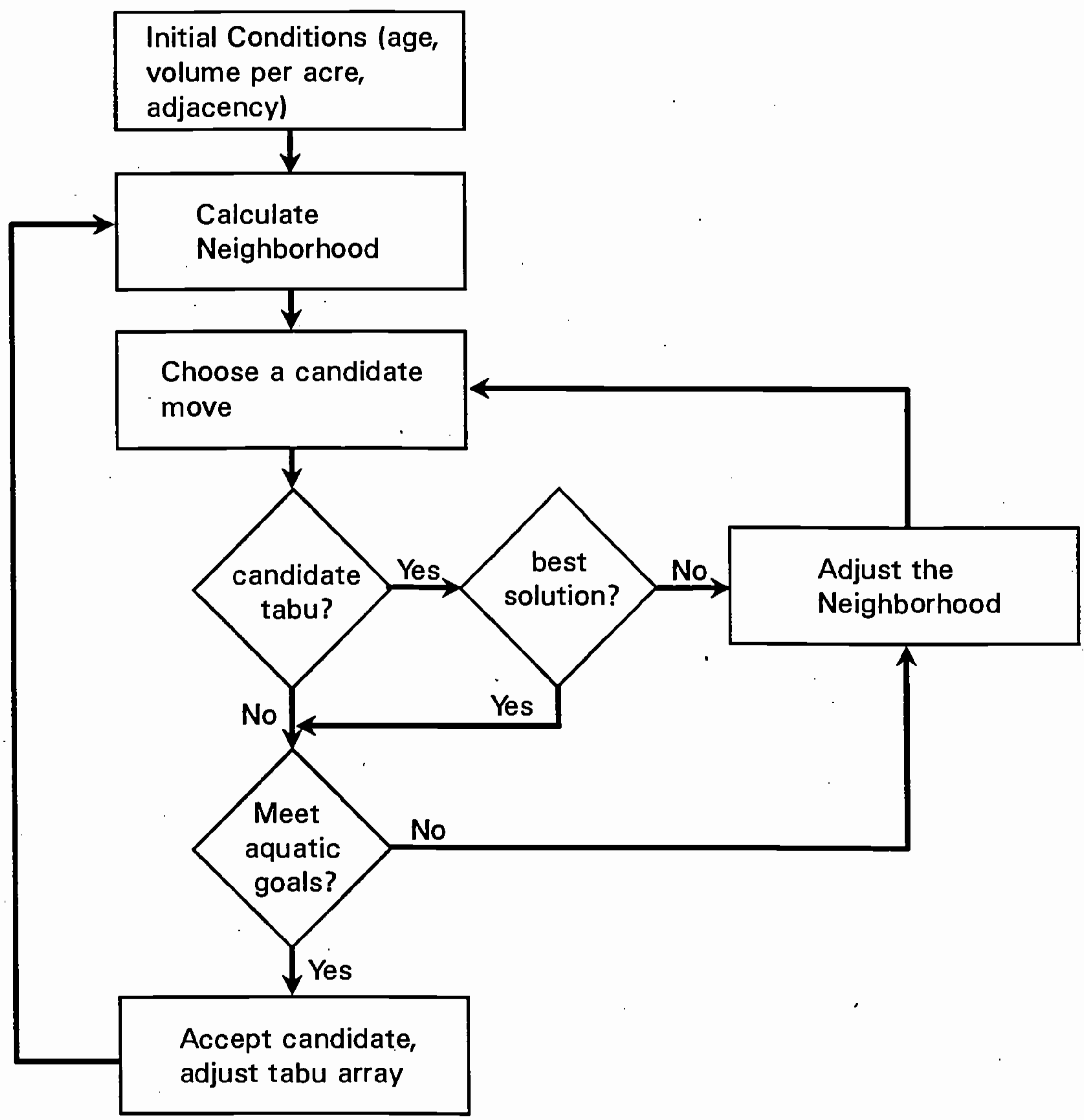
Tabu search has been successfully applied to a number of important problems in areas outside of forestry and wildlife management, such as scheduling, transportation, and layout and circuit design problems (Glover and Laguna 1993). Within forestry it has been applied to problems formulated for scheduling timber harvests subject to simple adjacency (green-up) requirements (Murray and Church 1993, Thompson et al. 1994), and for meeting spatial goals for elk (Bettinger et al. 1996).

We developed a Tabu search model to schedule timber harvesting and road management activities while attempting to achieve an even-flow of timber harvest volume and while meeting aquatic habitat quality goals over ten 10-year planning periods. Dijkstra's algorithm (Smith 1982) is used to determine the shortest path (based on distance) from each unit to a mill location. A general description of Tabu search is illustrated in Figure 2.3. A detailed description of the model structure, files, and variables can be found in Appendix A.

Making Decision Choices

Our implementation of the Tabu search model starts with a randomly defined set of management regimes, representing harvesting (either clearcut, thinning, or partial cut) 5 percent of the watershed area in the first decade. With each successive iteration (j) of the model, a new feasible solution ($\mathbf{x}_j$) is created from a transformation of the previous feasible solution ($\mathbf{x}_{j-1}$) by a move (σ). For this problem, a σ can consist of the following:

Figure 2.3. General Tabu search model flow using short-term memory and aquatic habitat quality goal restrictions.



- scheduling a unit for a series of harvests (in a pre-defined management regime)
- unscheduling a unit for harvest (not harvesting in any period)
- changing the period that a management regime begins for a unit
- changing a management regime for a unit

However, σ cannot consist of the following:

- harvesting a unit using two or more management regimes
- harvesting a unit that does not meet the age requirements

A σ may represent the best possible improvement in a solution, or the least deterioration of the objective function value (Voß 1993). For scheduling timber harvests, the evaluation of each σ consists of considering how a change in a unit's status may affect the objective function value.

Three silvicultural management regimes were utilized in this study. First, for lodgepole pine units, the management regimes could consist of a series of thinning and clearcut harvests. For units between 50 and 100 years old, a thinning could be the first treatment scheduled, followed two periods later by a clearcut. For units 100 to 150 years old, a clearcut could be the first treatment scheduled. After clearcutting, the management regime consists of thinning at age 50, and clearcutting at age 70. If a unit becomes older than 150 years, no treatment is applied. The second and third management regimes are applied to all other species types (including lodgepole pine), and consist of partial cutting in either 30-year or 50-year intervals.

Partial cutting in this study assumes that 33 percent of the merchantable volume in a unit will be harvested, with the harvest evenly distributed among diameter classes. No units under age 50 or over age 150 are applied a partial cutting treatment. Units with average ages over 150 years are not harvested, in order to protect late-successional habitat (Eastside Forests Scientific Society Panel 1994, Perry et al. 1995), since this type of habitat is under-represented in our case study watershed. Empirical data used in the case study includes all unit characteristics (e.g., initial age, volume, basal area, average tree height), and data regarding the spatial location of units in the case study watershed (e.g., whether units are in a riparian management area, distance to the nearest U.S. Forest Service class 1-4 stream, etc.).

Defining the Neighborhood

The neighborhood ($N(\mathbf{x}_j, \sigma_{mr,j,i})$) of the current solution $\mathbf{x}_j$ is a set of choices that can be reached from $\mathbf{x}_j$ by a move $\sigma_{mr,u,i}$ (the choice of starting management regime *mr*, for unit *u*, in period *i*). The neighborhood in our example consists of potential implementation of a management regime for each unit, and four types of harvesting systems (ground-based, cable, skyline, helicopter). In an effort to ensure an even-flow of timber volume harvested, the neighborhood only consisted of $\sigma_{mr,u,i}$ that could begin in the period with the lowest total volume harvested. Not harvesting is implicitly a choice, and if a unit is in the solution with a harvest schedule, unscheduling the management regime for the unit is a choice. The neighborhood is developed by calculating a potential objective function value which represents the addition of a single $\sigma_{mr,u,i}$ to $\mathbf{x}_j$.

The neighborhood of potential moves is adjusted to exclude from consideration all $\sigma_{mr,u,i}$ that have been rejected (for whatever reason) during the current iteration of the model. For example, if a $\sigma_{mr,u,i}$ is rejected because its acceptance would violate the achievement of an aquatic habitat goal, the $\sigma_{mr,u,i}$ will not have the opportunity to be considered again until the model moves forward one iteration (i.e., after another $\sigma_{mr,u,i}$ is formally accepted into the solution). A neighborhood is not explicitly defined for road standard change choices, because this would entail evaluating the shortest paths for each road standard choice that involves the obliteration of a road segment. Therefore, we assume road standards can only be changed when the sediment goal is violated.

If a sediment goal is violated, three potential actions can occur: 1) the $\sigma_{mr,u,i}$ being considered can be rejected, 2) a road segment can be obliterated, or 3) a road segment can be designated for CTI use. Each of these three actions has an equal probability of occurring. The road standard changes are used specifically to reduce the sediment levels in the period where sediment levels are too high. Roads are evaluated for their contribution of natural sediment per unit length, and the road with the largest contribution is considered first for a road standard change. If a temperature goal is violated, only one action can occur: the $\sigma_{mr,u,i}$ being considered is rejected.

Tabu Lists

The Tabu restrictions may prevent the formal acceptance of a $\sigma_{mr,u,i}$, or a road standard change choice. A Tabu list is developed which keeps track of choices which have been recently made. In Tabu search this is called short-term memory. For example, if a $\sigma_{mr,u,i}$ (or road standard change choice) is formally accepted into the solution during iteration *j* it is given the Tabu value *z* in the Tabu list. After each subsequent iteration of the model, *z* is decreased by one. When *z* equals zero once again, $\sigma_{mr,u,i}$ is not considered Tabu, and will not be subject to the Tabu restriction. The Tabu restriction disallows the selection of a unit unless formal acceptance will result in an objective function value which is better than any previously observed objective function value. This is called meeting the "aspiration criteria." As a result, units recently formally accepted into a solution may not be eligible for selection (and are thus considered "Tabu") again until a user-defined number of iterations from the current iteration of the model. Short-term memory essentially keeps the model from cycling back to a local optimum that has already been identified (Murray and Church 1993, Voß 1993). We used a Tabu state (z) of 150 moves in our model.

One diversification technique in Tabu search involves counting the number of times a unit has been formally accepted into the solution. To diversify the search, when a unit has been formally accepted a pre-defined number of times, the potential objective function value for the unit in $N(\mathbf{x}_j,\sigma_{mr,u,i})$ can be penalized, possibly preventing the selection of the unit (using any *mr* and *i* combination) again. Or, a provision can be made to prohibit the selection of a unit for an extended length of iterations after a certain frequency of use has been reached. This type of diversification in the search process is considered a long-term memory structure. This type of technique was not incorporated into our model, although we recommend that this option be investigated in future developments.

Case Study Watershed, Empirical Data Used, and Estimation of Constraints

A 14,643 acre watershed in eastern Oregon (Figure 2.4) was used as a case study for the application of the heuristic technique. Our decision to use a large watershed to test the scheduling model was based on our desire to emulate an operational tactical planning process, and to evaluate cumulative effects at a watershed scale. GIS databases depicting the road system, stream system, and vegetation and soils resources were developed in ArcInfo (ESRI 1995). The road network for the watershed (Figure 2.5) consists of 474 road segments, 443 of which are physically located within the watershed, and for which the effects of sediment produced by the roads will be evaluated. Roads were classified into three categories: obliterated, paved, and rock. Empirical data included average road widths, road slope percent, and the shortest distance from each road segment to a U.S. Forest Service class 1-4 stream. These data were derived from a sample of roads within the watershed, topographic maps, and GIS processes.

The stream system (Figure 2.6) consists of 9.6 miles of U.S. Forest Service class 1 streams (namely the Upper Grande Ronde River); however, stream density varies by stream class (Table 2.1). Empirical data for the stream network includes: stream widths by stream class, tree overhang percent, shade density, tree-channel distance, stream orientation, and terrain slope percent. These data were derived from a sample of streams within the watershed, topographic maps, and aerial photographs.

Average flow rates the downstream reach in the watershed were obtained from an actual monitoring station. Riparian areas were developed using the

Figure 2.4. The Upper Grande Ronde River basin in eastern Oregon, and the 14,643 acre case study watershed.

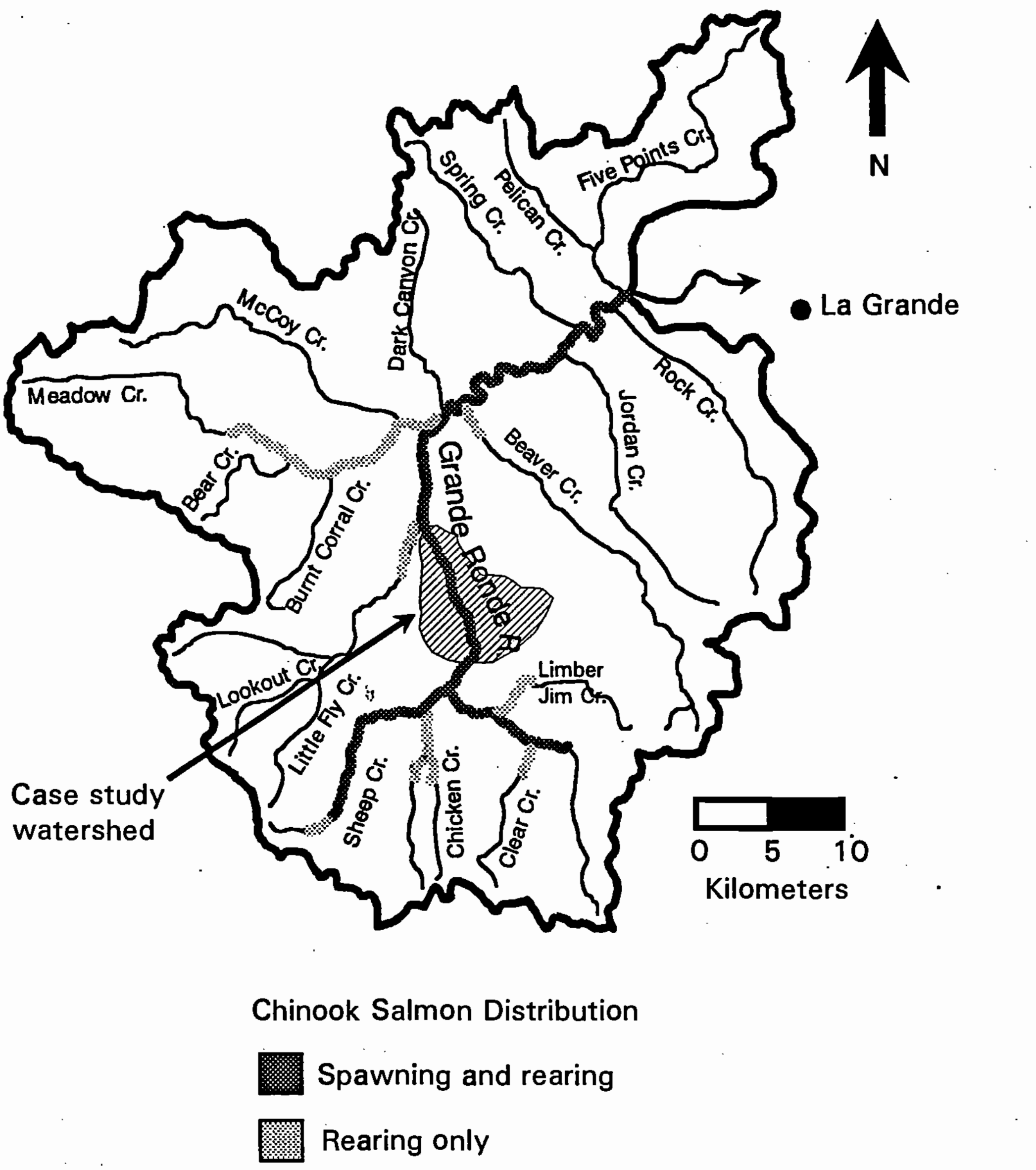


Figure 2.5. Initial road standards for a 14,643 acre case study watershed in eastern Oregon.

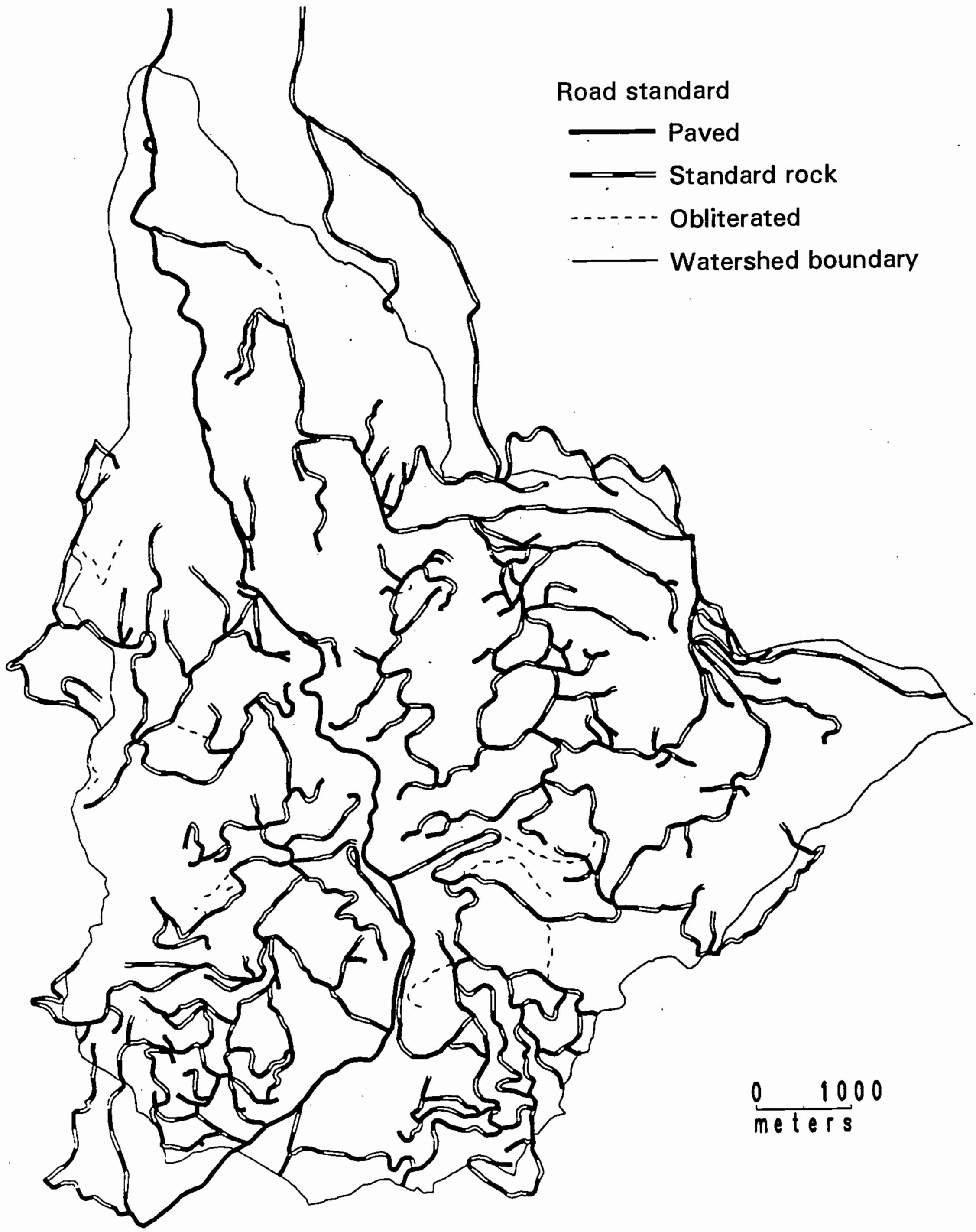


Figure 2.6. Stream classification, based on U.S. Forest Service stream guidelines, for a 14,643 acre case study watershed in eastern Oregon.

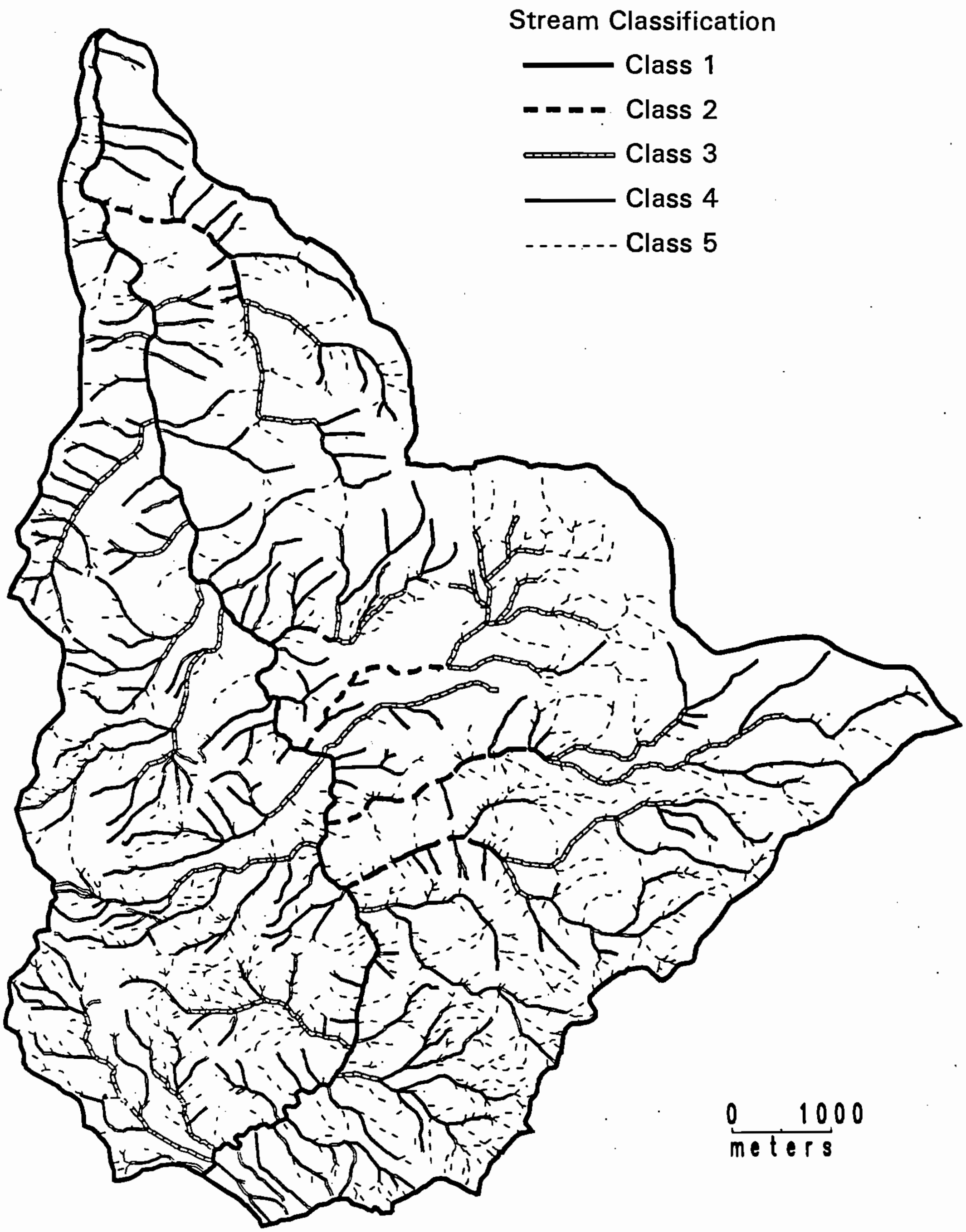


Table 2.1. Stream density in the 14,643 acre case study watershed, by U.S. Forest Service (USFS) stream class.

USFS stream class	Stream density (mi/mi^2)
1 - Perennial, used by anadromous fish and resident fish	0.42
2 - Perennial, used only by resident fish	0.25
3 - All other perennial streams not classified	0.94
4 - All intermittent streams	3.66
5 - All ephemeral streams	3.65
Total	8.92

PACFISH guidelines (USDA Forest Service and USDI Bureau of Land Management 1995). U.S. Forest Service class 1 and 2 streams were buffered 300 feet; class 3 streams 150 feet; and class 4 streams 100 feet. The buffered coverage was combined with the vegetation coverage to explicitly identify riparian areas. In our Tabu search model, we allow partial cutting in riparian areas, but not clearcutting. To create land unit decision variables, the riparian GIS coverage was combined with a vegetation coverage. This process created many sliver polygons, thus all polygons outside of riparian areas and less than 2 acres were eliminated and merged with an adjacent polygon which shared the longest common boundary. Land units inside riparian areas were not altered to protect the geographical integrity of the riparian areas. As a result we had 1,436 land units to use as decision variables. The number of land unit and road management decision variables therefore exceeded 120,000, given the harvest systems and silvicultural management regimes available.

Empirical data for the vegetation and soils databases included: average merchantable volume per acre, average basal area per acre, average age of dominant trees, dominant tree species, average height of dominant trees, ground slope percent, soil type, texture of erodible material, erosion hazard rating, and other site-specific variables. These data were accumulated from files located at the La Grande Ranger District (La Grande, OR) of the Wallowa-Whitman National Forest, the Wallowa-Whitman National Forest Supervisor's Office (Baker City, OR), and from aerial photographs taken from 1984-1989.

All revenues and costs were assumed to occur in the mid-point of a period, and were discounted by 4 percent per year in calculating the net present value (NPV). No stumpage price appreciation was used in this analysis. Empirical data used in the forthcoming case study include stumpage prices, harvesting costs, road maintenance costs, and road standard change costs for the Blue Mountains region of eastern Oregon. Harvesting and road costs were accumulated from recent sale proposals developed for the La Grande Ranger District timber sale program.

The stream sediment index and stream temperature index goals we used were obtained by estimating the extent and location of harvest activity during the previous 10 years in the case study watershed, and evaluating the impact of those activities on the stream sediment and temperature indices. The sediment (28.7 tons/square mile/year) and temperature (77.0°F) index levels we estimated were then used as goals not to be exceeded during the analysis.

Model Verification and Validation

Verification is concerned with determining whether the model is working as intended (Law and Kelton 1991). Our verification processes included the following steps: 1) coding and debugging the model in steps, 2) checking and debugging the paths for data between parts of the model, and 3) checking model output results for reasonableness. Validation is concerned with determining how closely the model represents the actual system (Law and Kelton 1991), and how closely it produces results comparable to optimal results for the problem specified. We are not concerned here in validating whether the stream sediment and stream temperature models represent the actual system. Although we utilize established hydrologic models in our model, we feel the validation of those models should be left to professional hydrologists. Our objective will be to validate how well the model can obtain feasible and efficient solutions by comparing them to a global optimum. However, since heuristics cannot guarantee that a global optimum will be located, validation of heuristic solution methods to large combinatorial problems is difficult due to the impracticality of obtaining the global optimum solution (Dannenbring 1977).

Statistical inference can be used to provide an estimate of the quality of heuristic solutions (Reeves 1993). The techniques that can be applied to combinatorial optimization problems involve the theory of extreme values, and were first developed by McRoberts (1971), and later extended by Dannenbring (1977), Golden and Alt (1979), and Los and Lardinois (1982). Applications of extreme value theory are common in the study of size effect on material strengths, the occurrence of floods and droughts, and the study of what are known as "record values" or "breaking values" (Koltz et al. 1982).

The theory of extreme values primarily concerns itself with the distribution of the smallest or largest values of a distribution. Two assumptions underlie the use of applying extreme value theory to the distribution of local optima. First, the sample observations, or set of local optima, must be statistically independent. This assumption cannot be rigorously justified here, since all of the samples share a common goal, that the heuristic process has tried to lead them to the same global optimum (Los and Lardinois 1982). However, a random generation of initial starting solutions to the heuristic process may induce the creation of statistically independent samples (Golden and Alt 1979, Los and Lardinois 1982). Second, the theory of extreme values is valid for continuous distributions. Combinatorial problems possess a discrete solution value distribution, where the number of possible solutions is finite. The number of possible solutions, however, grows exponentially with increases in the number of decision choices, making the approximation of a continuous distribution by a discrete distribution acceptable in practice (Dannenbring 1977, Los and Lardinois 1982).

If we assume that samples $X_1, X_2, \ldots, X_n$ are independent and identically distributed from a distribution which is assumed to be continuous, we are concerned with the distribution of the largest value of $X_1, X_2, \ldots, X_n$. The probability that the largest value X_n is smaller than the extreme value, x, can be expressed as the probability that all n observations are smaller than x:

$$F_{(x)} = Pr[X_1 < x, X_2 < x, \ldots, X_n < x]$$

Because of the independence assumption we can then say:

$$F_{(x)} = \prod_{m=1}^{n} Pr\,[\,X_m < x\,]$$

In many cases, however, the distribution of X_n does not take a simple form when n becomes large. In fact, the distribution of $F_{(x)}$ is known as the asymptotic (or limiting) distribution of extreme values when $n \to \infty$ (Koltz et al. 1982). As $n \to \infty$, $F_{(x)}$ approaches the Weibull distribution,

$$F_{(x)} = 1 - \exp\left(-\left(\frac{a - X_m}{b}\right)^{c}\right)$$

where a, b, and c are ≥ 0 and $a \geq X_m$.

We fit a three-parameter Weibull function to the distribution of independently generated solutions to estimate the global optimum NPV, using maximum likelihood procedures described by Sinha (1986). The three-parameter Weibull probability density function is:

$$(\,X_m \mid a,b,c\,) = \left(\frac{c}{b}\right)\left(\frac{a - X_m}{b}\right)^{c-1} \exp\left(-\left(\frac{a - X_m}{b}\right)^{c}\right)$$

Where: X_m = local optima derived from an independent run of the heuristic

a = Weibull location parameter

b = Weibull scale parameter

c = Weibull shape parameter

$X_m < a,\ b > 0,\ c > 0$

We developed a Quick BASIC program to follow the iterative process in Sinha (1986). We first choose arbitrary starting and ending values for the scale parameter c, then arbitrary starting and ending values for the location parameter a (where X_m < starting a < ending a). For each c we evaluate

$$\psi_c(a) = \sum_{m=1}^{n}\left(\frac{1}{a - X_m}\right)\left[1 + \left(\frac{\sum_{m=1}^{n}\log(a - X_m)}{n}\right) - \left(\frac{\sum_{m=1}^{n}(a - X_m)^c \log(a - X_m)}{\sum_{m=1}^{n}(a - X_m)^c}\right)\right]$$

$$- \left(\frac{n\sum_{m=1}^{n}(a - X_m)^{c-1}}{\sum_{m=1}^{n}(a - X_m)^c}\right)$$

increase a to a′ such that

$$\psi(a) > 0$$

and

$$\psi(a') < 0$$

or vice versa, then interpolate for (a′′) such that

$$\psi(a'') = 0$$

We then substitute c and a′′ into

$$b = \left(\frac{\sum_{m=1}^{n} (a'' - X_m)^c}{n} \right)^{1/c}$$

and evaluate the log-likelihood function

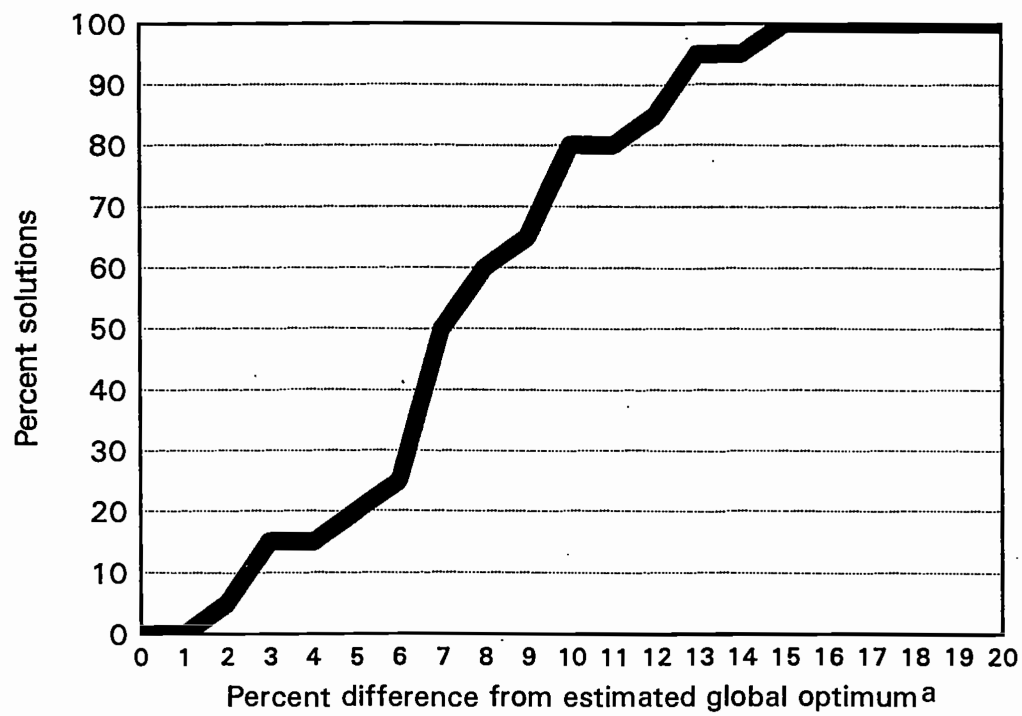
$$\log L = n \log c - nc \log b + (c - 1)\sum_{m=1}^{n} \log(a'' - X_m) - \sum_{m=1}^{n} \left(\frac{a'' - X_m}{b} \right)^c$$

We repeat this process for each estimate of c, a'', and b, and select the corresponding estimates of a'', b, and c which maximizes log L as the estimates describing $F_{(x)}$. Here we are interested in the estimation of the location parameter (a), which may be assumed to be the extreme maximum of a distribution (Bailey and Dell 1973, Reeves 1993).

Results

The Tabu search model produced solutions which were feasible, according to the estimated stream sediment and temperature index levels, with each decision choice. Detailed results of the 20 independent runs can be found in Chapter 3. Twenty percent of our independent solutions were within 5 percent of the estimated global optimum, and 80 percent of the solutions were within 10 percent of the global optimum (Figure 2.7). However, all of the solutions were within 15 percent of the estimated global optimum, and one was within 2 percent of the estimated global optimum.

Figure 2.7. Performance of a land management scheduling model, based on 20 independent runs where net present value is maximized subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.



[a] Global optimum estimated by fitting sample solution net present value data (local optima) to a Weibull distribution; estimated global optimum = $2,789,670; scale parameter = $241,218; shape parameter = 2.353.

Of the two aquatic habitat goals, stream sediment index levels were the most limiting across all 10 projection periods (Table 2.2). As a result, an average of 1.24 miles of standard rock road were obliterated per period in each solution. Most of the road obliteration occurred in the first period (Figure 2.8), thus providing some alleviation of sediment index levels for later periods. On average, 8.4 miles of standard rock road were assigned to CTI use per period. There was a sharp increase in CTI use in the last period due to an increase in clearcutting as a result of the need to maintain even-flow harvest levels. Partial cutting levels fell off in the last few periods as many stands became too old to harvest (Figure 2.9). With a heavy reliance on road obliteration to reduce sediment index levels in the first period, fewer options were available to obliterate roads in the later periods, since roads that are assumed to be used to transport timber could not be considered for road obliteration, thus the increase in CTI use.

The stream temperature index was a limiting factor only during the first few projections periods (Table 2.2). While only partial cutting in riparian areas was allowed, this reduced the density of shade reaching the stream system, and as a result $\sigma_{mr,u,i}$ were allowed in riparian areas only if the temperature goal remained below 77°F. Another major factor in the calculation of the temperature index, besides shade density, is the average tree height for units adjacent to the stream system. As riparian units continue to grow, tree heights grow according to tree height growth rates used in the analysis. Thus the decrease in shade density from partial cutting may be offset by increases in shade from tree height growth.

Table 2.2. Average levels of outputs per 10-year periods in a 14,643 acre case study watershed in eastern Oregon, using 20 runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.[a]

	Period									
	1	2	3	4	5	6	7	8	9	10
Volume harvested (MBF)	6310 (259)	6333 (270)	6349 (280)	6957 (401)	6501 (299)	6336 (285)	6373 (287)	6364 (310)	6329 (239)	5912 (297)
Stream sediment index (tons/mi^2/year)	28.6 (0.09)	28.5 (0.12)	28.4 (0.20)	28.3 (0.32)	28.5 (0.14)	28.6 (0.06)	28.5 (0.16)	28.0 (0.22)	28.5 (0.13)	28.4 (0.14)
Stream temperature index (°F)	76.8 (0.11)	76.6 (0.29)	76.6 (0.38)	75.8 (0.30)	75.9 (0.36)	76.1 (0.38)	75.4 (0.28)	74.8 (0.02)	74.6 (0.02)	74.6 (0.03)

[a] standard deviations are in parentheses.

Figure 2.8. Average length of road miles by road standard, for each of ten 10-year periods in a 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

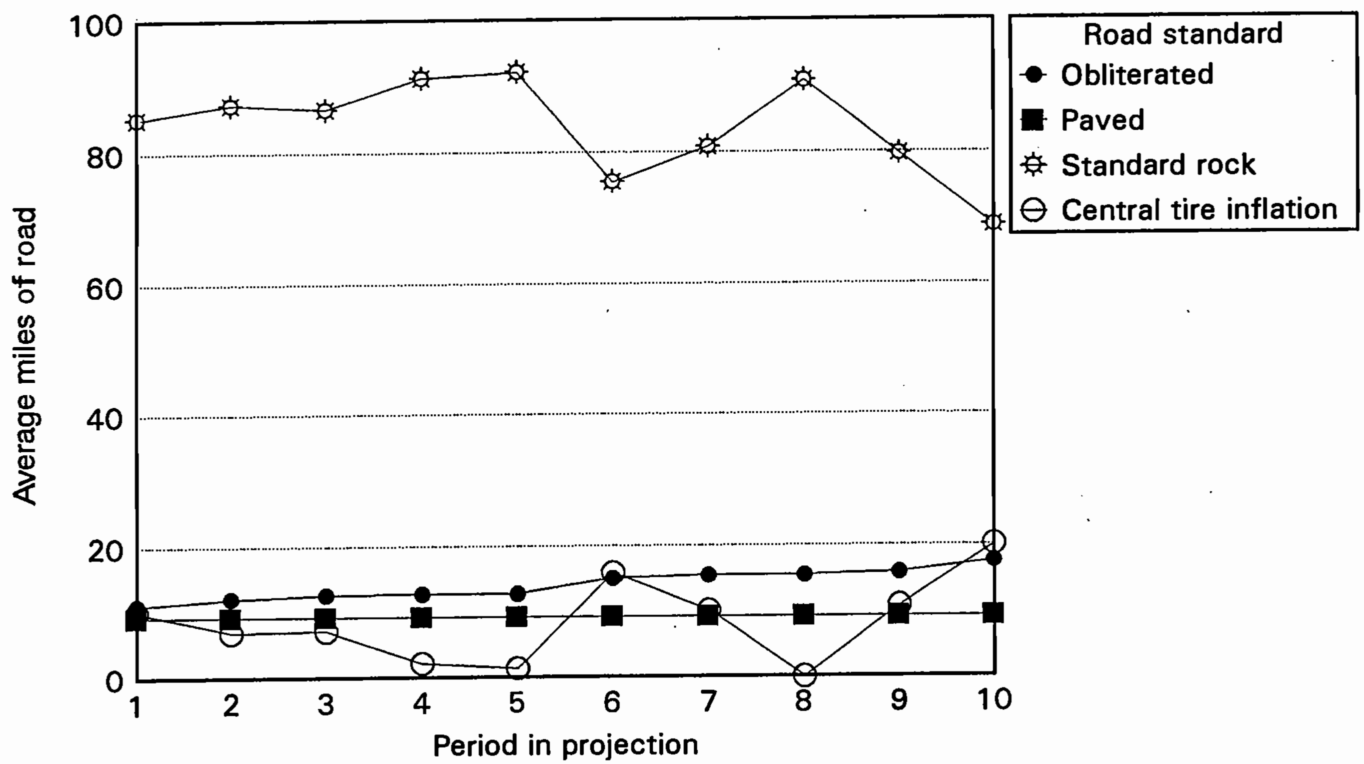
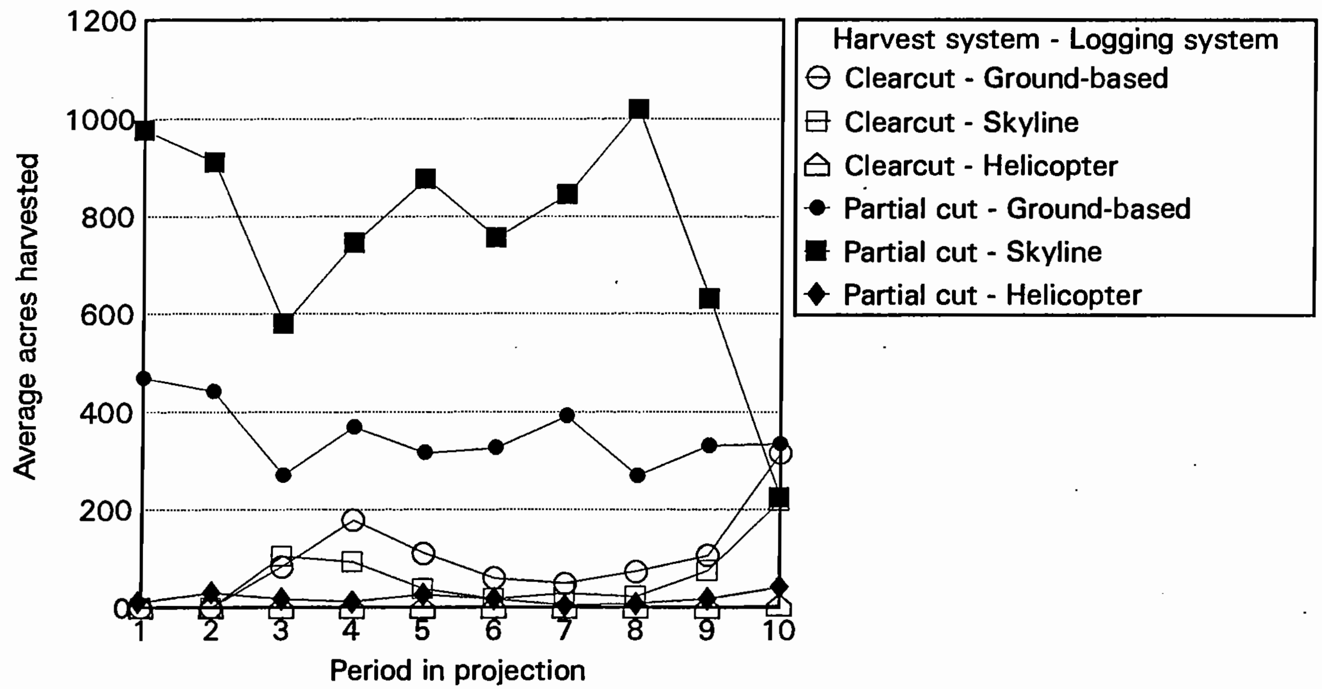


Figure 2.9. Average number of acres in harvest system - logging system combinations, for each of ten 10-year periods in a 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.



Average harvest levels range from a high of 6,957 thousand board feet (MBF) in period 4 to a low of 5,912 MBF in period 10. Period 10 levels are lower than all others due in part to the nature of the even-flow procedures we use, and due to limitations placed on harvesting activities based on average unit ages. For example, no units with dominant trees over 150 years of age could be harvested, precluding harvesting many units in later periods simply because the dominant trees are too old. Earlier periods benefitted more from management regimes which start with younger-aged units and allow 1-2 partial cutting harvest entries prior to the dominant trees becoming too old. We did not include a provision in our even-flow procedures for penalizing high-volume periods by eliminating some harvesting activities in those periods. Such a procedure may have been used to decrease the difference in timber harvest volumes between the highest-volume and lowest-volume periods.

Discussion

Each of the solutions obtained with this model are spatially and temporally feasible with regard to the aquatic habitat indices. Eighty percent of the solutions were within 10 percent of the estimated global optimum, and all were within 15 percent. Therefore we reason that the model performs reasonable well, as compared to an estimated global optimum. One might expect that if many runs of the model were made, one of the solutions would be close to the unknown global optimum.

There are several reasons why the land management scheduling model did not produce solutions which were all within 1-2% of the estimated global optimum. First, the random starting mechanism, which was designed to provide independent solutions, assigned management regimes to many units that were perhaps not the most efficient regime to use. Second, once a unit is in the solution, the unit is considered Tabu for 150 moves, preventing a change in management regimes unless the change would satisfy the aspiration criteria. Third, our method of obtaining an even-flow of volume harvested among the 10 periods was to only consider units with management regimes which could start in the period with the lowest total volume. While this succeeded in adequately meeting the even-flow constraint, it reduced the size of the neighborhood we examined, preventing the examination of management regimes starting in other periods.

Fourth, we modeled road standard change decision choices as contingencies within the sediment model structure. Standards could only be changed as a result of violating the sediment goal, and when this occurred those roads with the highest amount of sediment produced per length were given highest priority. In addition, only roads not planned for use could be obliterated. Thus the timing and location of road standard changes were not explicitly modeled as a neighborhood of choices, possibly preventing better alternative road systems from being considered. Finally, roads that were obliterated as a result of violating the sediment goal may have effectively reduced potential management options for many units by eliminating a path from the unit to the mill. While helicopter logging remained an option through the analysis (i.e., entry nodes to the road network for helicopter logging were mainly to paved roads, which we assumed could not be obliterated), options for ground-based and cable logging may have been eliminated.

To identify solutions which may form a tighter distribution near the global optimum, one might forgo the generation of a random starting point for the Tabu search process, and instead identify those $\sigma_{mr,u,i}$ which contribute most to the objective function by starting the silvicultural management regimes in the first few periods. However, this would not allow the generation of independent samples from which one could attempt to validate the model, since the process would generally start from a non-random point in the solution space. On the other hand, such procedures have been used in other land management scheduling algorithms (e.g., SNAP II+ [Sessions and Sessions 1993]), with some success.

Conclusions

The large number of integer variables required in our case study watershed and the complexity of the aquatic habitat evaluation procedures make locating an optimal solution with a traditional mathematical programming method (e.g., integer programming) a computationally difficult process in locating the optimal solution. We developed a heuristic programming method to ensure the compatibility of aquatic habitat goals and land management activities, and used extreme value theory to estimate a global optimum from our sample data. A comparison of our model with other algorithms is not presented because no other algorithm has at its disposal the exact evaluation procedures for the aquatic habitat quality goals that are utilized in this study.

We have demonstrated that a Tabu search model can be developed to simultaneously meet aquatic habitat goals with each decision choice. Therefore, we ensure that land management activities are compatible with aquatic habitat goals by always staying in the feasible region of solutions. In developing a plan of forest activities we feel this approach shows promise for efficiently and explicitly incorporating aquatic habitat goals into forest plans.

The types of aquatic habitat goals that we have examined here may lend themselves well to using non-linear or integer programming because the response to the goals from harvesting a unit or changing a road standard is predictable. However, since all unit and road choice variables are considered integer variables, the solution time may be unacceptable. While the land management scheduling model developed here may not arrive at the "true" global optimum, one thing is clear - the solutions we obtain using our model are feasible, both spatially and temporally. We consider our heuristic process to be an important alternative to the approach of "optimally" solving a relaxed problem without the aquatic habitat goals, and then checking to see if the solution is feasible using a posterior analysis. Future research might combine the two approaches by finding a solution to the relaxed problem and then using Tabu search to move from the optimal, but infeasible, solution for the relaxed problem to a feasible solution to the original problem. This approach would provide additional insight into the forest planning problem. First, we would obtain a measure of the cost of the aquatic habitat goals, and second, we would have the starting point to move toward feasibility. How efficient this approach might be is not known.

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Chapter 3

Ensuring the Compatibility of Aquatic Habitat and Commodity Production Goals in Eastern Oregon with a Tabu Search Procedure: Detailed Results

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Abstract

Stream sediment and temperature levels have been identified as important measures of aquatic habitat quality in eastern Oregon. Ensuring that aquatic habitat quality is maintained or restored is an important goal for National Forest Management. Results of a land management scheduling model used to ensure the compatibility of land management activities and aquatic habitat goals indicate that for a 14,643 acre watershed in eastern Oregon, on average, the net present value of solutions was $175.91 per acre. Most of the road obliteration choices are scheduled for period 1, which provides some relief for later periods. However, some obliteration, and an increase in central tire inflation (CTI) use, is required in later periods to further provide harvesting opportunities. The average length of road assigned to CTI use was small, however, and highly variable across the ten projection periods. Partial cutting using skyline logging systems averaged 757 acres per period, followed by partial cutting with ground-based logging systems (352 acres per period). Some helicopter logging operations were used in units which had too little volume to cover a fixed transportation cost for standard rock roads, but where stumpage prices could cover helicopter logging and other variable transportation costs if wood was transported via helicopters to landings at paved roads.

Of the silvicultural treatments available, the partial cutting regime with a 30-year return interval averaged over 5,000 acres per run of the model, with a very low coefficient of variation. Clearcutting also had a low coefficient of variation, but was only applied to lodgepole pine stands. This indicates that a very similar amount these two types of treatments were scheduled in each run.

A fixed transportation cost incurred on a per-unit basis for paths (routes from the harvest site landing to the mill) which utilize standard rock roads prevented many units from being scheduled with a management regime. Perhaps grouping small stands into a single management choice may be appropriate for management problems which assume high fixed transportation costs.

Equivalent clearcut acres (ECA), a measure of landscape use, increases through time because partial cutting tends to reduce basal area levels, and because cumulative growth rates are less than the partial cutting rate (33%). Clearcutting activities also increase in the last two projection periods, decreasing basal area levels there, and adding to the increase in ECA levels. Stream sediment levels were about at their maximum across all ten projection periods, indicating that this constraint was the most binding of the two aquatic habitat goals. Stream temperature levels were about at their maximum for the first few periods, after which increases in tree height growth in units adjacent to streams offsetting the amount of solar radiation reaching the stream system from partial cutting activities. Timber harvest levels were fairly even across the ten projection periods, with a maximum deviation of about 15 percent between the highest and lowest periods. The difficulty in scheduling treatments in the last period due to a decline in partial cutting activities was the most influential factor.

Introduction

A land management scheduling model was developed to schedule timber harvests subject to even-flow, stream sediment, and stream temperature goals. The theoretical complexity of the model was established in chapter 2. This chapter summarizes in detail the average results of 20 independent runs of land management scheduling model. In addition, results are illustrated for the best solution of the 20 independent solutions obtained from running the model.

Methods

A land management scheduling model was developed to simultaneously schedule timber harvest choices and road management choices subject to even-flow of timber harvest volume, stream sediment, and temperature constraints. Twenty independent solutions of the model were obtained for a 14,643 acre case study watershed. Results included net present value (NPV), stream sediment and temperature index levels, equivalent clearcut acre (ECA) levels, timber harvest volume levels, the number of road obliteration miles per period, and the number of central tire inflation (CTI) miles per period assigned. Average levels for each of these results are determined, along with a measure of dispersion among the samples. Also summarized are the total number of acres in three types of silvicultural management regimes: 1) partial cutting with a 30-year return interval, 2) partial cutting with a 50-year return interval, and 3) a thinning-clearcut regime. Finally, summarized are the average number of acres treated with six harvest system - logging system combinations.

The decision choices available to the model were:

Harvesting systems:

- Partial cutting on a 30-year return interval, all tree species, no cutting before age 50 or after age 150.

- Partial cutting on a 50-year return interval, all tree species, no cutting before age 50 or after age 150.
- Clearcutting and thinning. If thinning is the first harvesting activity, it can occur between the ages of 50 and 100. Clearcutting follows 20 years later. If clearcutting is the first harvesting activity, it can occur between the ages of 101 and 150. After a clearcut has occurred, thinning occurs at subsequent age 50, and clearcut at age 70. Lodgepole pine stands only.
- Not harvesting a unit.

Logging systems:

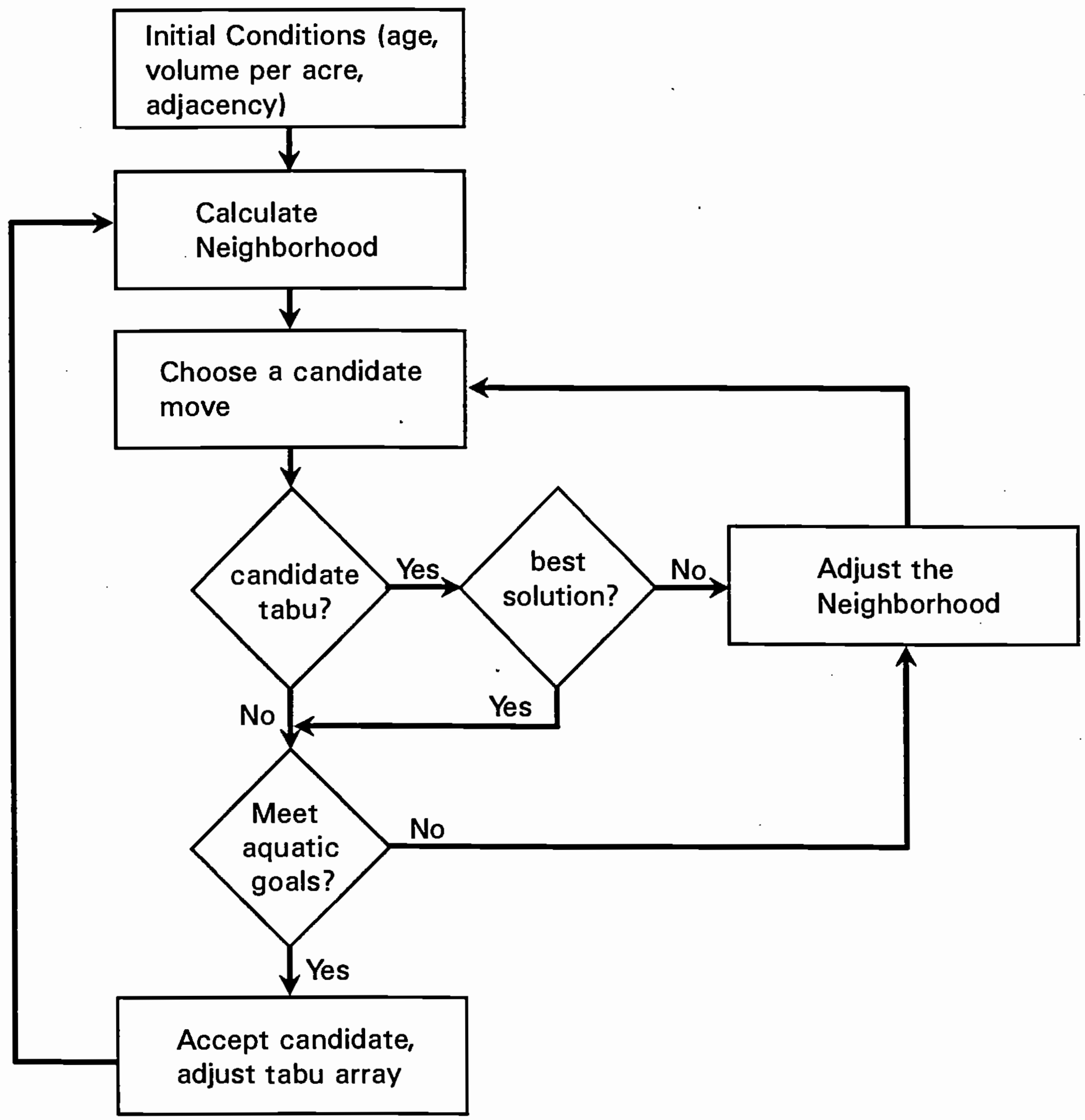
- Ground-based
- Skyline
- Helicopter

Road standard changes:

- Standard rock to central tire inflation
- Standard rock to obliterated
- No change in road standard

The model used a Tabu search procedure to evaluate candidate land unit decision variables (Figure 3.1). If a decision variable was not considered Tabu, it was temporarily entered into the solution and evaluated against the sediment and temperature goals. If the sediment goal was violated, one of three actions could occur: 1) the candidate decision choice was rejected, 2) a road was obliterated to

Figure 3.1. General Tabu search model flow using short-term memory and aquatic habitat quality goal constraints.



reduce sediment levels, or 3) a road was assigned CTI use to reduce sediment levels. If the temperature goal was violated, only one action could occur: the candidate choice was rejected.

Results

On average, the NPV of the 20 independent solutions was $2,575,872 (Table 3.1), or $175.91 per acre. The highest solution obtained was $2,744,441 ($187.42 per acre), and the estimated global optimum was $2,789,670 ($190.51 per acre). Chapter 2 describes the methodology behind the location of the estimated global optimum. Eighty-percent of the solutions obtained were within 10 percent of the estimated global optimum, and all were within 15 percent of the estimated global optimum. One of the 20 independent runs produced a NPV within 2 percent of the estimated global optimum. The land management scheduling model seemed to perform well when individual runs start with a randomly defined starting point.

The length of road obliterated per period averaged 1.24 miles, although it was highly variable (Table 3.2). Most of the obliteration occurred during the first period. Later periods benefitted from the reduction in sediment realized during the first period. However, some obliteration was required in later periods to further provide harvesting opportunities within limits set by the sediment goal. When an obliteration choice is made for a single road segment, it is assumed that the road is obliterated for all subsequent periods in the projection. However, the same road may be considered again (as a decision choice) for obliteration in periods previous to the scheduled obliteration period. CTI choices are only made

Table 3.1. Net present value results for a 14,643 acre case study watershed in eastern Oregon, using 20 runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

	Sample size	Mean	Standard deviation	Coefficient of variation	Minimum	Maximum	Estimated global optimum
Net present value	20	$2,575,872	$99,585	3.9	$2,371,474	$2,744,441	$2,789,670

Table 3.2. Mean length of roads obliterated per period and roads assigned to central tire inflation use per period, for a 14,643 acre case study watershed in eastern Oregon, using 20 runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

Period	Length	Standard deviation	Percent of rock roads available in period
	(Miles)	(Miles)	(%)
Road obliteration			
1	5.92	2.07	6.2
2	1.03	1.39	1.1
3	0.51	0.90	0.6
4	0.06	0.25	0.1
5	0.03	0.08	0.0
6	2.30	1.83	2.6
7	0.37	0.78	0.5
8	0.00	0.00	0.0
9	0.41	0.85	0.5
10	1.73	1.87	2.0
Central tire inflation			
1	10.02	4.33	10.3
2	6.91	4.67	7.5
3	7.14	4.97	7.8
4	2.21	2.82	2.4
5	1.40	2.21	1.5
6	15.75	5.94	17.8
7	10.13	5.61	11.5
8	0.03	0.14	0.0
9	10.75	6.78	12.2
10	19.96	9.17	22.7

for single periods per road, and do not assume that CTI will also be used in previous or subsequent periods. The length of roads assigned to CTI use averaged 8.43 miles per period, but was also highly variable across the 10 periods (Table 3.2). The road system for the best of the 20 solutions, over time, is illustrated in Figures 3.2-3.11.

Of the three silvicultural management regimes available, the partial cutting regime with a 30-year return interval was allocated to 34.6 percent of the watershed (Table 3.3), while partial cutting with a 50-year return interval was allocated to 3.5 percent of the watershed, and thinning-clearcut regime to 9.5 percent of the watershed. Meadows account for 20.1 percent of the watershed, and are not scheduled for activities. Thus about 32 percent of the watershed was not given a silvicultural management regime. Even so, the land management scheduling model had reached a steady-state area in obtaining solutions for each individual run, where deviations in NPV and even-flow of timber volume had become minuscule (see Figure 3.12 for an example). The coefficient of variation (CV) for partial cutting with a 30-year return interval was very low, indicating a similar usage of this across all 20 runs. The clearcutting management regime, applied only to lodgepole pine stands, also had a very low CV, also indicating that for the 20 runs, a very similar amount of clearcutting activity was assigned to lodgepole pine stands in the watershed.

Since partial cutting was the dominant silvicultural management regime employed, combinations of these harvest systems with ground-based and skyline logging systems were the most common harvest system - logging system choices (Table 3.4). Some helicopter logging operations were scheduled for stands which

Figure 3.2. Road standards in period 1 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

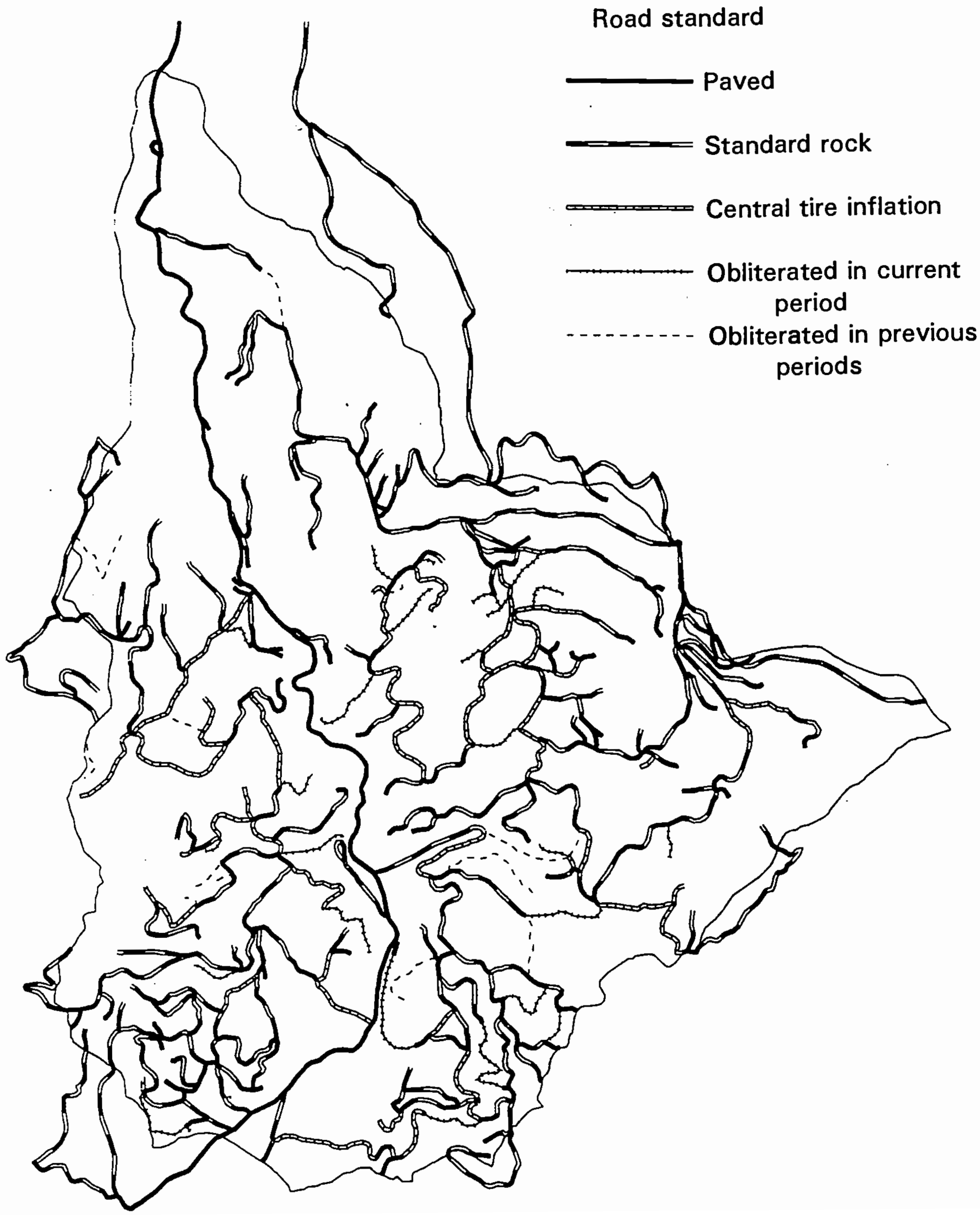


Figure 3.3. Road standards in period 2 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

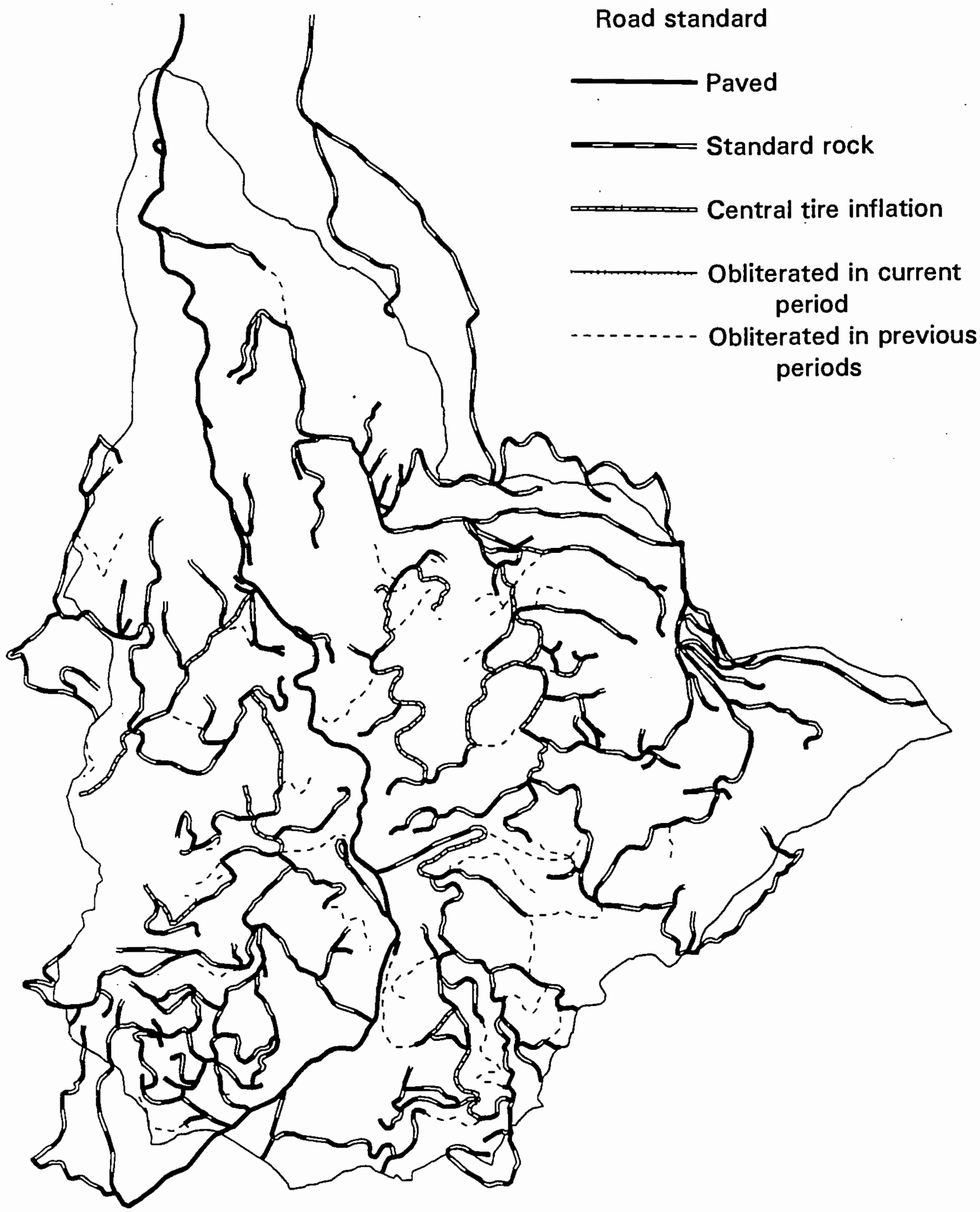


Figure 3.4. Road standards in period 3 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

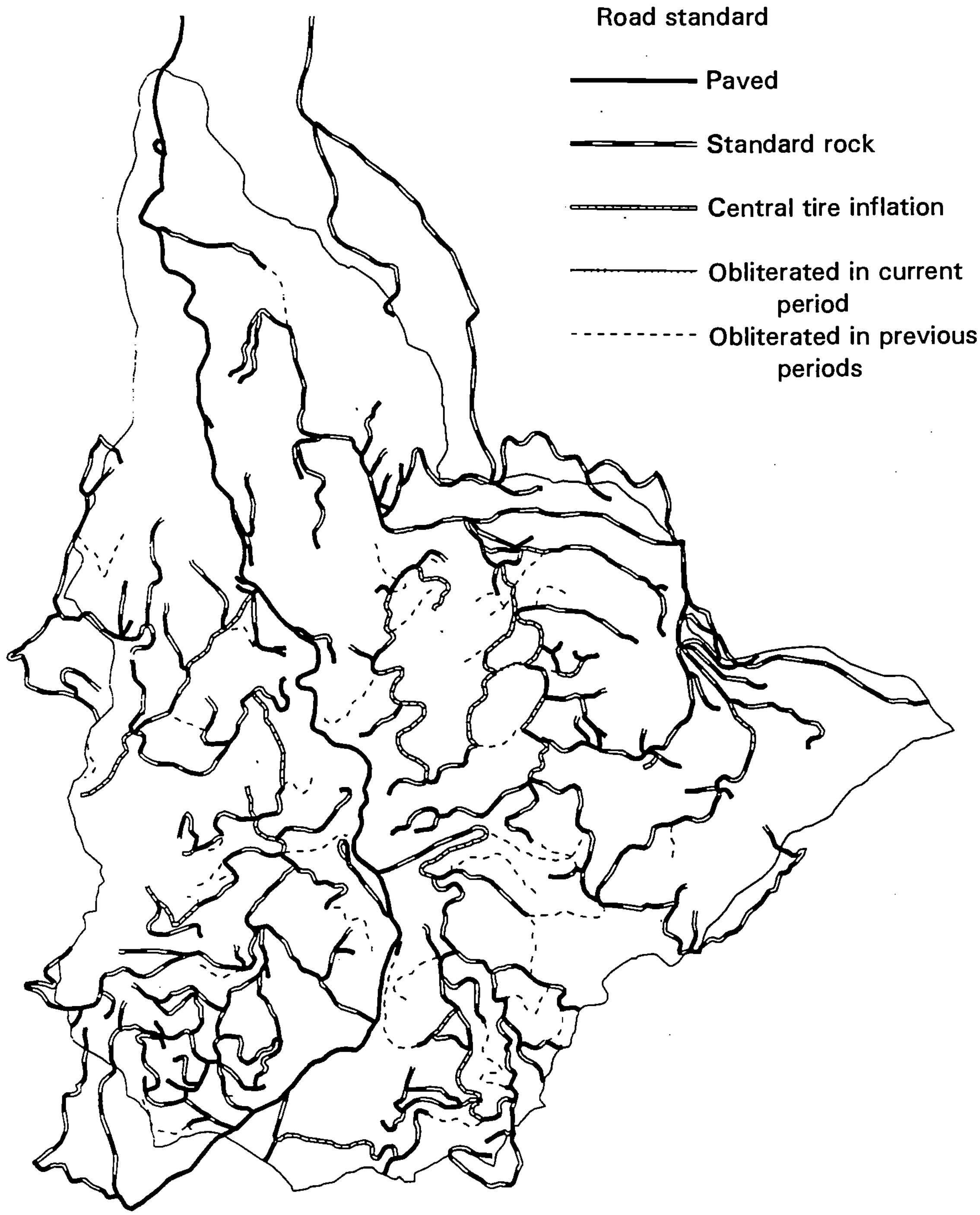


Figure 3.5. Road standards in period 4 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

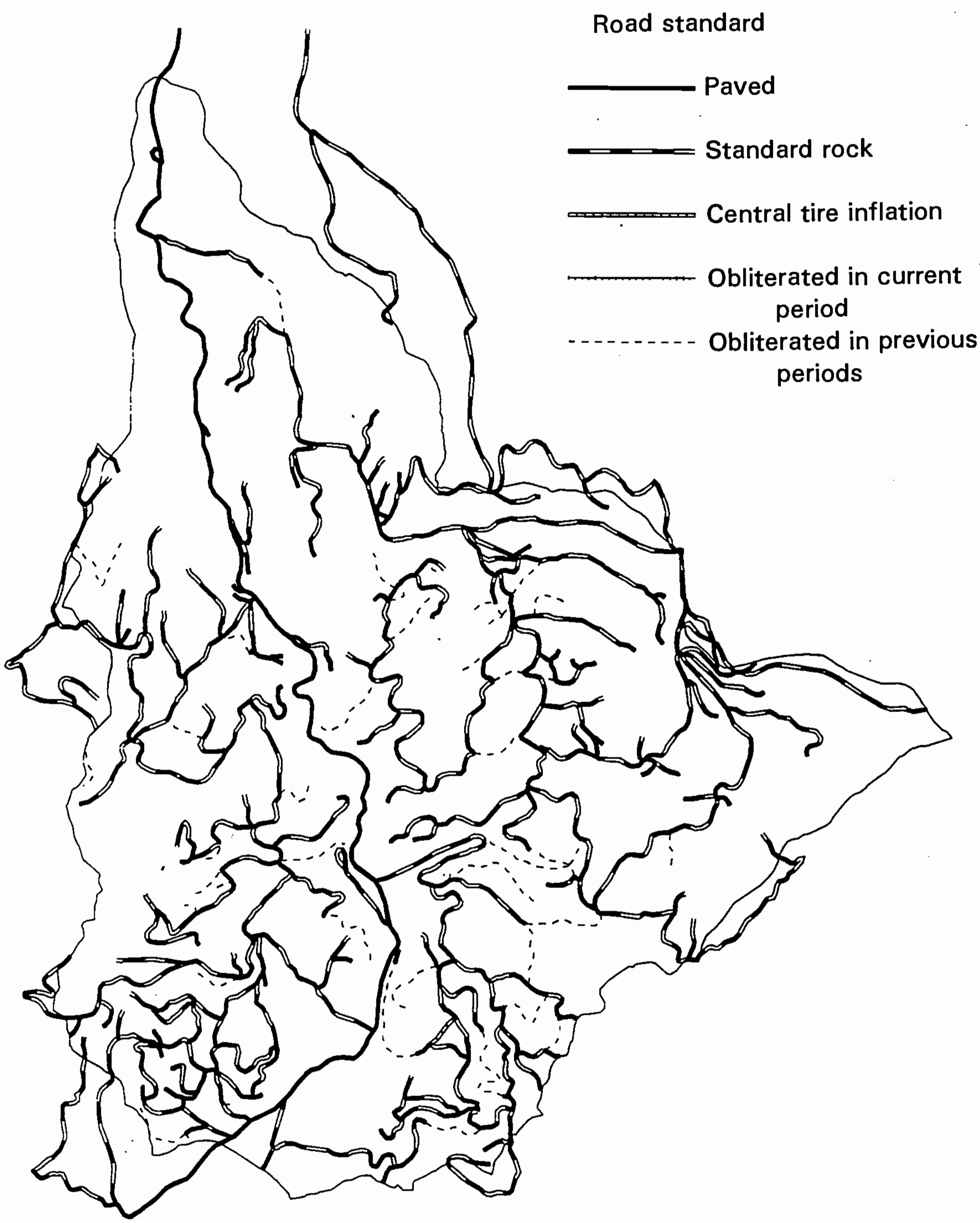


Figure 3.6. Road standards in period 5 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

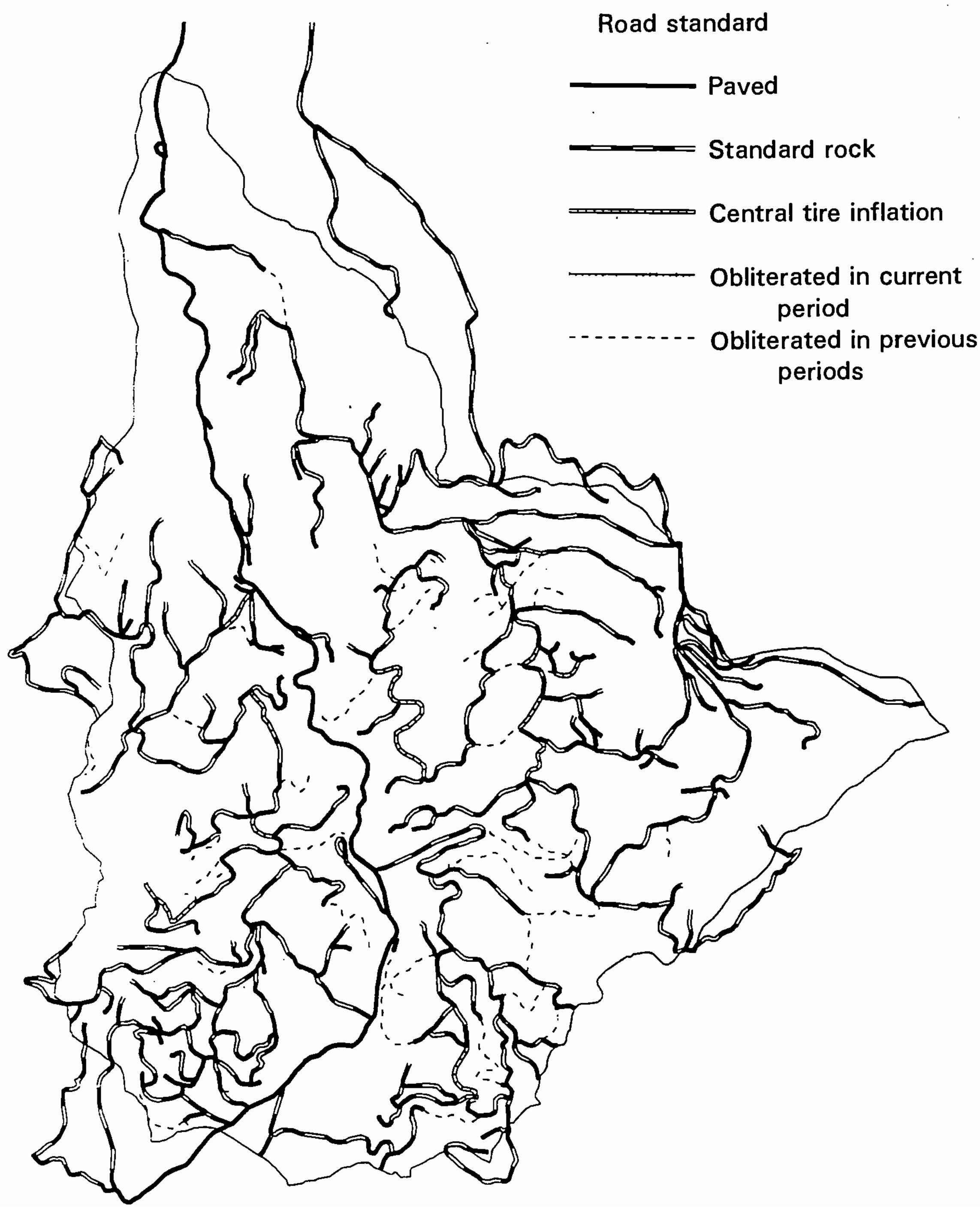


Figure 3.7. Road standards in period 6 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

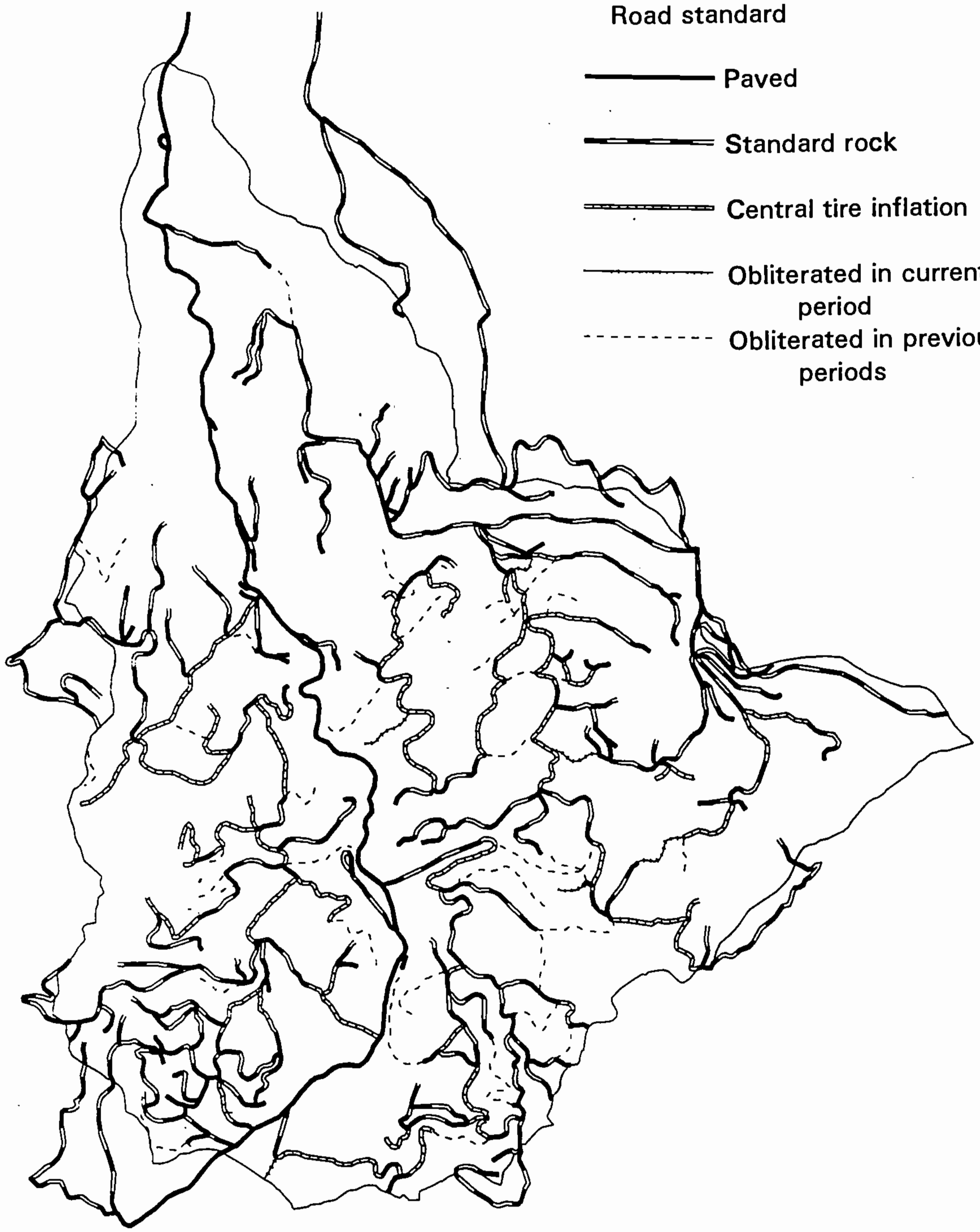


Figure 3.8. Road standards in period 7 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

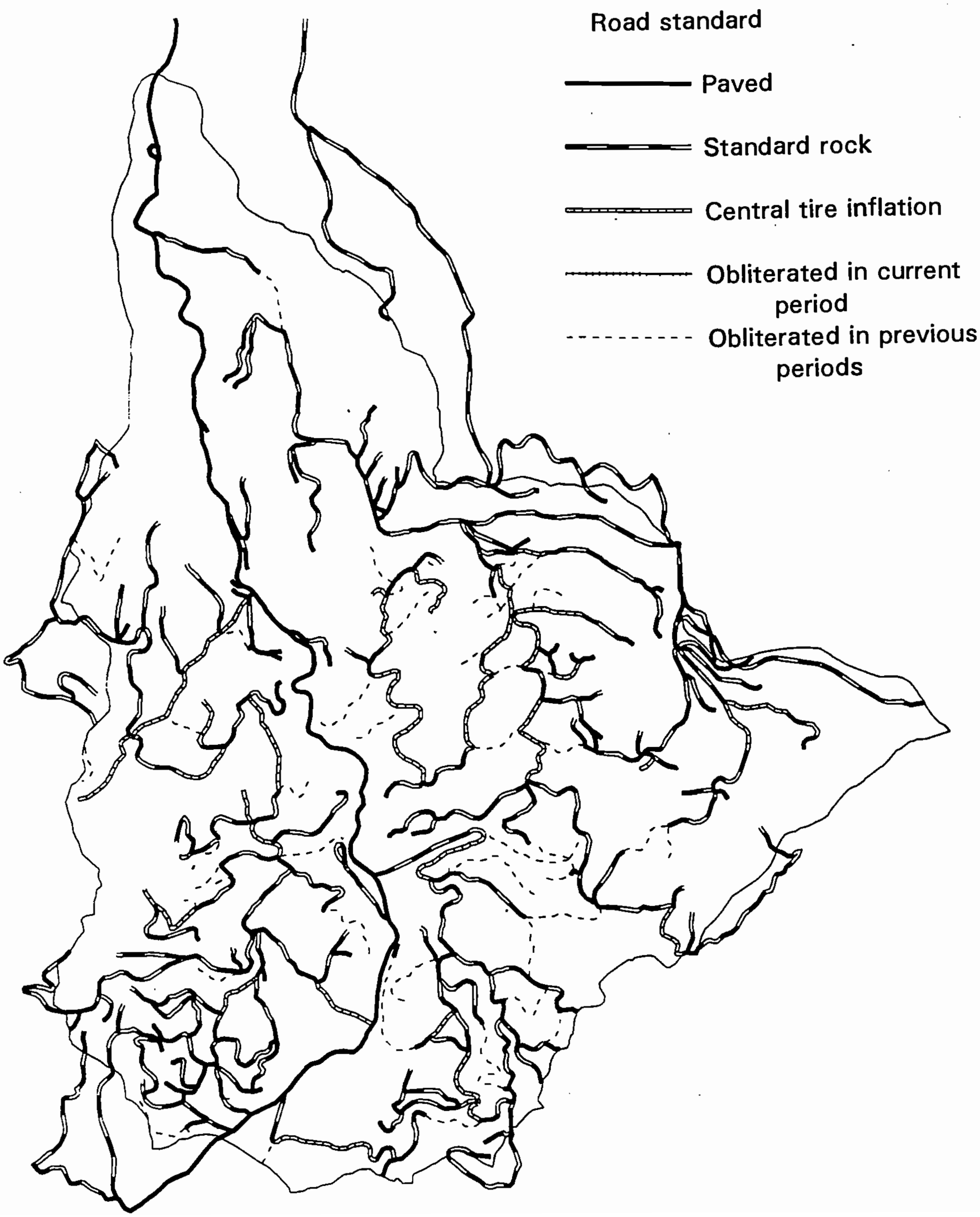


Figure 3.9. Road standards in period 8 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

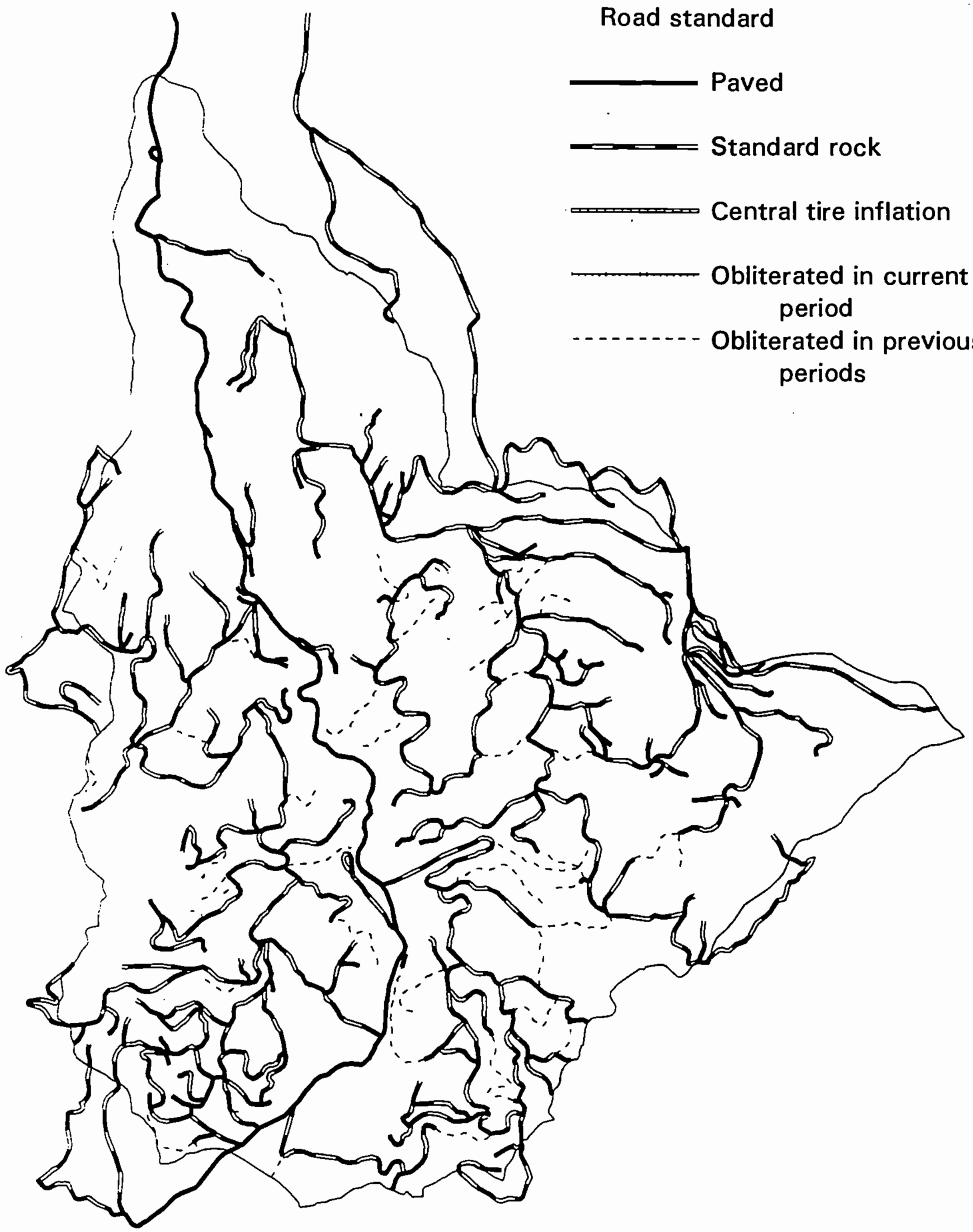


Figure 3.10. Road standards in period 9 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

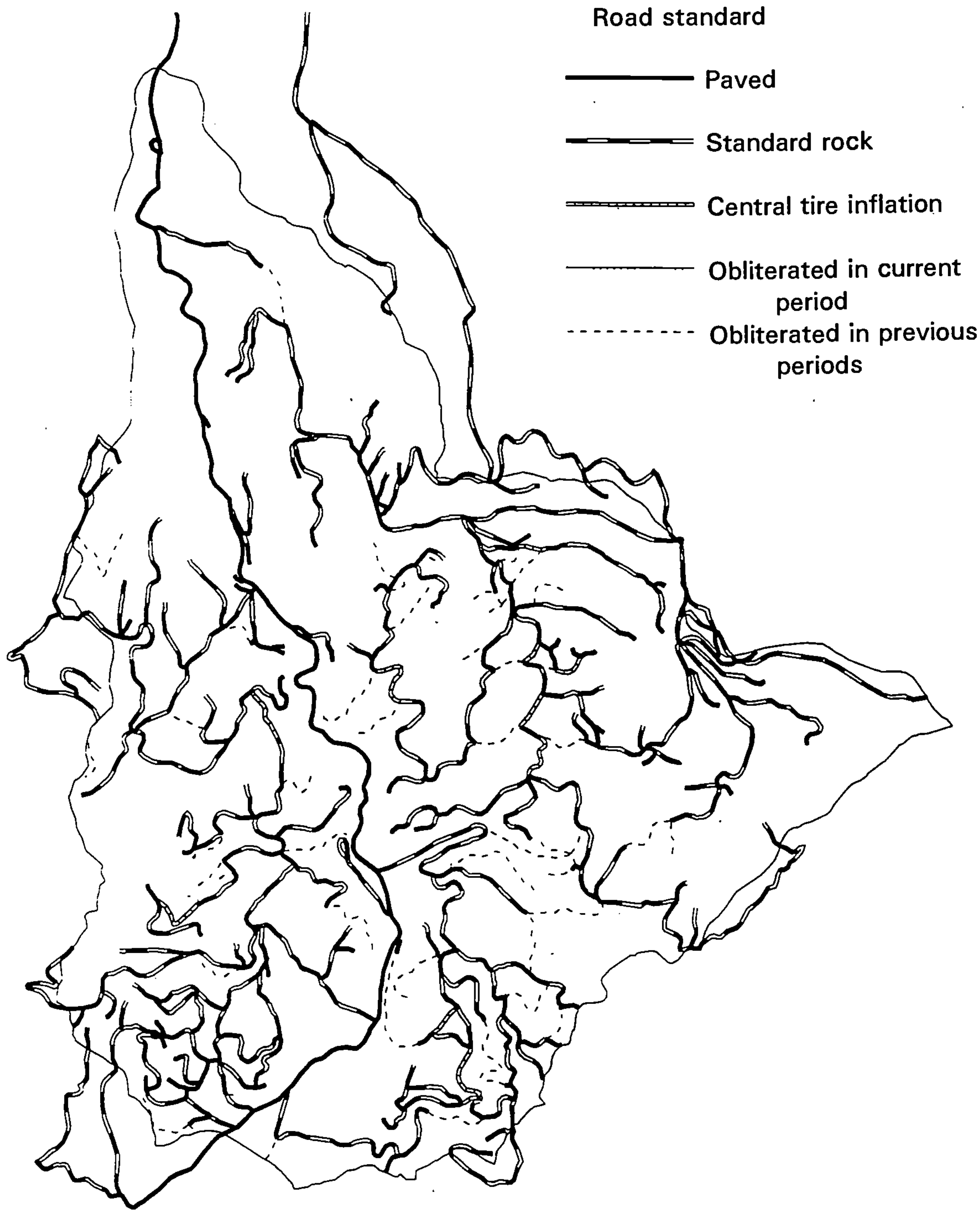


Figure 3.11. Road standards in period 10 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

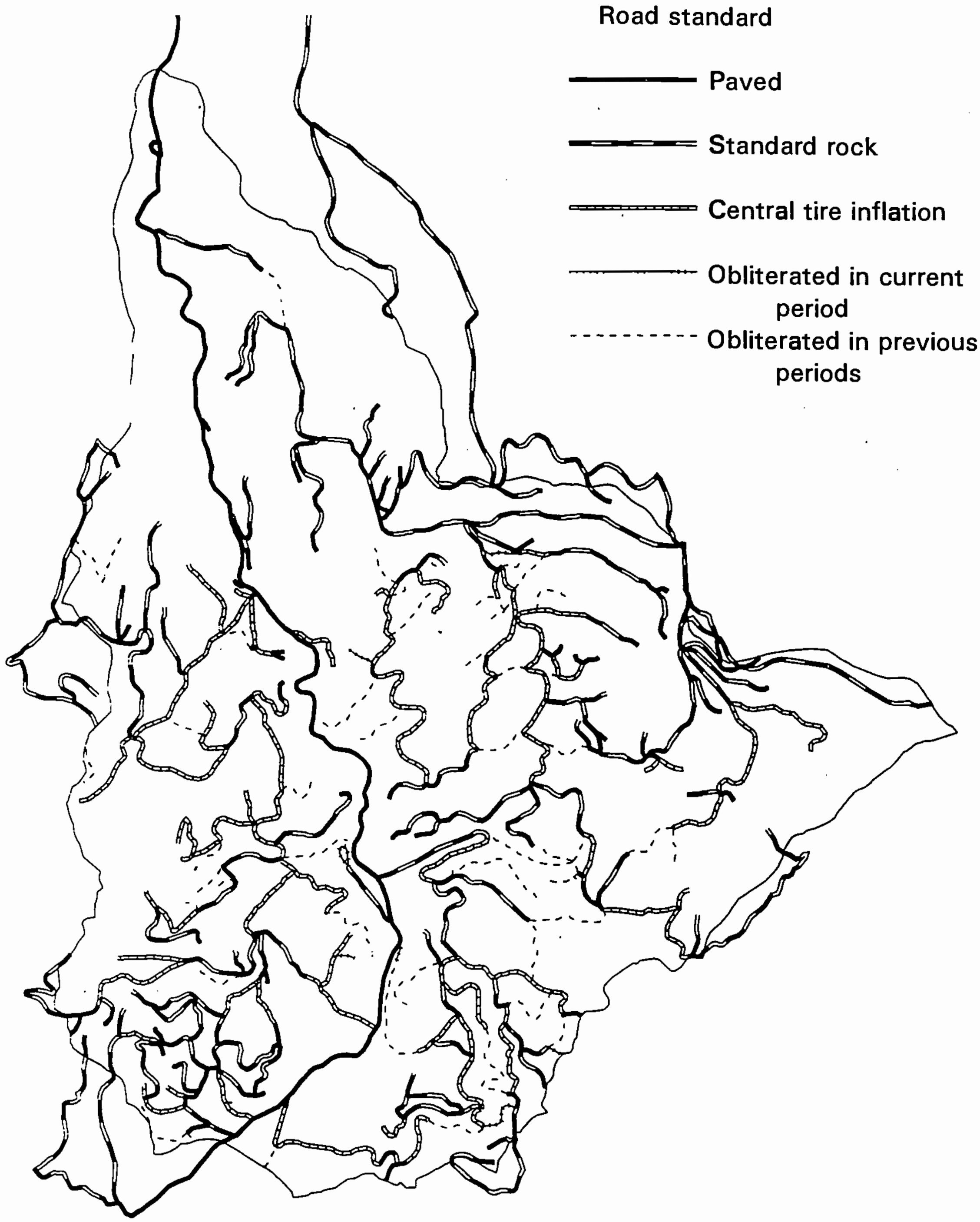


Table 3.3. Mean area assigned to silvicultural management regimes, for a 14,643 acre case study watershed in eastern Oregon, using 20 runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

Silvicultural management regime	Mean area per run	Standard deviation	Coefficient of variation	Percent of watershed
	(acres)	(acres)	(%)	(%)
Partial cutting, 30-year return interval[a]	5,072.5	216.9	4.3	34.6
Partial cutting, 50-year return interval[a]	519.1	109.9	21.2	3.5
Clearcut-thinning[b]	1,394.9	38.5	2.8	9.5

[a] Harvesting activities can occur in units with ages between 50 and 150 years.
[b] If the first activity is a thinning, it can occur between ages 50 and 100; if the first activity is a clearcut, it can occur between ages 101 and 150. After a clearcut activity has occurred, thinning occurs at age 50, with a subsequent clearcut at age 70.

Figure 3.12. Net present value and deviation from even-flow of timber harvest volume for 1600 iterations in the development of a management plan for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

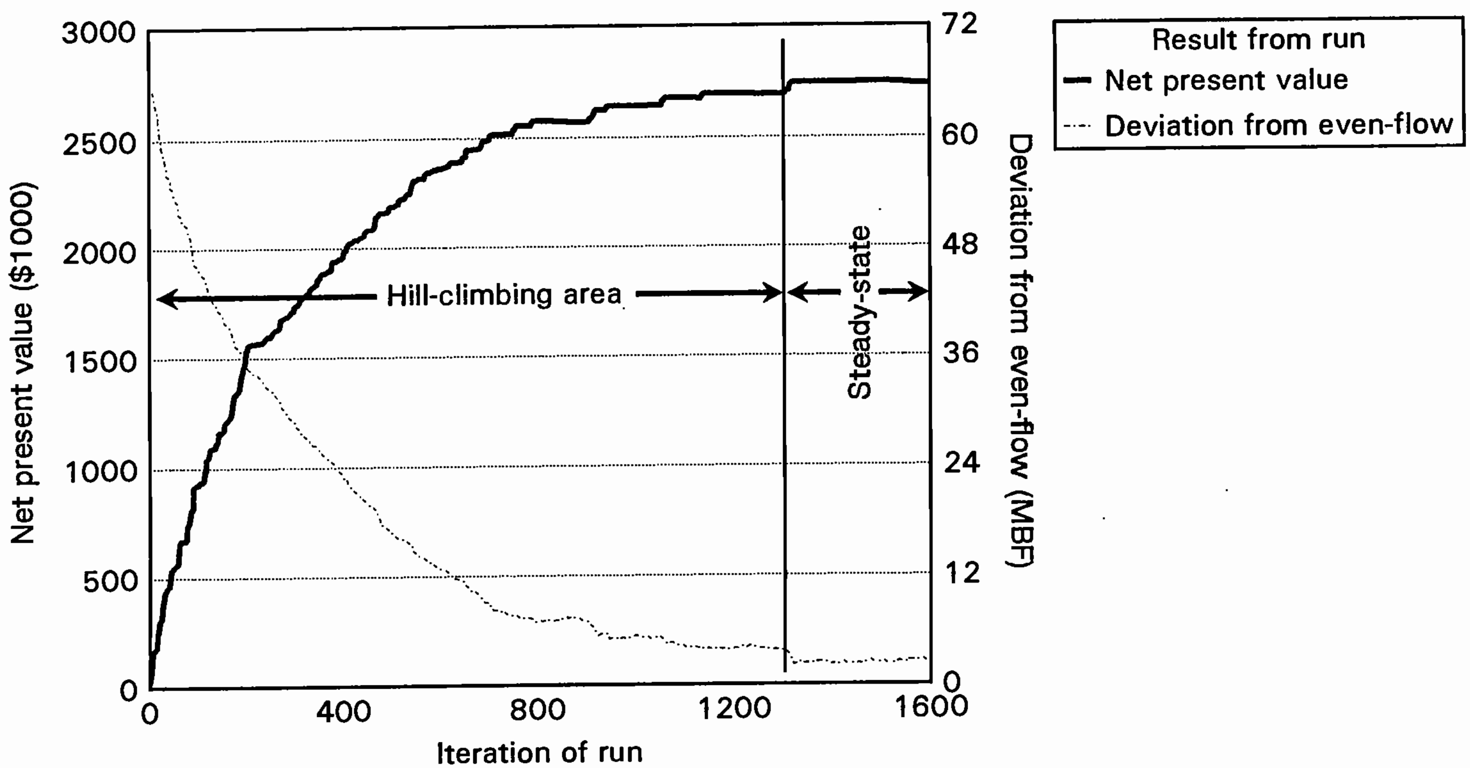


Table 3.4. Average area of harvest system - logging system activity per ten 10-year periods in a 14,643 acre case study watershed in eastern Oregon, using 20 runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

Harvest system - logging system	Average area per period	Standard deviation	Coefficient of variation	Percent of watershed per period
	(acres)	(acres)	(%)	(%)
Clearcut - ground-based	97.7	93.9	96.1	0.7
Clearcut - skyline	60.1	69.6	115.8	0.4
Clearcut - helicopter	0.6	3.9	645.4	0.0
Partial cut - ground-based	352.0	91.9	26.1	2.4
Partial cut - skyline	756.5	239.2	31.6	5.2
Partial cut - helicopter	19.0	19.4	102.0	0.1

perhaps could not cover the high fixed transportation costs for paths that used standard rock roads. Figures 3.13-3.22 illustrate the harvest system - logging system choices for the best solution located among the 20 runs. Over time partial cutting declines in the last two periods (Figure 3.23) because many units become too old to allow harvest activities to occur. After age 150, no logging is allowed. Clearcutting is used more heavily in the last 2 periods to make up for the shortfall in volume from partial cutting.

Average timber harvest volume levels are fairly constant across all ten projection periods (Table 3.5), as are average sediment index levels. The even-flow constraint appears to provide an adequate flow of timber per projection period without large deviations in harvest volumes. The maximum deviation in even-flow levels is about 15 percent (comparing period 4 to period 10). The constant sediment levels indicate that, of the two aquatic habitat goals, the sediment index was the most binding across all ten projection periods. Stream temperature index levels are constraining only during the first few periods, and decrease slightly as one moves across projection periods. Because of tree height growth in polygons adjacent to streams, and the fact that most polygons in riparian areas are small and possibly may not be scheduled for harvest, stream shading increases with time and lower stream temperature index levels are realized. Equivalent clearcut acres (ECA), a measure of landscape use, increases through time because partial cutting tends to reduce basal area levels because cumulative growth rates are less than the partial cutting rate (33%). Clearcutting activities also increase in the last two projection periods, decreasing basal area levels there, and adding to the increase in ECA levels.

Figure 3.13. Harvest system - logging system combinations in period 1 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

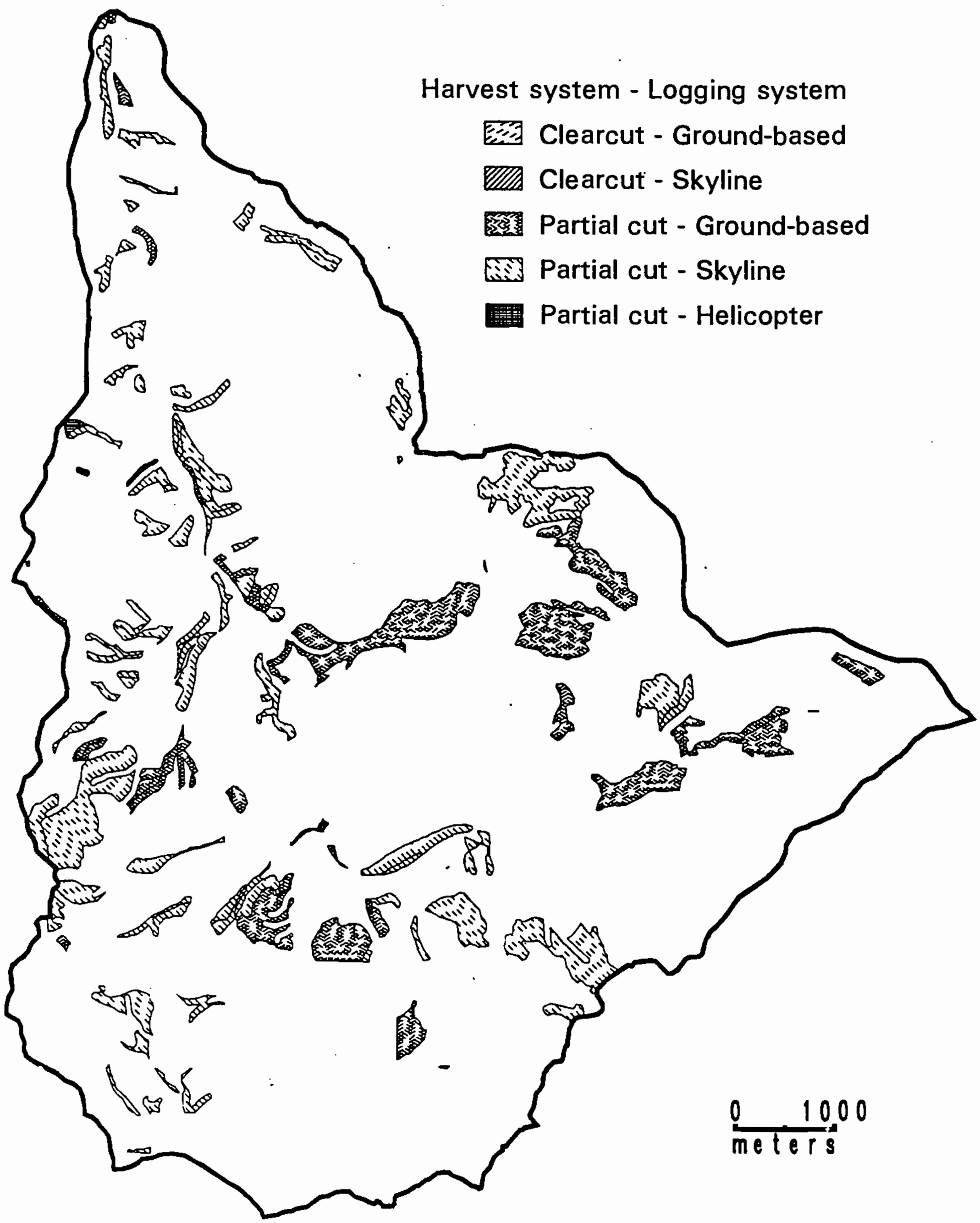


Figure 3.14. Harvest system - logging system combinations in period 2 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

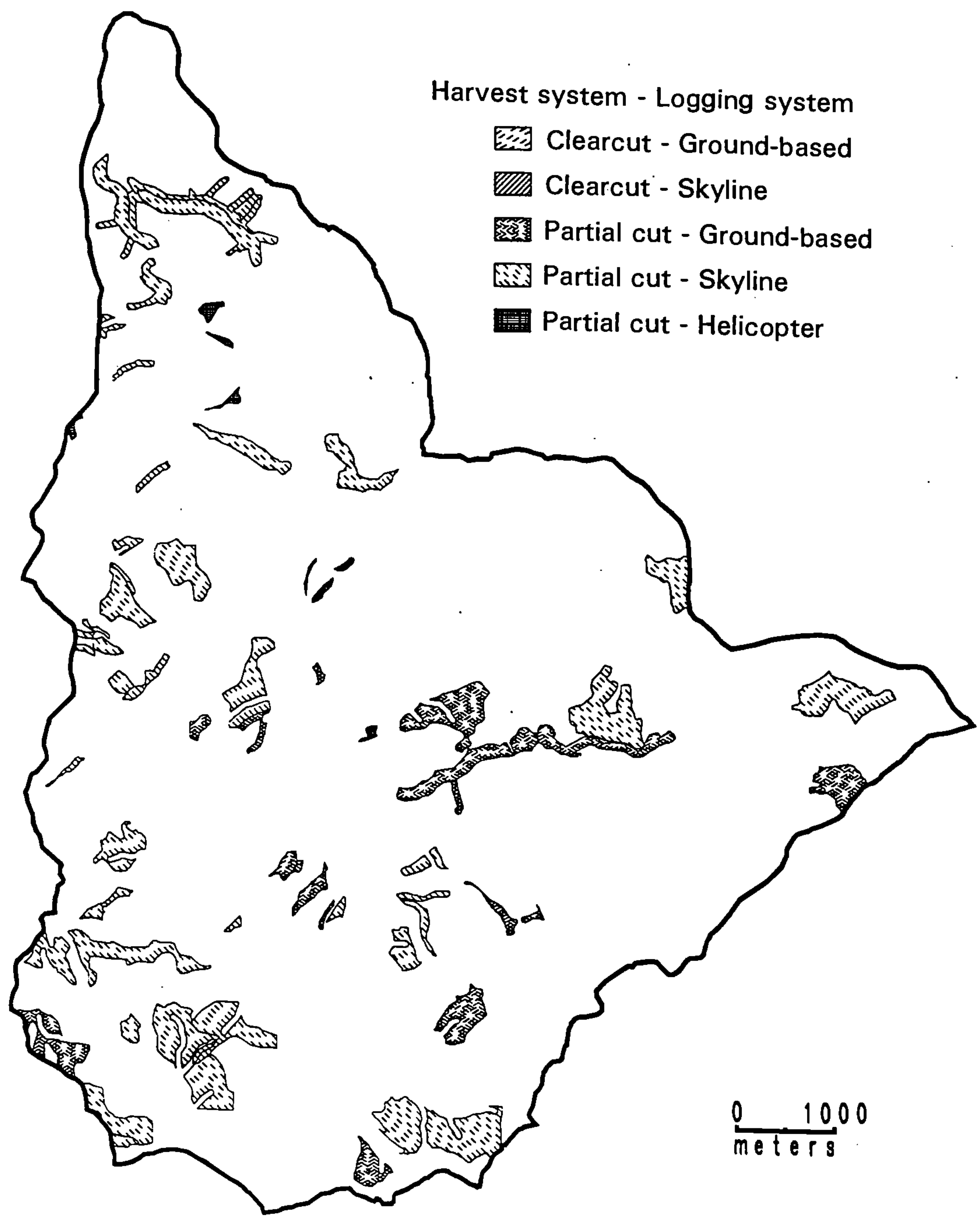


Figure 3.15. Harvest system - logging system combinations in period 3 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

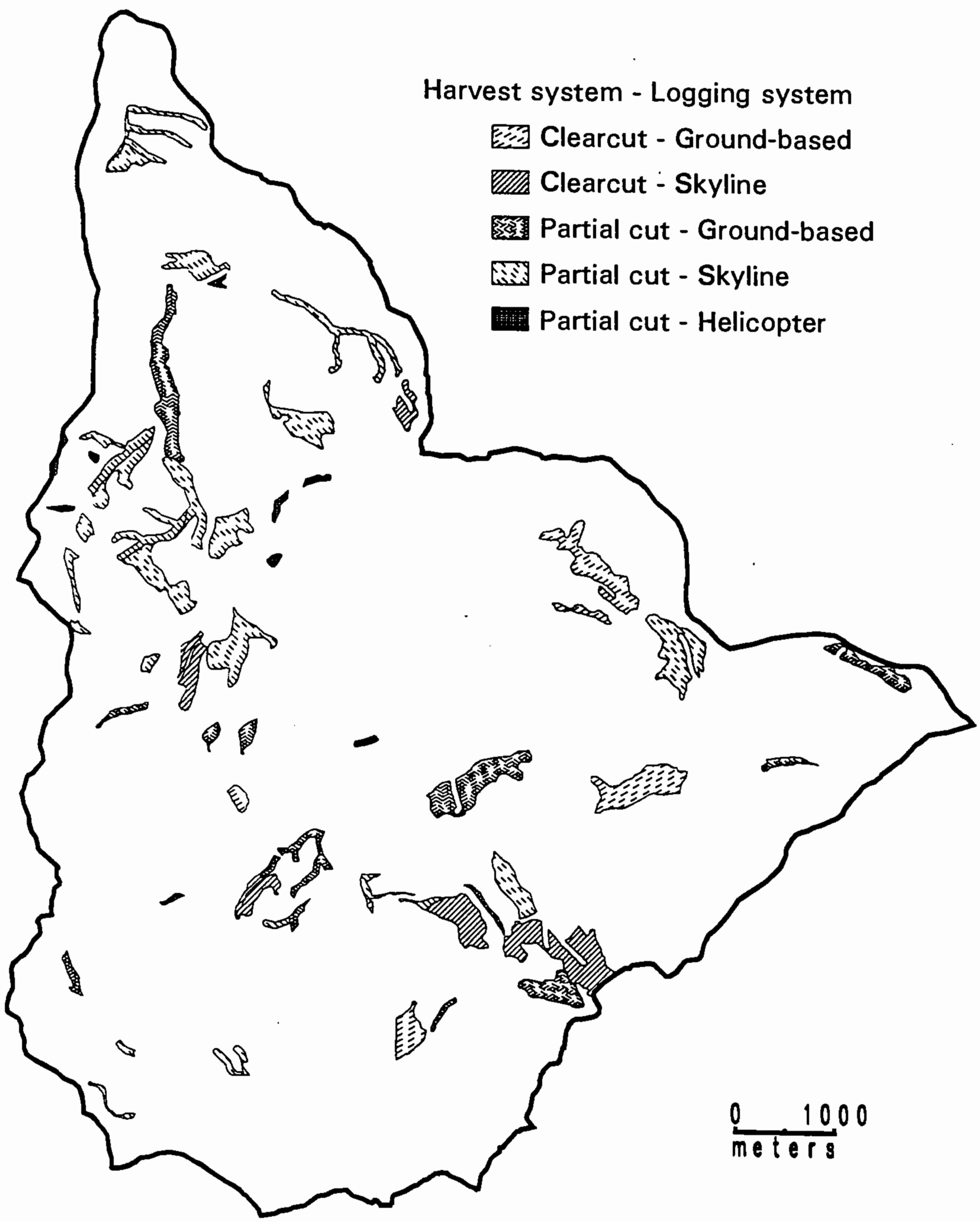


Figure 3.16. Harvest system - logging system combinations in period 4 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

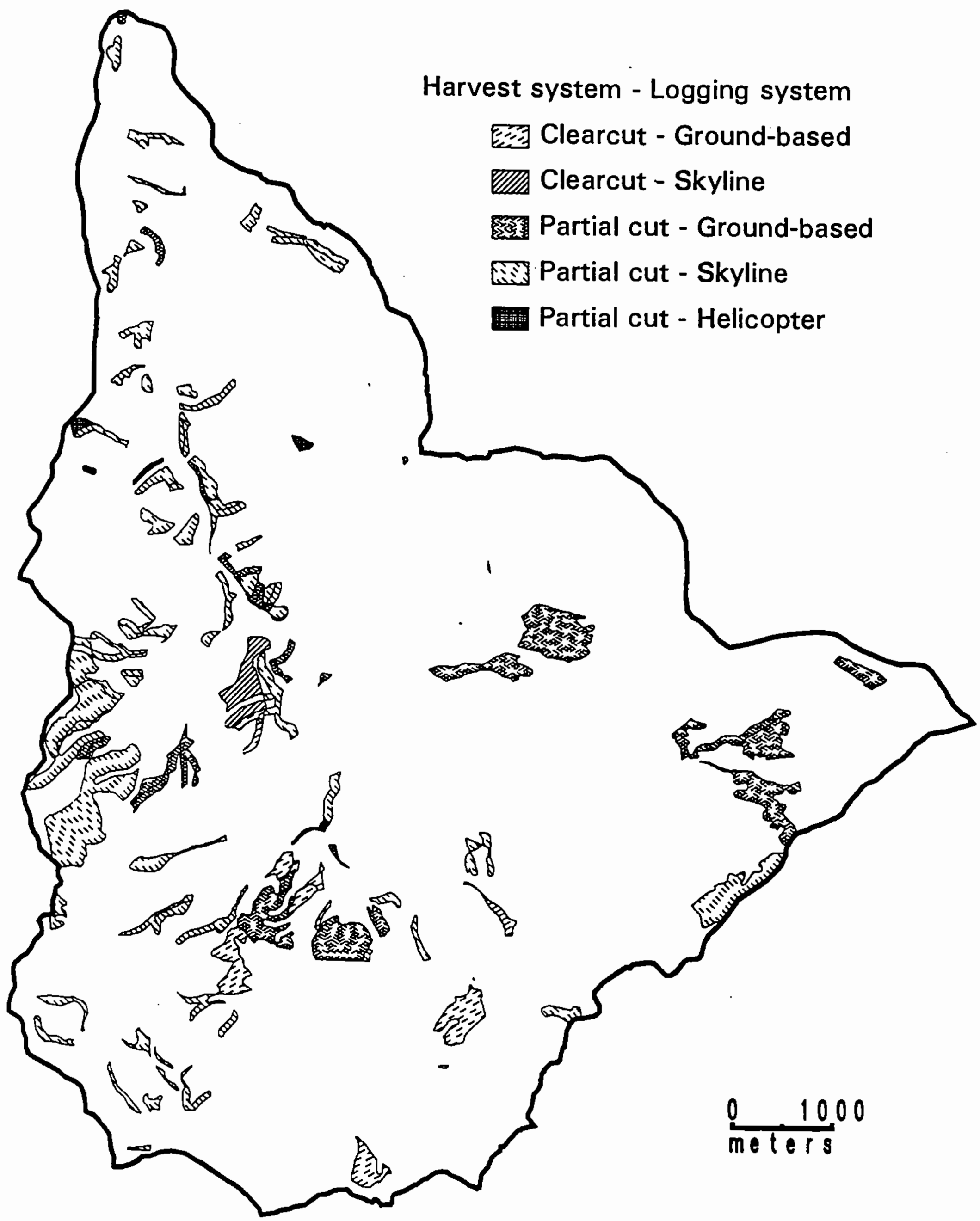


Figure 3.17. Harvest system - logging system combinations in period 5 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

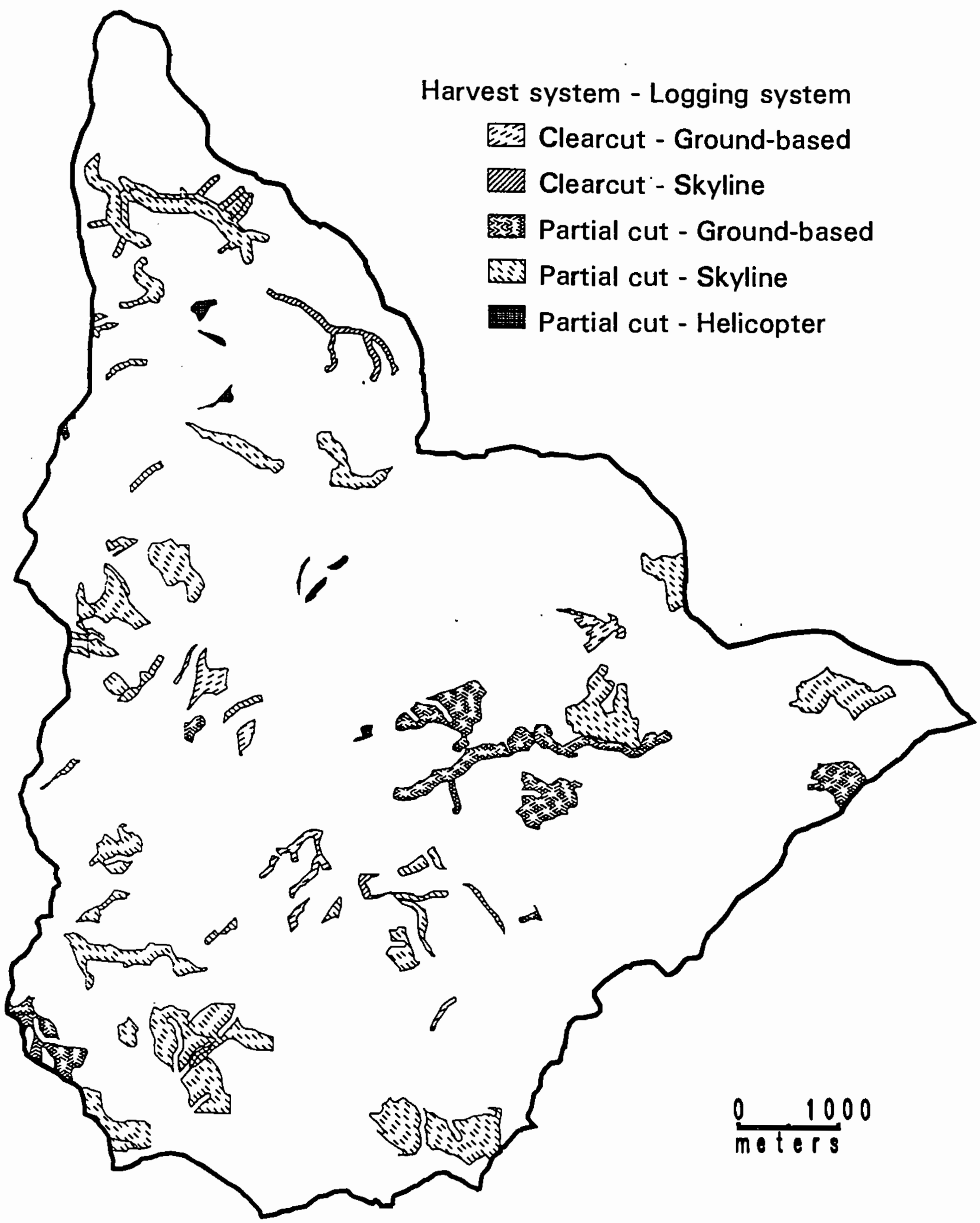


Figure 3.18. Harvest system - logging system combinations in period 6 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

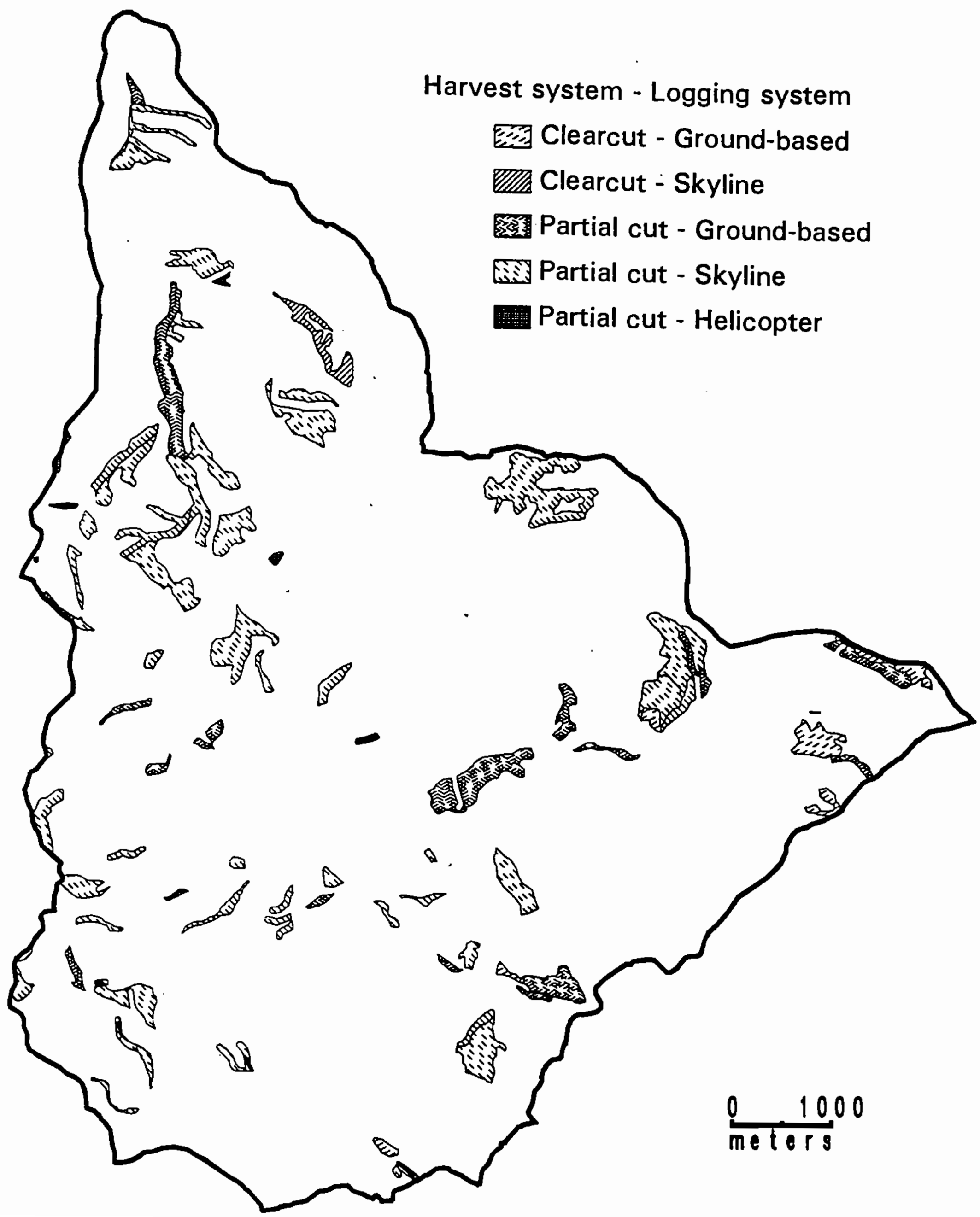


Figure 3.19. Harvest system - logging system combinations in period 7 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

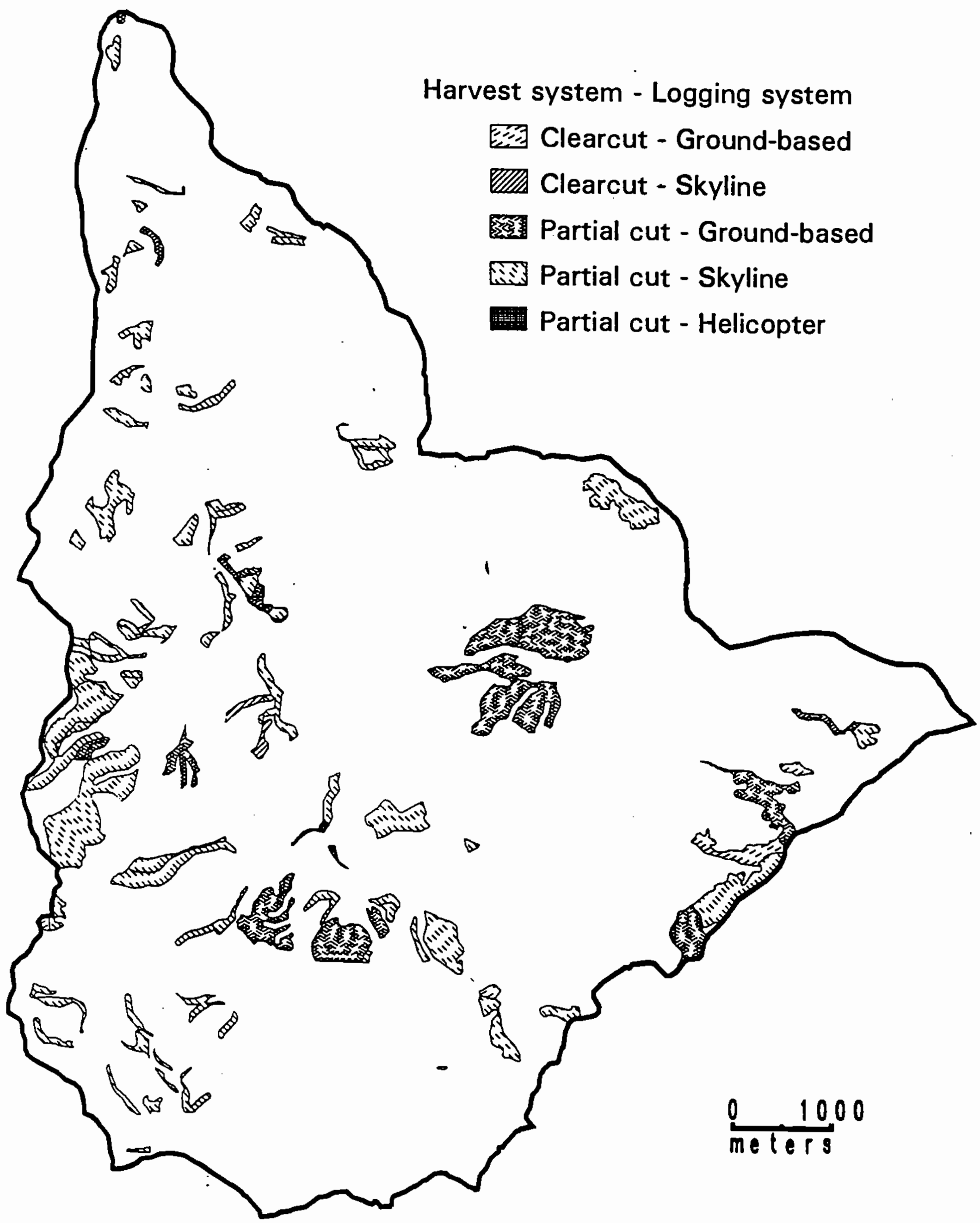


Figure 3.20. Harvest system - logging system combinations in period 8 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

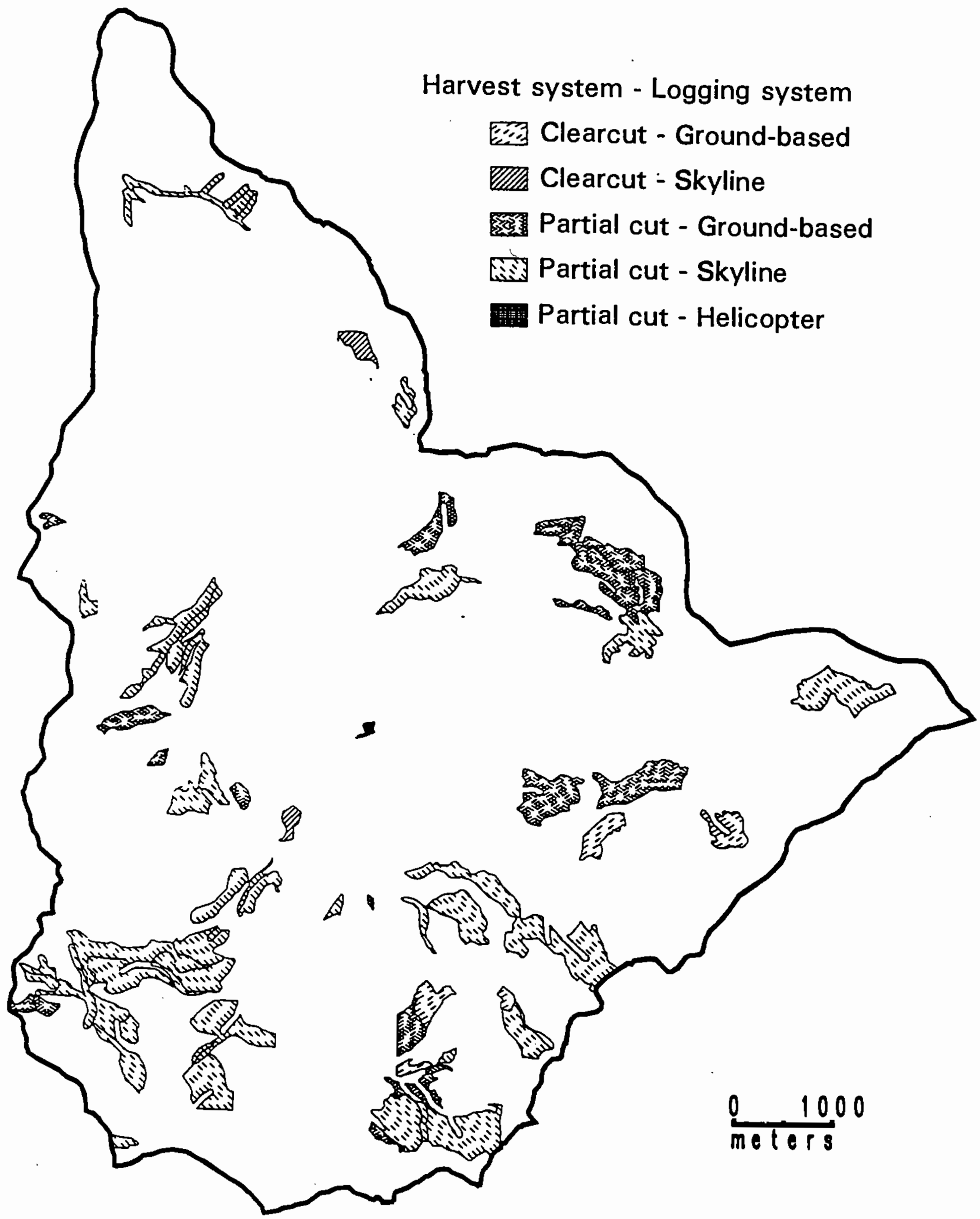


Figure 3.21. Harvest system - logging system combinations in period 9 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

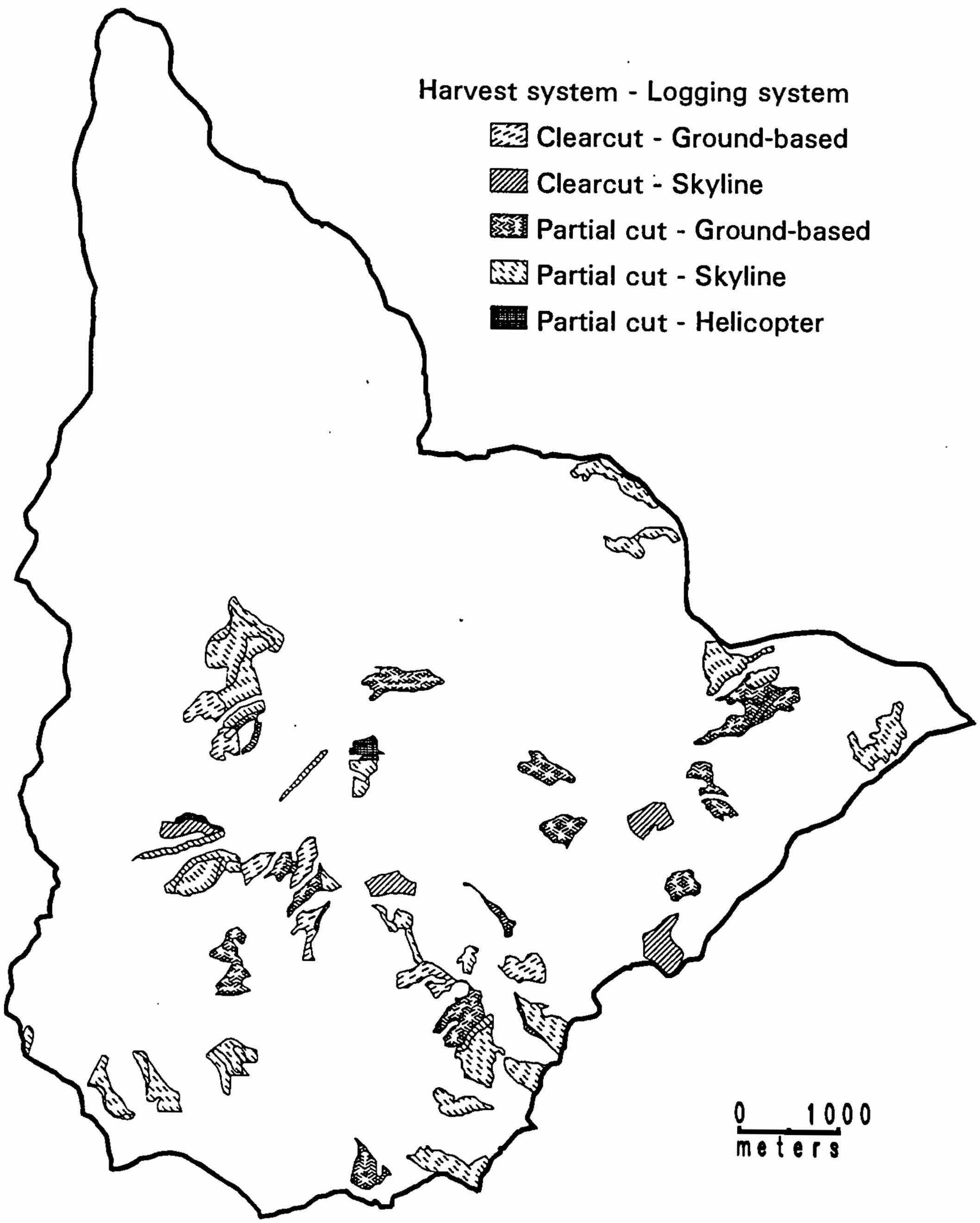


Figure 3.22. Harvest system - logging system combinations in period 10 of a ten period, 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from the best of the 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

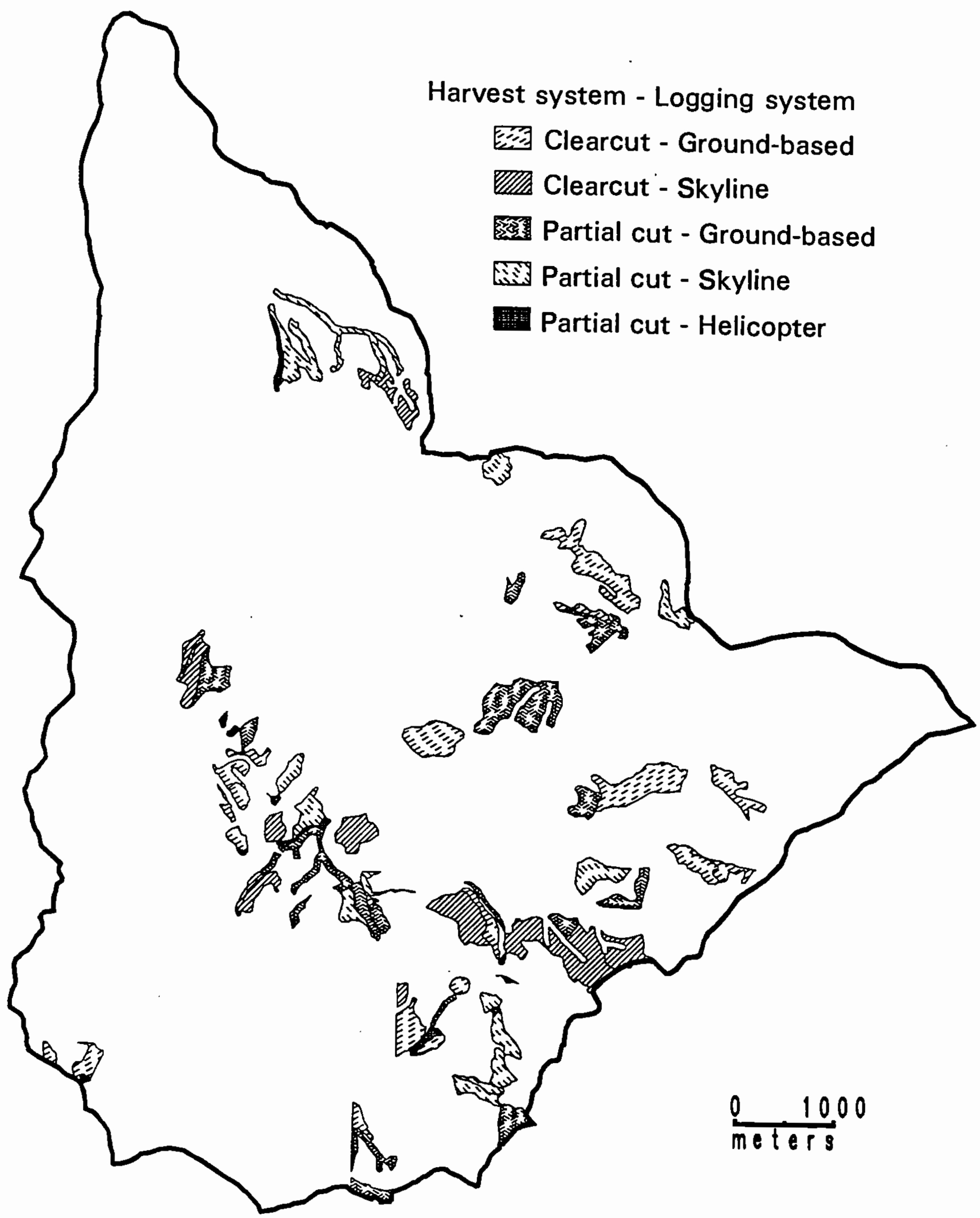


Figure 3.23. Average number of acres in harvest system - logging system combinations, for each of ten 10-year periods in a 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are derived from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

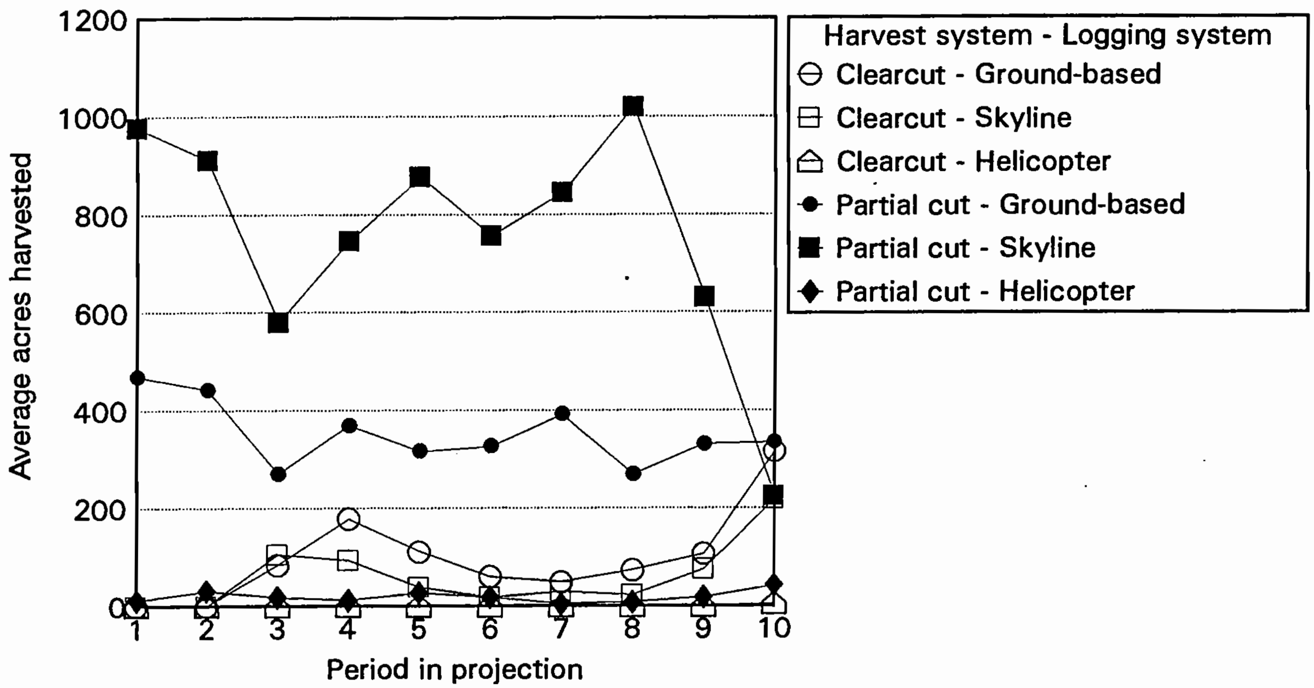


Table 3.5. Average levels of outputs per 10-year periods in a 14.643 acre case study watershed in eastern Oregon, using 20 runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.[a]

	Period									
	1	2	3	4	5	6	7	8	9	10
Volume harvested (MBF)	6310 (259)	6333 (270)	6349 (280)	6957 (401)	6501 (299)	6336 (285)	6373 (287)	6364 (310)	6329 (239)	5912 (297)
Stream sediment index[b] (tons/mi²/year)	28.6 (0.09)	28.5 (0.12)	28.4 (0.20)	28.3 (0.32)	28.5 (0.14)	28.6 (0.06)	28.5 (0.16)	28.0 (0.22)	28.5 (0.13)	28.4 (0.14)
Stream temperature[c] index (°F)	76.8 (0.11)	76.6 (0.29)	76.6 (0.38)	75.8 (0.30)	75.9 (0.36)	76.1 (0.38)	75.4 (0.28)	74.8 (0.02)	74.6 (0.02)	74.6 (0.03)

[a] standard deviations are in parentheses.
[b] maximum level is 28.72 tons/mi^2/year.
[c] maximum level is 77° Fahrenheit.

Discussion

The sediment constraint, when violated, requires one of three actions to occur: 1) reject the harvest choice, 2) obliterate an unused standard rock road, or 3) assign a CTI use to a standard rock road. If a road is obliterated, it is not allowed to change back to a standard rock road in subsequent periods, or in later iterations of the scheduling model. Land units without a path to the mill, as a result of a road obliteration, will never be scheduled for harvest in that particular run of the model. This may cause logistical problems for time periods beyond the 100-year projection period assumed here, and one may want to modify the model to allow the rebuilding of obliterated roads in future periods. In addition, one may want to assume that obliterated roads can be revegetated with tree species, perhaps allowing an alleviation of ECA levels.

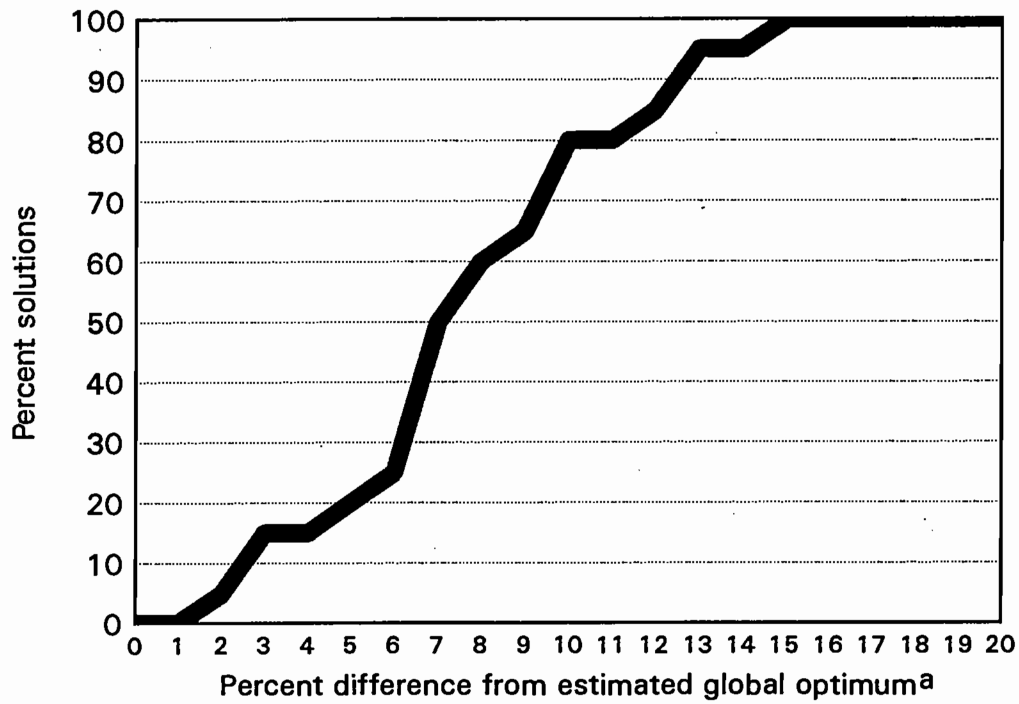
The temperature constraint, when violated, simply disallows the scheduling of the land unit which leads to the violation of the constraint. These two constraints are the only ones that force the model to spatially and temporally arrange land management activities on the landscape. For example, when either goal is violated, the model must either consider another decision choice (perhaps a different unit further from the stream system), or in the case of the sediment constraint, alleviate the problem by managing high sediment-producing roads differently. The even-flow constraint does not recognize the spatial location of activities, but does act to temporally arrange harvest activities to fulfill the even-flow goal.

The even-flow, sediment, and temperature constraints, as well as stumpage prices, logging costs, and transportation costs all affect the choices that can be made. In our model, to achieve an even-flow of timber harvest volume, only one management regime at a time is added to the solution set, and only those units which have potential silvicultural management regimes that can *start* in the period with the lowest timber harvest volume are considered. This ensures that of the ten periods, the one with the lowest amount of timber volume will actually have volume added to it. This procedure provided an adequate method for ensuring an even-flow of timber harvest volume when considering management regimes that had multiple harvests over several periods.

Some units may not have been scheduled due to age restrictions or economic considerations. As mentioned earlier, we assume units greater than 150 years of age cannot be harvested. Due to the age structure of the watershed, and the fact that stands over 150 years of age (on average) could not be harvested, opportunities to harvest timber in the last two periods became limited, and the model relied on increased clearcutting in lodgepole pine stands. A fixed transportation cost assigned to each unit at the time of harvest may also preclude scheduling smaller units which require a path consisting of (at least in part) standard rock roads. Grouping these small units together into one decision choice may allow the group to cover these costs, and may thus provide more harvesting opportunities.

In reflection, the land management scheduling model performed reasonably well, with 80 percent of the solutions obtained being within 10 percent of the estimated global optimum solution (Figure 3.24). All of the solutions were within 15 percent of the estimated global optimum, and one of them was within 2 percent of the estimated global optimum. One might expect that with a large

Figure 3.24. Performance of a land management scheduling model, based on 20 independent runs where net present value is maximized subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.



[a] Global optimum estimated by fitting sample solution net present value data (local optima) to a Weibull distribution; estimated global optimum = $2,789,670; scale parameter = $241,218; shape parameter = 2.353.

number of independent runs, at least one solution would be very close to the global optimum solution.

Chapter 4

Evaluating the Correlation between Equivalent Clearcut Acres, Stream Sediment and Temperature Indices, and Timber Harvest Levels in Eastern Oregon

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Abstract

A land management activity scheduling algorithm that performs a multi-period, simultaneous evaluation of aquatic habitat quality and commodity production goals, and which requires spatial data regarding land units and roads, was utilized to evaluate whether there is any correlation between a measure of landscape use (equivalent clearcut acres [ECA]), two measures of aquatic habitat quality (stream sediment and stream temperature indices), and timber harvest volume levels. The scheduling algorithm utilized a Tabu search procedure to guide the selection of timber harvests and road standards for a 14,643 acre case study watershed in eastern Oregon. Results from 20 independent runs, each containing ten 10-year periods of analysis, were used to test the hypothesis that there is no significant correlation among the variables.

Two techniques were utilized to evaluate the correlation among variables: a basic correlation analysis, and a bootstrapping technique that sampled with replacement from the sample data. Both techniques produced similar results. With both techniques we found significant negative correlation between ECA and stream temperature index levels. No significant correlation was observed between all other combinations of variates when the bootstrap technique was used. All four measures required a different set of spatial and non-spatial data in their evaluation, thus variation in one measure did not necessarily imply that a corresponding positive (or negative) variation in another measure will occur.

Our results were contradictory from what we had expected. ECA was expected to have been positively correlated with the stream sediment and temperature indices, since ECA is a measure of watershed use, and with more

use one would expect higher impacts on aquatic habitat. ECA, however, uses non-spatial data, and was unconstrained in our analysis, whereas the stream sediment and temperature indices use spatial data, and were constrained to upper threshold levels, and timber harvest volumes were assured to be fairly even across the 100-year projection due to an even-flow constraint. We may expect that by constraining the land management scheduling model with respect to ECA, different results would be observed. We hypothesize that by doing this there would be significant positive correlation among the variables. The main conclusion to draw from this work is that different relationships between these measures may be observed, depending on how the problem is formulated, therefore stream sediment and temperature levels may not be good proxies for ECA (or vice versa).

Introduction

Protection for wild fish stocks has become important in the past decade, as many species in the Pacific Northwest have become listed as threatened or endangered by the federal government. The compatibility of land management activities and aquatic habitat quality is a function of local effects and their spatial and temporal arrangement across a landscape. Without assurance of protection of aquatic habitat quality, forest management activities on western National Forests, which are designed to achieve multiple goals of recently adopted Forest Plans, are unlikely to go forward. In identifying goals for management of key resources in eastern Oregon, it has become clear that three aquatic habitat quality goals are important: 1) reduce stream sediment levels, 2) reduce stream temperature levels, and 3) increase the number of pools. This research focused on two of these goals: stream sediment and temperature. The third goal was not included because we could not identify a model to estimate the effects of land management activities on pools. The objective of this research is to identify the correlation between a measure of landscape use (ECA), stream sediment and temperature index levels, and timber harvest volume levels within a watershed, from results obtained with a land management scheduling model.

In eastern Oregon, the National Marine Fisheries Service (NMFS) uses ECA concept as part of their evaluation in determining whether activities may have a non-beneficial effect on stream habitat and fish populations (National Marine Fisheries Service 1995). In fact many western National Forests use ECA procedures to estimate streamflow responses to vegetation removal. However, ECA has been shown to underestimate average annual streamflow following harvest and road building in Idaho (King 1989). ECA was designed primarily as a planning tool to aid U.S. Forest Service personnel in assessing the cumulative effects of forest management options, and to estimate the changes in streamflow from those land management activities which remove vegetative cover (Belt 1980). Many different versions of ECA procedures exist; the differences among them are designed to reflect local conditions (King 1989). In comparing changes in measures of aquatic habitat quality with changes in equivalent roaded acres, a concept similar to ECA, McGurk and Fong (1995) found equivalent roaded acres to be negatively correlated with diversity of macroinvertebrate communities, and Roby and Azuma (1995) found equivalent roaded acres to be negatively correlated with dominance of macroinvertebrate communities. Here, we are interested in determining whether there is any correlation between ECA, stream sediment and temperature indices, and timber harvest volume levels.

Performance of the land management scheduling model has been established in Chapter 2. One hypothesis we test with the model results is that there is no correlation between ECA, stream sediment and temperature index levels and timber harvest volume levels. A second hypothesis is that there is no correlation between timber harvest volume levels and stream sediment and temperature index levels. A final hypothesis is that there is no correlation between the stream sediment index and stream temperature index levels.

Methods

Our objective is to measure the amount of correlation (linear association) between ECA, two measures of aquatic habitat quality (stream sediment index and stream temperature index), and timber harvest levels. Our intent is to study the association between these variables, and to determine whether they are interdependent. We neither know nor assume causation, but intend to estimate the degree to which they covary. We next provide a brief summary of the land management scheduling model formulation, including the assumptions behind stream sediment, stream temperature, and ECA measurement procedures. And prior to evaluating the results, we summarize the case study watershed and sampling techniques used to test the hypotheses.

<u>Model formulation</u>

The problem we attempt to solve with this research can be formulated as such:

maximize: net present value (NPV)

subject to: an even-flow of timber harvest volume

an upper limit on stream sediment levels

an upper limit on stream temperature levels

The decision choices we will use consist of:

Harvesting systems:

- Partial cutting on a 30-year return interval, all tree species, no cutting before age 50 or after age 150.
- Partial cutting on a 50-year return interval, all tree species, no cutting before age 50 or after age 150.
- Clearcutting and thinning. If thinning is the first harvesting activity, it can occur between the ages of 50 and 100. Clearcutting follows 20 years later. If clearcutting is the first harvesting activity, it can occur between the ages of 101 and 150. After a clearcut has occurred, thinning occurs at subsequent age 50, and clearcut at age 70. Lodgepole pine stands only.
- Not harvesting a unit.

Logging systems:

- Ground-based
- Skyline
- Helicopter

Road standard changes:

- Standard rock to central tire inflation (CTI) use
- Standard rock to obliterated
- No change in road standard

It is important to note that some of these decision choices involve land allocation issues (e.g., timber harvesting, road obliteration), while one involves changes in management practices (requiring lower log-truck tire pressures on certain roads, via CTI). Here, the state of the road is not changed when CTI use is required. What also is important is that sediment and temperature index levels utilize spatial information and are constrained in the analysis, while ECA uses non-spatial information and is unconstrained.

Objective Function

The land management scheduling model uses an objective function that maximizes the net present value of all harvesting and road management-related activities. The objective function is formulated as:

maximize:

$$\sum_{m=1}^{n}\left(\frac{\sum_{k=1}^{u}((P_m - H_m) * V_{km}\Phi_{km}) - \sum_{k=1}^{u}(FC_{km}\Phi_{km} + (VC_{km} * V_{km}\Phi_{km}))}{(1 + i)^{(m-1)+5}}\right)$$

$$- \sum_{m=1}^{n}\left(\frac{\sum_{s=1}^{q}(RC_{sm}\omega_{sm})}{(1 + i)^{(m-1)+5}}\right)$$

Where: m = Period

n = Total number of periods

k = Unit

u = Total number of units

ϕ_{km} = Variable indicating the extent to which unit k is harvested in period m

P_m = Stumpage price ($/MBF) in period m

H_m = Harvesting cost ($/MBF) in period m

V_{km} = Total volume (MBF) within unit k during period m

FC_{km} = Fixed road maintenance cost ($/mile) for the path associated with unit k in period m

VC_{km} = Variable road maintenance cost ($/MBF) for the path associated with unit k in period m

s = Individual road segment

q = Total number of individual road segments

RC_{sm} = Road standard change cost ($/mile) for road segment s in period m

ω_{km} = Variable indicating the extent to which a road standard has changed in period m

i = discount rate (percent)

In formulating the objective function for a linear programming (LP) problem, one would assume $1 \geq \phi_{km} \geq 0$ and $1 \geq \omega_{km} \geq 0$. For integer programming (IP) problems, ϕ_{km} and ω_{km} equal 0 or 1. Our approach utilizes the IP formulation of the objective function.

Even-flow constraint

There are various methods for ensuring an even-flow of timber harvest volume over time for a forest management problem. Classical timber management scheduling techniques address how many acres (area control) or how much volume to harvest (volume control). Area control can achieve a regulated forest in one timber rotation, yet often at the expense of near-term harvest level stability; volume control ensures near-term harvest level stability, yet may not achieve a regulated forest after one rotation (Davis and Johnson 1987). We are attempting to achieve a non-declining even-flow of timber harvest volume:

$$\sum (V_{km}\Phi_{km}) \leq \sum (V_{km+1}\Phi_{km+1})$$

Our approach to ensuring an even-flow of timber harvest volume, however, is not as strict as the constraint above. Our process adds incremental silvicultural management regimes, defined by a series of harvests over time, to the solution, by only considering those management regimes that can start with a harvest in the period that has the lowest harvest volume. So during the operation of our model, we examine the harvest rates over time, select the period with the lowest harvest volume, and select a management regime that can start in that period. We then are assured that the period with the lowest harvest volume will have volume added to it. It is a constraint in the sense that the set of potential decision choices is confined to those that can start with a harvest in the period with the lowest harvest volume.

Stream sediment goal

A formal declaration of our sediment goals is:

$$\textit{sediment goal for period } m \geq \sum_{k=1}^{u}(natu_{km}\phi_{km}) + \sum_{k=1}^{u}(sedu_{km}\phi_{km}) + \sum_{s=1}^{q}(sedr_{sm}\omega_{sm})$$

$$+ \sum_{s=1}^{q}(traffic_{sm}\omega_{sm})$$

Where: $natu_{km}$ = f (area, erosion hazard rating for unit k in period m)

$sedu_{km}$ = f (harvesting system, logging system, geologic erosion factor, natural sediment rate, ground slope, slope shape, surface roughness, ground cover, texture of erodible material, water availability, distance to the stream system for unit k in period m)

$sedr_{sm}$ = f (road standard, road width, road length, slope shape, surface roughness, slope gradient, ground cover, texture of erodible material, water availability, distance to the stream system for road segment s in period m)

$traffic_{sm}$ = f (volume transported across road, possible reduction factor for using CTI for road segment s in period m)

In formulating this constraint for an LP problem, $1 \geq \phi_{km} \geq 0$ and $1 \geq \omega_{sm} \geq 0$. For IP problems, ϕ_{km} and ω_{sm} equal 0 or 1. Our implementation of the sediment constraint follows the IP formulation. Since road construction is not an option in our problem, typical road trigger constraints (see Kirby et al. 1982) are not utilized.

The procedures that we use to evaluate stream sediment levels are derived from the "Guide to predicting sediment yields from forested watersheds" (USDA Forest Service 1981), known here as the Region 1 / Region 4 (R1/R4) sediment model. We selected this model because it is an established model, and because it provided the best documentation of the models we considered. The R1/R4 model separates erosional and delivery processes and considers them individually for each land unit and road. There are four major parts to the R1/R4 model: natural sediment yield, sediment from surface erosion, sediment from mass erosion, and routing of sediment to a critical reach.

The R1/R4 model was altered to evaluate surface erosion from road traffic resulting from logging activities, and to reduce sediment from road traffic by assigning CTI use to particular road segments. A factor of 0.0338 tons of sediment / thousand board feet (MBF) - mile was developed using the extreme case from Reid and Dunne (1984), and is applied to all roads which are scheduled to be used to haul timber volume. Although Reid and Dunne's research was from western Washington, we felt that it presented the most complete information (sediment produced per MBF transported across road segments) available for use in our study. In addition, a reduction of 60% in surface erosion from road traffic is assumed when CTI is assigned to a road, based on conservative results obtained from Foltz (1994).

The estimation of sediment from mass erosion is highly variable, and since it is not currently a major problem in our case study watershed (R. Beschta, Department of Forest Engineering, Oregon State University, Corvallis, OR, pers. comm.), it is not included in our estimation of stream sediment impacts from land management activities. Finally, stream sediment index levels are only measured at the downstream reach in the watershed. Sediment from all sources is routed to the downstream reach using a coefficient developed by Roehl (1962) that is based on watershed size. The amount of sediment routed to the downstream reach is considered here an index of sediment levels because the R1/R4 model has not been validated in eastern Oregon using empirical data. In fact, no sediment estimation models have been validated for forested watersheds in eastern Oregon.

Stream temperature goal

The stream temperature goal is a function of timber harvesting activities can be formulated as follows:

$$\textit{temperature goal for period } m \geq \sum_{k=1}^{u} (temp_{km})$$

for all {k | k is a unit adjacent to the stream}

Where: $temp_{km}$ = *f* (stream length, stream width, low flow (cfs), latitude of watershed, declination of watershed, ground slope, shade density, tree overhang percent, tree height, number of skyroads, percent canopy removed during harvest, stream orientation, distance from trees to channel, heat rate (BTU/square foot-minute), ground water temperature for unit k in period m)

The procedures to evaluate stream temperature levels were derived from the SHADOW model (USDA Forest Service 1993). This model calculates the area of unshaded streams, using stream orientation, solar angles, and other reach-specific data. Reach-specific data are spatial in nature in that they include only data (e.g., average tree height, terrain slope) associated with land units which are adjacent to a U.S. Forest Service class 1-3 stream reach (Table 4.1). An equation developed by Brown (1969) is used with SHADOW to predict the increase in stream temperature (as a result of solar heating) over groundwater

Table 4.1. Stream density in the 14,643 acre case study watershed, by U.S. Forest Service (USFS) stream class.

USFS stream class	Stream density (mi/mi^2)
1 - Perennial, used by anadromous fish and resident fish	0.42
2 - Perennial, used only by resident fish	0.25
3 - All other perennial streams not classified	0.94
4 - All intermittent streams	3.66
5 - All ephemeral streams	3.65
Total	8.92

temperature levels. The resulting estimated temperature at the downstream reach in a watershed is considered here as an index because SHADOW has not been validated in eastern Oregon using empirical data. Only one stream temperature model has been validated for use in eastern Oregon (Bohle 1994), and then only for small stream reaches. SHADOW, however, has been applied to large watersheds, and is supported by Region 6 of the U.S. Forest Service.

Equivalent Clearcut Acres

The ECA concept is defined as a watershed index of the snowmelt and evapotranspiration rates relative to a baseline condition where tree stands are completely canopied. ECA is used to estimate a change in magnitude of the highest 6-day peak flow from a watershed (Wallowa-Whitman National Forest 1991). Changes in peak flow are important where there exists objectives for maintaining or improving stream channel stability. In addition, it has been used as an index of watershed use, where a threshold level is set, and once exceeded, no further activities can occur. Threshold ECA levels are used by the National Marine Fisheries Service (NMFS) in considering the effect of land management activities on aquatic habitat quality in the Columbia River basin. The general rule of thumb is that once an ECA for a watershed gets above a certain level, measurable changes in aquatic habitat occur. NMFS has developed a rule of thumb where if ECA levels exceed 15 percent of a potentially forested area, a watershed analysis must be performed prior to initiating any action that would increase ECA (National Marine Fisheries Service 1995). After watershed analysis, actions that would increase ECA can proceed only if there is no more than a *de minimis* risk of adversely affecting aquatic habitat. While neither uses of ECA provide a direct linkage of land management activities to resource impacts, the one imposed by NMFS seems to be the most constraining given the current legal situation.

The most influential factor in measuring ECA is the amount of area altered by nature or by land management activities (Belt 1980). The amount of area which can be described as being in a clearcut condition is defined in terms of the density of residual vegetation. Each particular land use area (e.g., roads, timber stands) is given a "clearcut-equivalent factor" (CEF), which is subsequently multiplied by the area disturbed to arrive at an equivalent clearcut acre value. For example, clearcuts and roads are generally given a CEF of 1.0, while partial cuts are given a value from 0 to 1, depending on the density (basal area) of residual vegetation (Table 4.2). The more open a unit is, the closer it emulates the

Table 4.2. Clearcut equivalent factors used in equivalent clearcut acres calculations.

	Clearcut Equivalent Factor						
Species	1.00	0.90	0.70	0.50	0.30	0.10	0.00[a]
	Range of basal area (ft^2/acre)[b]						
Subalpine fir	0	1-6	7-14	15-28	29-46	47-75	76+
Lodgepole pine	0	1-9	10-17	18-25	26-38	39-50	51+
Grand fir	0	1-12	13-24	25-46	47-73	74-103	104+
Douglas-fir	0	1-13	14-24	25-46	47-64	65-89	90+
Ponderosa pine	0	1-8	9-15	16-23	24-32	33-42	43+

[a] Assumed hydrologically recovered at this point.
[b] Post-harvest basal areas, and basal areas during recovery. Basal areas after clearcutting are an explicit function of stand age.

snowmelt and evapotranspiration characteristics of a similar stand that is completely clearcut.

An implicit recovery factor is employed in ECA calculations, and is determined by the growth rates used in models to estimate vegetative regrowth of a particular site. Thus the effects of land management activities over space and time are aggregated and standardized into a single measure (ECA). ECA can then be compared to a threshold level that corresponds with the onset of an undesirable change in the environment (McGurk and Fong 1995).

The ECA model used here does not represent factors which add variability to the amount of degradation from a disturbance, such as proximity to the stream system. Menning et al. (1996) have proposed an alternative model which utilizes spatial zones around riparian areas in the calculation of equivalent roaded acres. This ECA model also does not take into account other activities which may affect ECA, such as fire or cattle grazing. ECA is not used as a constraint in our model, although we could formulate the model to constrain it to upper (or lower) threshold levels. The mathematical formulation for estimating ECA is:

$$ECA\ for\ period\ m = \left(\frac{\sum_{k=1}^{u} (CEF_{km} Area_{km}) + \sum_{s=1}^{q} (CEF_{sm} Area_{sm})}{Total\ landscape\ area} \right)$$

Where: CEF_{km} = a clearcut equivalent factor for unit k during period m, based on tree species and average basal area

$Area_{km}$ = the area of land covered by unit k during period m

CEF_{sm} = a clearcut equivalent factor for road s during period m

$Area_{sm}$ = the area of land covered by road s during period m

A CEF for an individual unit may vary through time, based on harvest intensity and growth rates of residual tree stands, however CEFs for roads are assumed not to vary in our model. One may assume (although we did not) that abandoned or obliterated roads may eventually become revegetated with tree species. Under this assumption, an area of land formerly represented by a road may, in the future, be represented by a stand of trees which has a basal area of a certain level that would require the use of a CEF lower than 1.0.

Case Study Watershed, Empirical Data Used, and Estimation of Constraints.

A 14,643 acre watershed in eastern Oregon (Figure 4.1) was used as a case study for the application of the land management scheduling model. Our decision to use a large watershed to test the model was based on our desire to use the model to emulate an operational tactical planning process, and to evaluate cumulative effects at a watershed scale. GIS databases depicting the road system, stream system, and vegetation and soils resources were developed in ArcInfo (ESRI 1995). The road network for the watershed consists of 474 road segments, 443 of which are physically located within the watershed, and for which the effects of sediment produced by the roads will be evaluated. Roads were classified into three categories: obliterated, paved, and rock. Empirical data included average road widths, road slope percent, and the shortest distance from each road segment to a U.S. Forest Service class 1-4 stream. These data were derived from a sample of roads within the watershed, topographic maps, and GIS processes.

The stream system (Figure 4.2) consists of 9.6 miles of U.S. Forest Service class 1 streams (namely the Upper Grande Ronde River); however stream density varies by stream class (Table 4.1). Empirical data for the stream network include: stream widths by stream class, tree overhang percent, shade density, tree-channel distance, stream orientation, and terrain slope percent. These data were derived from a sample of streams within the watershed, topographic maps, and aerial photographs.

Average flow rates the downstream reach in the watershed were obtained from an actual monitoring station installed and maintained by the Wallowa-

Figure 4.1. The Upper Grande Ronde River basin in eastern Oregon, and the 14,643 acre case study watershed.

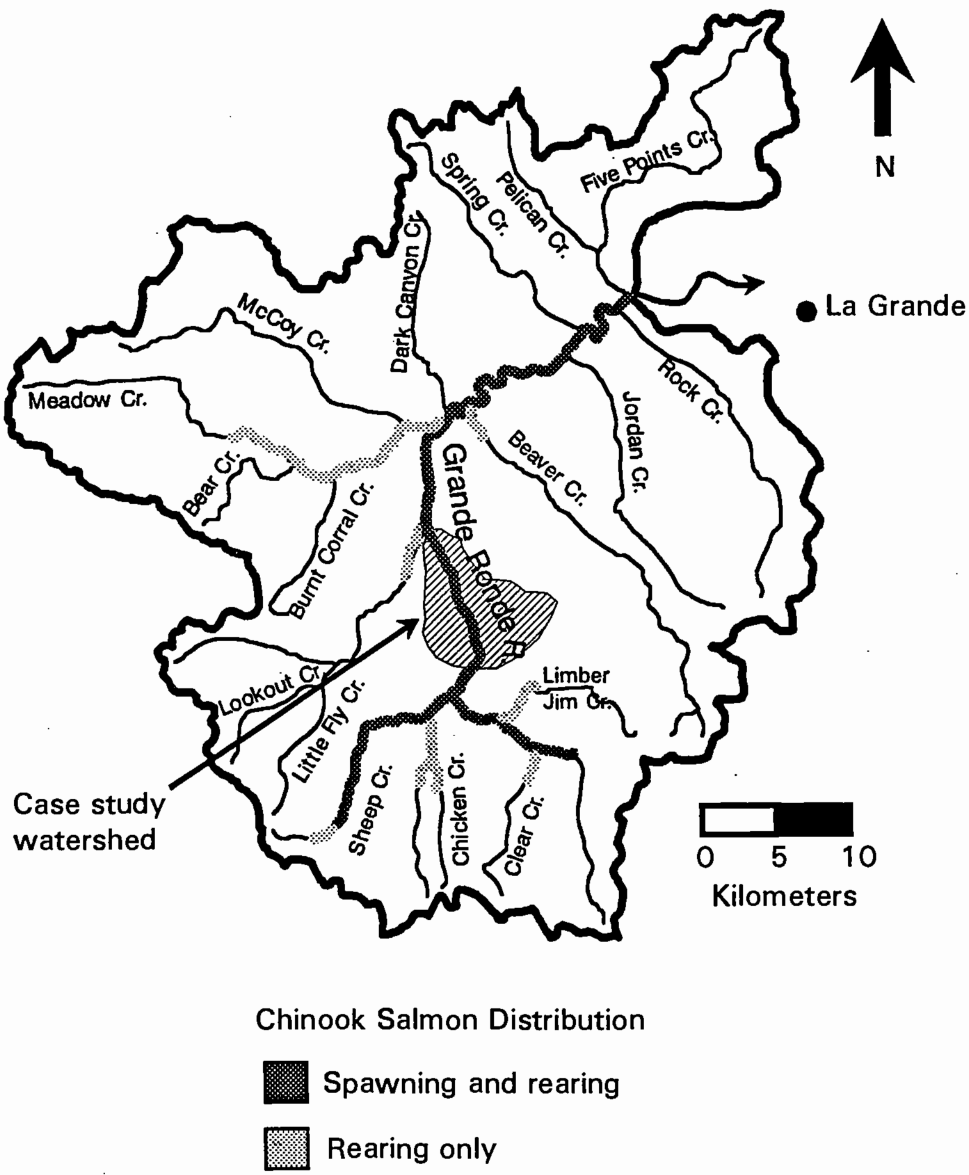
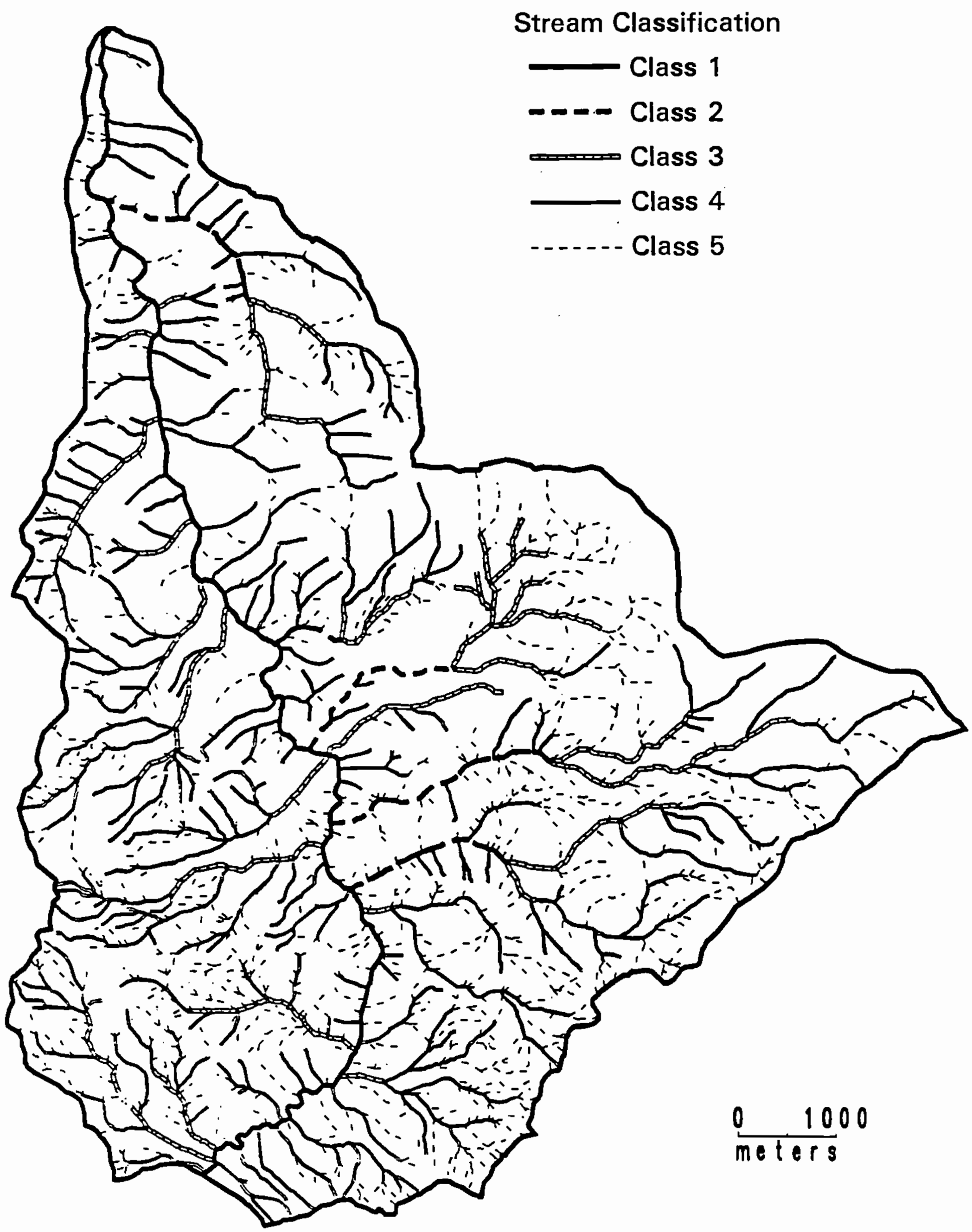


Figure 4.2. Stream classification, based on U.S. Forest Service stream guidelines, for a 14,643 acre case study watershed in eastern Oregon.



Whitman National Forest. Riparian areas were developing using the PACFISH guidelines (USDA Forest Service and USDI Bureau of Land Management 1995). U.S. Forest Service class 1 and 2 streams were buffered 300 feet; class 3 streams 150 feet; and class 4 streams 100 feet. The buffered coverage was combined with the vegetation coverage to explicitly identify riparian areas. In our Tabu search model, we allow partial cutting in riparian areas, but not clearcutting. To create land unit decision variables, the riparian GIS coverage was combined with a vegetation coverage. This process created many sliver polygons, thus all polygons outside of riparian areas and less than two acres were eliminated and merged with an adjacent polygon which shared the longest common boundary. Land units inside riparian areas were not altered to protect the geographical integrity of the riparian areas. As a result we had 1,436 land units to use as decision variables. The number of land unit and road management decision variables therefore exceeded 120,000, given the harvest systems and silvicultural management regimes available.

Empirical data for the vegetation and soils databases included: average merchantable volume per acre, average basal area per acre, average age of dominant trees, dominant tree species, average height of dominant trees, ground slope percent, soil type, texture of erodible material, erosion hazard rating, and other site-specific variables. These data were accumulated from files located at the La Grande Ranger District (La Grande, OR) of the Wallowa-Whitman National Forest, the Wallowa-Whitman National Forest Supervisor's Office (Baker City, OR), and from aerial photographs taken from 1984-1989.

All revenues and costs were assumed to occur in the mid-point of a period, and were discounted by 4 percent per year in calculating the net present value (NPV). No stumpage price appreciation was used in this analysis. Empirical data used in the forthcoming case study include stumpage prices, harvesting costs, road maintenance costs, and road standard change costs for the Blue Mountains region of eastern Oregon. Harvesting and road costs were accumulated from recent sale proposals developed for the La Grande Ranger District timber sale program.

The stream sediment index and stream temperature index goals we used were obtained by estimating the extent and location of harvest activity during the previous 10 years in the case study watershed, and evaluating the impact of those activities on the stream sediment and temperature indices. The sediment (28.7 tons/square mile/year) and temperature (77.0°F) index levels we estimated were then used as goals not to be exceeded during the analysis.

Sampling Techniques

ECA, the stream sediment and stream temperature indices, and timber harvest levels are estimated using a land management scheduling algorithm which schedules timber harvest and road standard choices over ten 10-year periods. The algorithm uses a heuristic process (Tabu search) in scheduling management alternatives. The theoretical complexity is established in Chapter 2. Twenty solutions were generated, each a result of the algorithm starting with an initial, randomly defined set of management alternatives for timber harvests. Each solution can then be considered to be independent (Golden and Alt 1979, Los and

Lardinois 1982); the results obtained include ECA, stream sediment and temperature index levels, and timber harvest volume levels for each of ten 10-year periods in a 100-year planning horizon. From the 20 independent solutions, we have 200 ECA-aquatic habitat index-timber harvest volume sets:

Solution #1:	X_{11},	X_{12},	X_{13},	....,	$X_{1,10}$
Solution #2:	X_{21},	X_{22},	X_{23},	....,	$X_{2,10}$
"	"	"	"	"	"
"	"	"	"	"	"
Solution #20:	$X_{20,1}$,	$X_{20,2}$,	$X_{20,3}$,	....,	$X_{20,10}$

Where: X_{ij} = a set containing ECA, stream sediment index, stream temperature index, and timber harvest volume data for solution *i*, period *j*

Although there are no variables in the calculation of each measurement that require estimated levels from previous periods, and there are many activities that take place during each period - the location and timing determined by many factors (e.g., violation of a goal, even-flow constraints), one may argue that many stands simply grow from one period to the next, perhaps implying some temporal autocorrelation among X_{ij} sets. So, we consider the 200 X_{ij} sets to not be independent, and identically distributed from an unknown population. Thus we randomly sample 30 of the 200 pairs of X_{ij} data, and perform a correlation analysis on this sample. SAS (SAS Institute Inc. 1991) is used to determine the correlation among variates. The randomly selected sample of data from the 200 pairs, however, is only one combination of data that may be used to represent the results. Therefore, we used a second method, bootstrapping, to produce correlation results.

Bootstrapping is a method of resampling data to infer the variability of an estimate (Felsenstein 1985). Bootstrapping is most useful when we either do not know the distribution of our sample data X_{ij}, or when the method of statistical estimation is so complicated that its standard error is difficult to compute (Felsenstein 1985). The justification for using this technique is that one can view each data point as having evolved independently from the others according to a stochastic process, and one can consider each as a random sample from the distribution of all possible configurations of sample data. The configuration of sample data drawn randomly can then be seen as drawn independently and identically distributed (Felsenstein 1985).

We carry out a random resampling procedure by sampling with replacement using the 200 sets of data generated from the 20 independent runs. We again use a sample size of 30 to estimate the correlation among variates. The resampling process produces a resampled set of n points from the original data points, and for each the estimate t^* is computed, where t^* can be one of many parametric statistics (here it is the correlation coefficient). We then have a collection of estimates (t^*) of a parameter which has a distribution that approximates the distribution of the actual estimate t. Averaging the collection of t^* produces a bias-corrected estimate of the parameter t. It has been shown that the mean of the estimated statistics from these bootstrapped samples approximates the mean of the population (Sokal and Rohlf 1995). Further, the variance of t can be inferred by computing the variance of the collection of t^* values, and confidence intervals can be produced using the approximate upper and/or lower percentiles of the distribution of t^* values. The standard deviation of these bootstrapped samples also approximates the standard error of the estimated statistic, just as if we had repeatedly sampled from the unknown population without replacement.

The correlation coefficients for the bootstrapping technique are transformed using the z-transformation,

$$z = \left(\frac{1}{2}\right) \ln\left(\frac{1 + r}{1 - r}\right)$$

Where: r = correlation coefficient

because values of z are approximately normally distributed for any value of its parameter, whereas the distribution of correlation coefficients are skewed for values close to ±1.0. We determine confidence intervals around the z-transformed data using a parametric standard deviation:

$$\sigma_z = \left(\frac{1}{\sqrt{n - 3}}\right)$$

The confidence limits to the z-transformed data are then:

$$z \pm t_{\alpha(\infty)}\sigma_z$$

We then transform these limits back to the r-scale by means of a hyperbolic tangent function, and the null hypothesis (H_0: $r = 0$) is tested by determining whether 95% and 99% confidence limits for r contain the value zero. A Quick BASIC program was written specifically to evaluate the correlation among variates using the bootstrapping technique. To produce these results, we utilized 1000 bootstraps, taking a 30 samples with replacement from the 200 original samples.

Results

Figures 4.3-4.8 illustrate the distribution of sample data among all six two-way comparisons of the data. In examining the results obtained from the basic correlation analysis, we found significant negative correlation between ECA and the stream temperature index, and between ECA and timber harvest volume levels (Table 4.3). These results utilized only one possible combination of 30 X_{ij} pairs (randomly selected) from the original 200 X_{ij} pairs. Results obtained from the bootstrapping technique produced slightly different results than the basic correlation analysis (Table 4.4). Here, only the negative correlation between ECA and stream temperature index was significant.

Figure 4.9 illustrates the average levels of ECA, stream sediment and temperature indices, and timber harvest volume levels from the 20 independent runs, for each of the ten 10-year periods in the 100-year projection. These average levels, along with the large number of samples (200), help explain why we found negative correlation between ECA and stream temperature index levels. Over time, ECA tends to increase as basal area levels decline due to harvesting

Figure 4.3. Scatter plot of stream temperature index and equivalent clearcut acres (ECA) results obtained from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints. Each run was comprised of ten 10-year periods, thus there are 200 stream temperature-ECA samples represented in the plot.

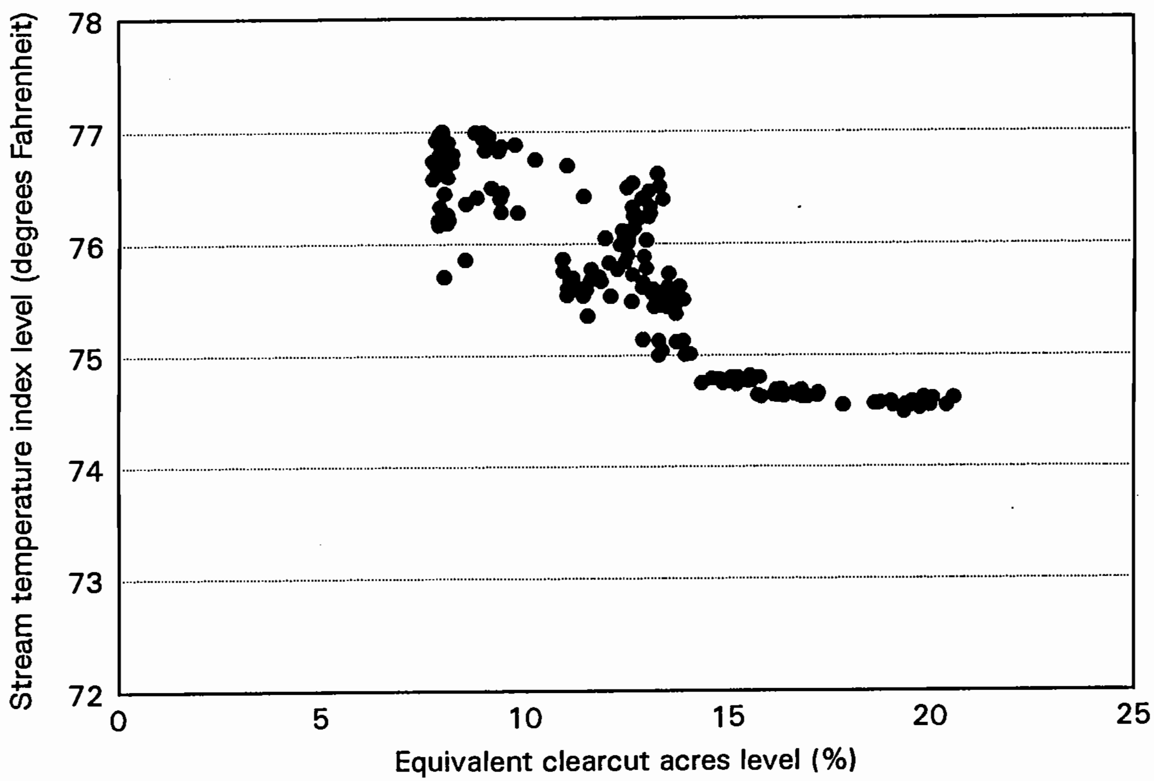


Figure 4.4. Scatter plot of stream sediment index and equivalent clearcut acres (ECA) results obtained from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints. Each run was comprised of ten 10-year periods, thus there are 200 stream sediment-ECA samples represented in the plot.

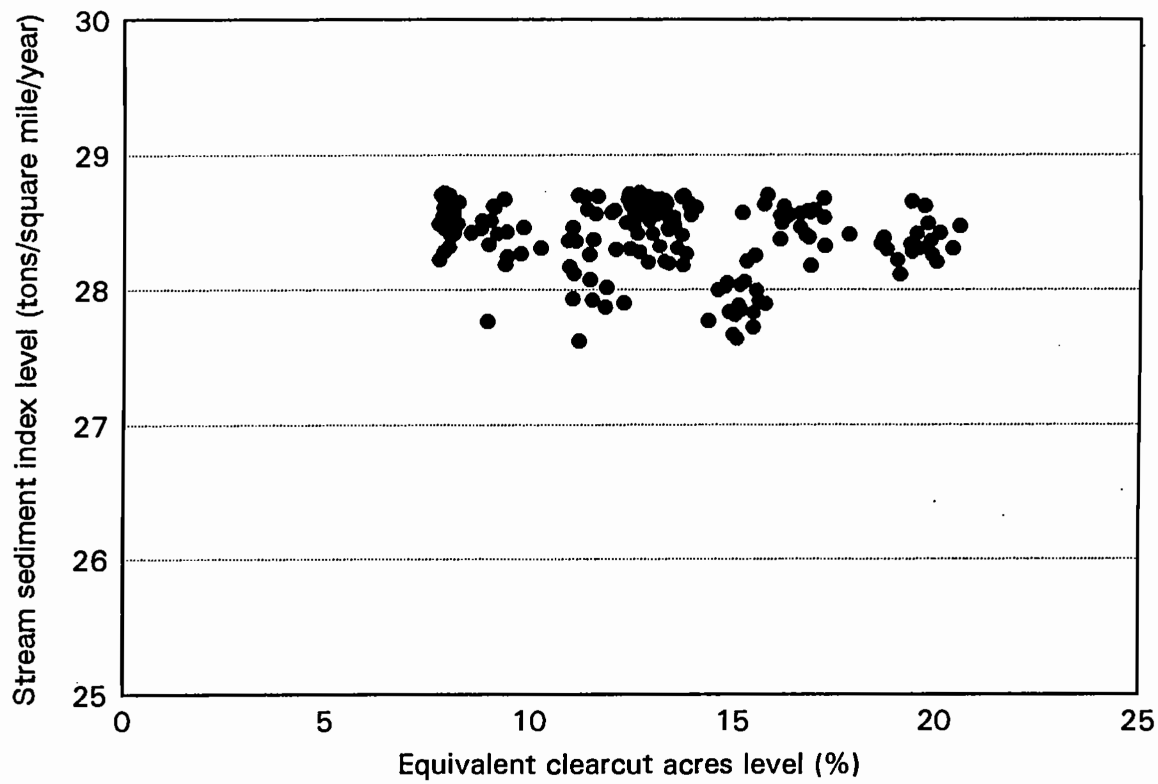


Figure 4.5. Scatter plot of timber harvest volume and equivalent clearcut acres (ECA) results obtained from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints. Each run was comprised of ten 10-year periods, thus there are 200 timber harvest volume-ECA samples represented in the plot.

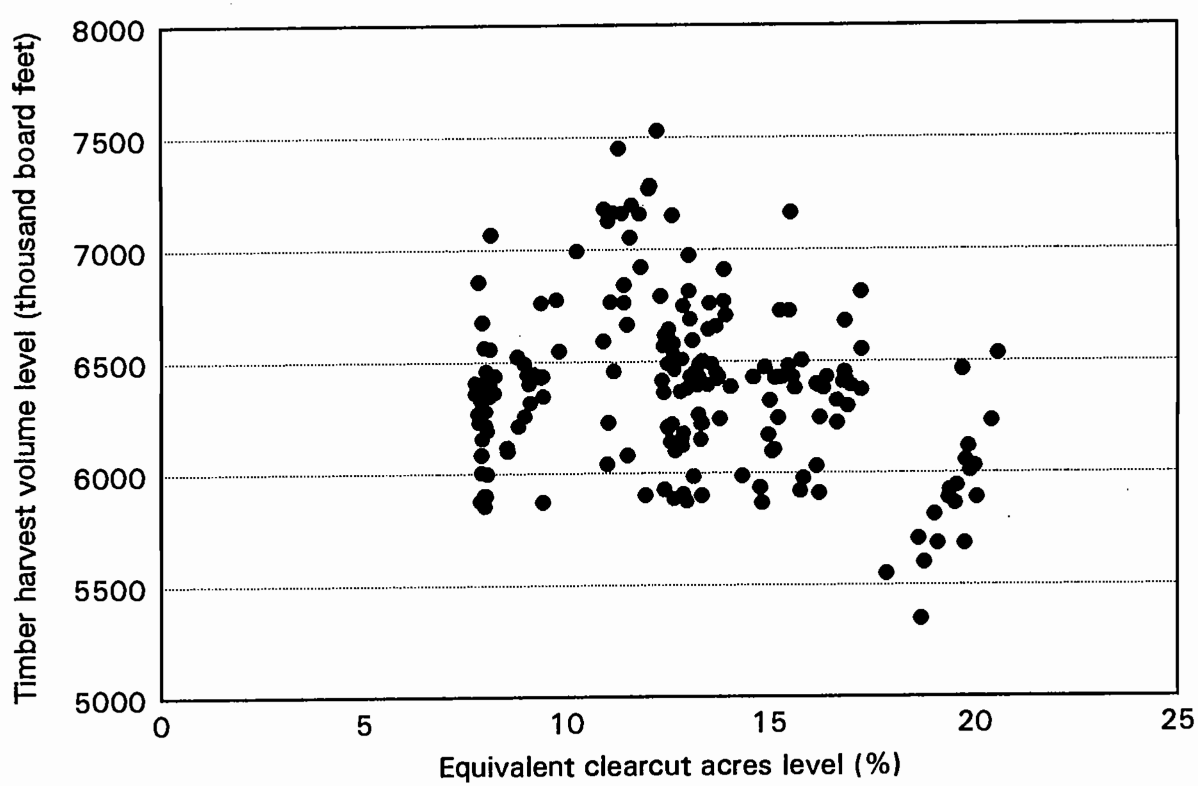


Figure 4.6. Scatter plot of stream temperature index and stream sediment index results obtained from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints. Each run was comprised of ten 10-year periods, thus there are 200 stream temperature-stream sediment samples represented in the plot.

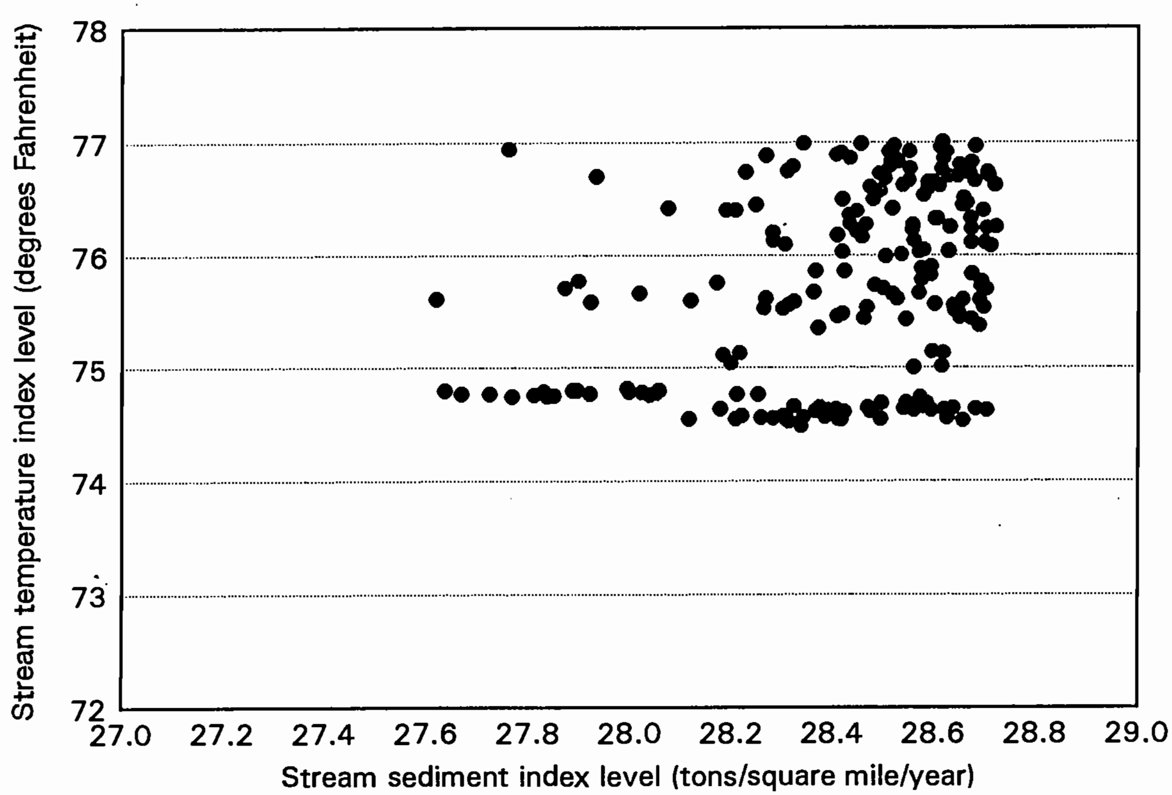


Figure 4.7. Scatter plot of timber harvest volume and stream temperature index results obtained from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints. Each run was comprised of ten 10-year periods, thus there are 200 timber harvest volume-stream temperature samples represented in the plot.

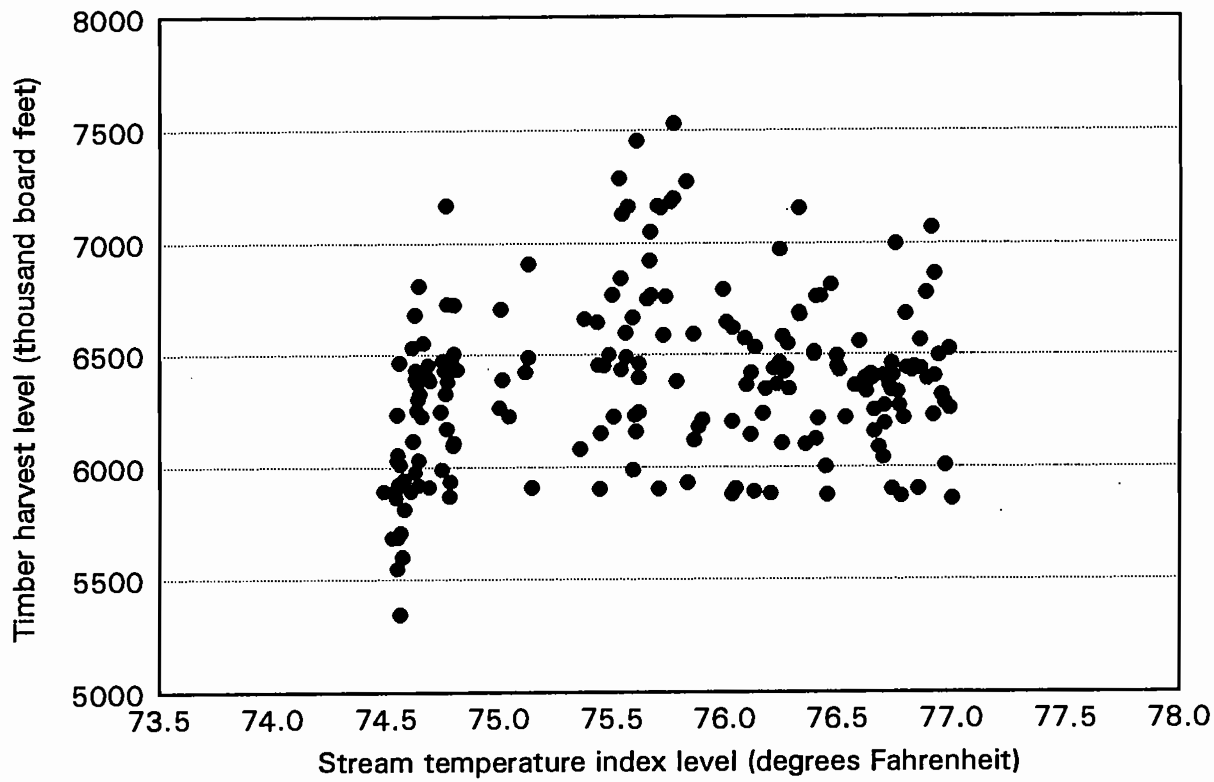


Figure 4.8. Scatter plot of timber harvest volume and stream sediment index results obtained from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints. Each run was comprised of ten 10-year periods, thus there are 200 timber harvest volume-stream sediment samples represented in the plot.

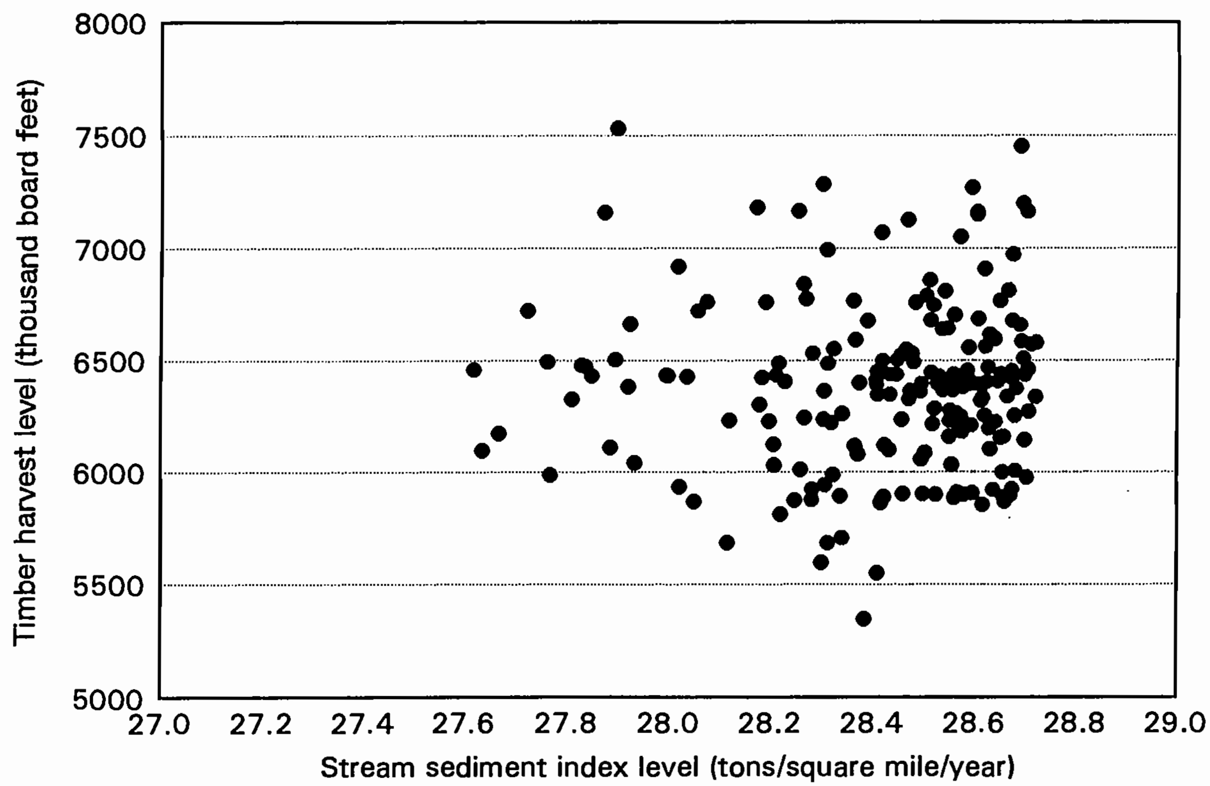


Table 4.3. Correlation between ECA, a stream sediment index, a stream temperature index, and timber harvest volume levels. Thirty randomly selected pairs of data are taken from 200 sample data pairs.

	Stream sediment index	Stream temperature index	Timber harvest levels
ECA	-0.189	-0.898 (**)	-0.370 (*)
Stream sediment index		0.344	0.116
Stream temperature index			0.331

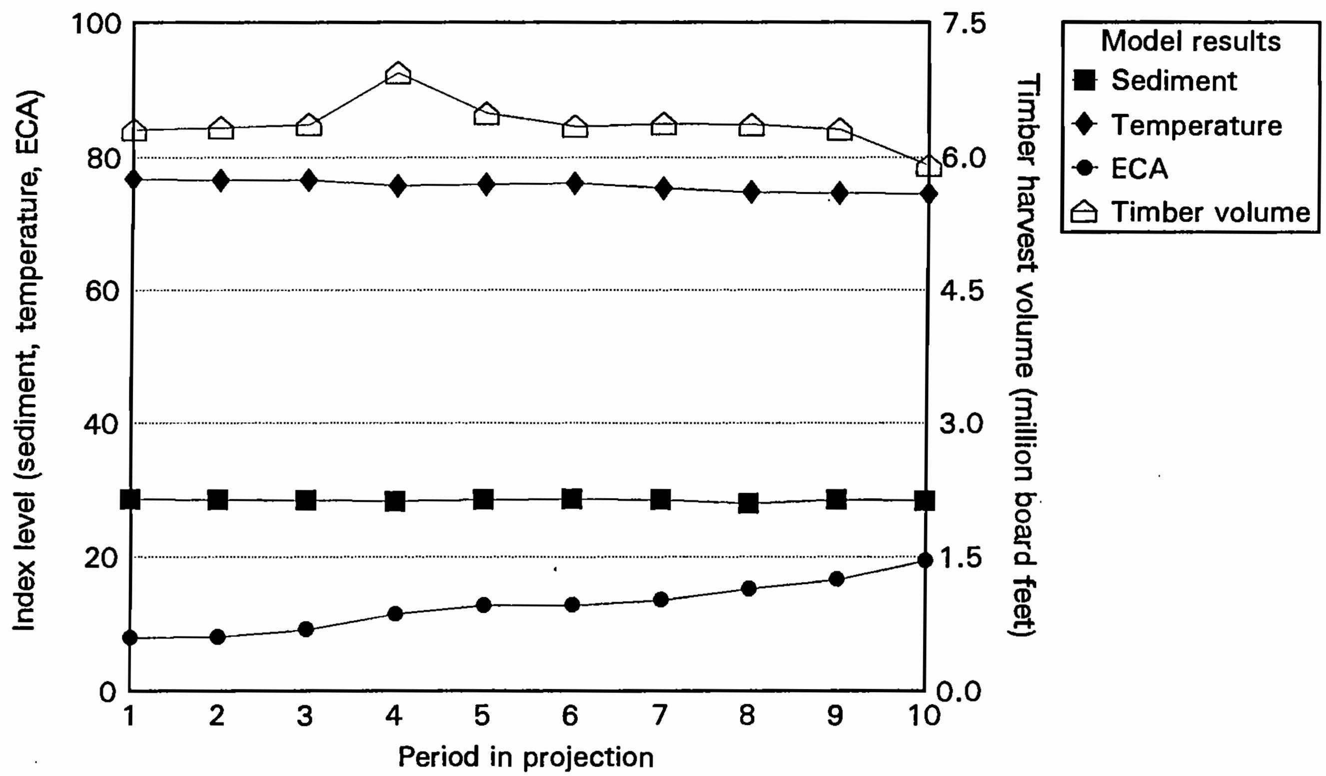
** $p < 0.01$
* $p < 0.05$

Table 4.4. Correlation between ECA, a stream sediment index, a stream temperature index, and timber harvest volume levels, using a bootstrapping technique, where 30 samples are taken with replacement from 200 sample data, and 1000 bootstraps are utilized.

	Stream sediment index	Stream temperature index	Timber harvest levels
ECA	-0.238	-0.895 (**)	-0.210
Stream sediment index		0.344	0.017
Stream temperature index			0.175

** $p < 0.01$
* $p < 0.05$

Figure 4.9. Average stream sediment index, stream temperature index, equivalent clearcut acre, and timber harvest volume results for ten 10-year periods in a 100-year planning horizon for a 14,643 acre case study watershed in eastern Oregon. Results are averages obtained from 20 independent runs of a land management scheduling model which maximizes net present value subject to even-flow, stream sediment, and stream temperature constraints.



activities. Two variables (stream sediment index and timber harvest levels), on the other hand, stay fairly constant, while the stream temperature index declines slightly over time. The stream sediment and temperature indices were constrained to upper threshold levels, while timber harvest levels are fairly constant as a result of an even-flow process incorporated in our land management scheduling model. ECA was unconstrained in our land management scheduling model.

Discussion

The negative correlation between ECA and stream temperature index levels is due to several causes (e.g., spatial location of harvest activities, road standard changes), but specific attributes of these causes (e.g., changes in basal area, location of activity in relation to the stream system, type of harvest system) actually determine the level of each variate. Since each measure is affected by a different mix of both spatial and non-spatial data, we know that the correlation between these variables would not be perfect. However, we had expected to realize a positive correlation between ECA, the stream sediment index, stream temperature index, and timber harvest volume levels. For example, we expected that as ECA levels rose, sediment and temperature index levels would also rise.

We also found a wide variation in results (ECA, stream sediment index, stream temperature index) with corresponding timber harvest volume levels. Harvests are spatially and temporally arranged to stay within the sediment and temperature goals, and several alleviation techniques can be used when these constraints are violated. Therefore, since each of the 20 runs of the model had a randomly defined initial set of harvesting activities, and given the Tabu restrictions are applied after an activity is chosen, we find that a different set of harvest and road management activities defines the final (best) solution from each run. Since the sediment, temperature, and ECA measures are estimated using different variables, the location and timing of harvest activities may produce a variety of results per timber harvest volume level.

The stream temperature index was only affected by activities which occurred adjacent to U.S. Forest Service class 1-3 (perennial) streams, while ECA and the stream sediment index are affected by activities which occur across the full range of the landscape. Thus while ECA and the stream sediment index vary as a result of activities scheduled for upslope locations, the stream temperature index does not. The stream sediment index, however, is only partially affected by the some of the same variables affecting ECA levels (e.g., harvest activities across the full range of the landscape), however, much more information is required to estimate stream sediment index levels, including soil type, shortest distance to U.S. Forest Service class 1-4 (perennial to intermittent) streams, and ground slope. A main point is that the measurement of ECA is not based on the spatial location of activities, whereas the sediment and temperature indices are. It would therefore seem unreasonable to assume that ECA levels could have captured much of the variation in the stream sediment and temperature index levels.

Although ECA seems to be a rational tool to use in evaluating the hydrologic condition of a watershed, the concept has several limitations. For example, the delivery of water yield as a result of management activities varies by topographic position (Belt 1980). The ECA model used here does not express differences in water yield as a result of the topographic position or spatial location of a treatment area with respect to the stream system. Further, ECA does not express differences in water yield as a result of applying several treatments to a particular site without allowing the site to hydrologically recover. ECA was generally most affected by the rate (30- to 50-year entry cycles for partial cutting, 70-year rotations for clearcutting) and intensity (partial cutting assumed 33% of the basal area would be harvested with each entry) of harvesting, which acted to reduce basal area levels over the long-term. Therefore since ECA levels were unconstrained in the analysis, ECA increased over the 10-period projection. The stream sediment and stream temperature indices showed different trends partly because they were constrained to upper threshold levels.

Since the correlations reported here are a result of the solution technique and problem formulation, one might wonder how the relationships may change if ECA levels were also constrained. If we assume ECA is constrained at 15 percent, we may have found that it becomes a limiting factor around period 4 in our analysis (Figure 4.9). This may have two main implications for harvesting activities. First, the level of partial cutting may decline over time, as activities are shifted so that they start in later periods. In effect, this may prevent multiple entries in many units during the 100-year planning horizon, allowing basal area levels to remain at higher levels in later periods than if multiple entries are allowed. Second, the level of clearcutting in later periods would probably decline as ECA is controlled. More clearcutting occurred in later periods to offset the loss in timber harvest volume as units which were partial cut became too old to allow more entries.

Both of these implications point to lower even-flow harvest levels than those reported here. On the other hand, we assume that obliterated roads are not revegetated with tree species, thus they continue (over time) to contribute to ECA at the same level as unobliterated roads. If we can assume that obliterated roads will be revegetated with tree species, eventually the basal area of these previously roaded areas would be high enough offset some of the increase in ECA as a result of harvesting activities, possibly allowing more harvesting activities to be scheduled.

In all, one might expect to find significant positive correlation between ECA and the other three variables if ECA, stream sediment, and stream temperature are all constrained, and an even-flow of timber harvest volume is ensured. If, however, ECA were the only variable to be constrained in our land management scheduling model (with the exception of the even-flow constraint), we may find some very unpredictable results regarding its relationship to stream sediment and temperature index levels. For example, if ECA were constrained to 15 percent, the spatial location of activities will not be a factor because our ECA model does not include a spatial element. Activities would then be scheduled without regard to the impact on sediment or temperature index levels. In this case we may observe no correlation between ECA, stream sediment and temperature indices, since we would expect ECA to be constrained at about 15 percent for all periods in all runs, yet sediment and temperature index levels might vary considerably.

Conclusions

While ECA is used to place upper limits on watershed use, perhaps to place limits on the expected increases in maximum monthly streamflow during spring snowmelt (King 1989), it may be unreasonable to expect that ECA levels would always be positively correlated with stream sediment and temperature index levels. The lack of positive correlation between ECA and stream sediment and temperature index levels observed here is mainly a factor of the functional relationships that are used to estimate each measure, and the assumptions we have made with respect to model specification and problem formulation.

The ECA model that we utilize here is based solely on non-spatial data. Stream sediment and temperature index levels are based in part on both spatial and non-spatial data. Each of these three metrics for evaluating cumulative effects of management activities on aquatic habitat quality are used for various management planning purposes. Our results show that stream sediment and temperature indices are not adequate proxies for ECA. Further, we speculate that if ECA is constrained, we may have observed much different results than shown here.

Many aquatic habitat models may be available to predict the relative changes in aquatic habitat quality as a result of land management activities, although we have only used three of them here. We do not ascertain that the models we have used here are the best models to use in every situation. In addition, the results derived from our model do not provide any empirical evidence that the sediment or temperature models can be validated for use in eastern Oregon. However, we have verified that the procedures we use emulate the procedures originally developed for these models, and believe that they can be used to illustrate the relative differences between alternative management activities.

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Chapter 5

Differences in Schedules of Land Management Activities when Considering Three Representations of Land Unit Decision Variables

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Abstract

A land management scheduling model that performs a multi-period, simultaneous evaluation of aquatic habitat and commodity production goals was utilized to evaluate the differences in model results when considering three representations of land unit decision variables. The scheduling model uses a Tabu search procedure to guide the selection of harvesting activities and road management choices. A 14,643 acre case study watershed is used to illustrate the results, using land units delineated by three scenarios: (1) vegetation, (2) soils, and (3) a combination of vegetation and soils polygons. Significant differences in net present value, the length of road miles designated for central tire inflation use, stream sediment and temperature index levels, equivalent clearcut acres, and timber harvest volume levels were observed.

The landscape represented by soils units produced solutions which had, on average, a 45.7 percent higher net present value than that defined by vegetation units. However, delineating harvest activities by soil type may be limited by operational constraints. Under this scenario land units were larger and more land area was represented as being occupied by tree species, so more harvesting opportunities existed as compared to other scenarios. Most importantly, smaller land units (in the other two representations) may not be economically attractive due to a fixed transportation cost applied on a per unit basis. Further, larger land units provided larger sediment pulses when scheduled for harvest, requiring more roads to be obliterated in the early periods of the analysis. The amount of sediment alleviation required via road management was thus minimal in later periods. The landscape delineated by a combination of soils and vegetation units

produced, on average, solutions with a 15.7 percent lower net present value than that defined by vegetation units because it had many small land units which may not have been economically attractive due to the fixed transportation cost.

Introduction

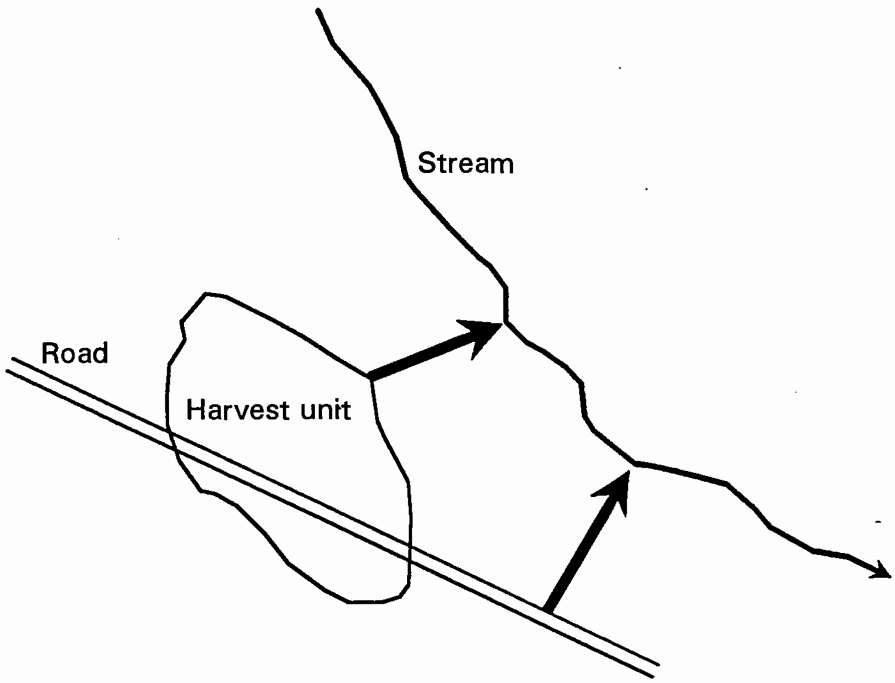
Protection for spotted owls (Strix occidentalis) and wild fish stocks in the Pacific Northwest has become important in the past decade, as these species have become listed as threatened or endangered by the federal government. Other natural resource issues, including big game management and forest health goals, also receive considerable support from the public, and result in numerous restrictions for timber sale planning on National Forests. The interrelationships of faunal and floral species and their habitats are complex, and the cumulative effects of seemingly insignificant alterations of habitat, whether caused by humans or natural processes, can possibly change the productivity and diversity of many resources (Meehan 1991). Considered here is the compatibility of land management activities and aquatic habitat quality, and how results from a land management scheduling model may change with different representations of land unit decision variables.

At the present time, an assessment of the quality of a land management plan with respect to most resource goals other than commodity production goals generally relies on a posterior measurement of suitability using a set of spatial statistics operating upon a spatial database (i.e. FRAGSTATS [McGarigal and Marks 1993]); with few exceptions [e.g. Bettinger et al. 1996]). In a few cases, specialized algorithms have been developed to measure the quality of a management plan for particular species such as elk (Cervus elaphus) (i.e. HEICALC [Hitchcock and Ager 1992], HEIWEST [Ager and Hitchcock 1992], SNAP II [Sessions and Sessions 1993]). These types of posterior analyses, however, do not assure that a management plan will actually be feasible with respect to a particular species, they simply measure the effectiveness of the plan once it has been developed.

As discussed in Chapter 2, I developed a land management scheduling model, which uses Tabu search techniques to ensure the compatibility of land management activities (timber harvesting and road management) and aquatic habitat goals (stream sediment and temperature). Sediment and temperature goals are considered important indicators of aquatic habitat quality in the interior Columbia River basin of the Pacific Northwest. The model I developed identifies a timber harvest and road management schedule which achieves the highest net present value, while simultaneously meeting the sediment and temperature goals, and attempts to provide an even-flow of timber volume over time. Thus a land management plan developed using this model is assured to be feasible with respect to these goals.

While one may argue that spatial analysis has always been considered in forest planning efforts, ecosystem management and watershed analysis have perhaps promoted the use of spatial data in forest management by emphasizing resource goals beyond timber outputs. In many cases within the realms of ecosystem management and watershed analysis, the use of sophisticated models - which have functional relationships that explicitly consider the location of activities on a landscape, is required (Figure 5.1). With the advent of geographic

Figure 5.1. Influence of spatial location of land management activities on stream sediment estimation.



Stream sediment impact from harvesting = f(soil type, harvest system, logging system, distance to stream, etc.)

Stream sediment impact from roads = f(road standard, road slope, road traffic, distance to stream, etc.)

information systems (GIS), planners and analysts now have an array of tools which may be used to create a theoretically unlimited number of different representations of a landscape, and thus should be able to provide data required by many modeling techniques. For forest planning purposes, landscapes can be represented by either vector or raster data structures, and developed using a wide variety of spatial resolutions.

Under ecosystem management land unit decision variables used in forest planning efforts should be developed with full consideration for all of the forest outputs identified as important. To develop land units, one would normally gather a series of maps representing various aspects of the forest landscape, then divide the landscape into a reasonable number of distinct units. GIS has allowed planners to accomplish this task at great speeds. The criteria for dividing the landscape into distinct units has traditionally been based on the capability of the land and the conflicts of interest that affect the land (Kirby et al. 1980).

Traditional land units used for forest planning are defined by distinct or abrupt changes in the age, species, or density of vegetation. If, within an ecosystem management context, an organization were to consider outputs from the vegetation resource (for example, timber production) as secondary, delineation of land units by changes in vegetation may not be the most appropriate representation of the landscape for planning purposes. For example, one argument is that the type of planning units used should be designed so that the non-commodity processes of interest (e.g., disturbance, vegetation succession, habitat structure, water cycling, wildlife) can be understood and modeled (Leavell et al. 1995). Using this argument, timber and other resource extraction products would be considered secondary, as a measurable outcome of managing for the health and sustainability of the ecological system.

In this research I assume two aquatic habitat goals (stream sediment and temperature) are the primary goals used for providing a measure of aquatic habitat in eastern Oregon. I developed three representations of a 14,643 acre watershed using: 1) vegetation units, 2) soils units, and 3) a combination of vegetation and soils units. My main objective is to determine how the results from a land management scheduling model may change with these different representations of the landscape.

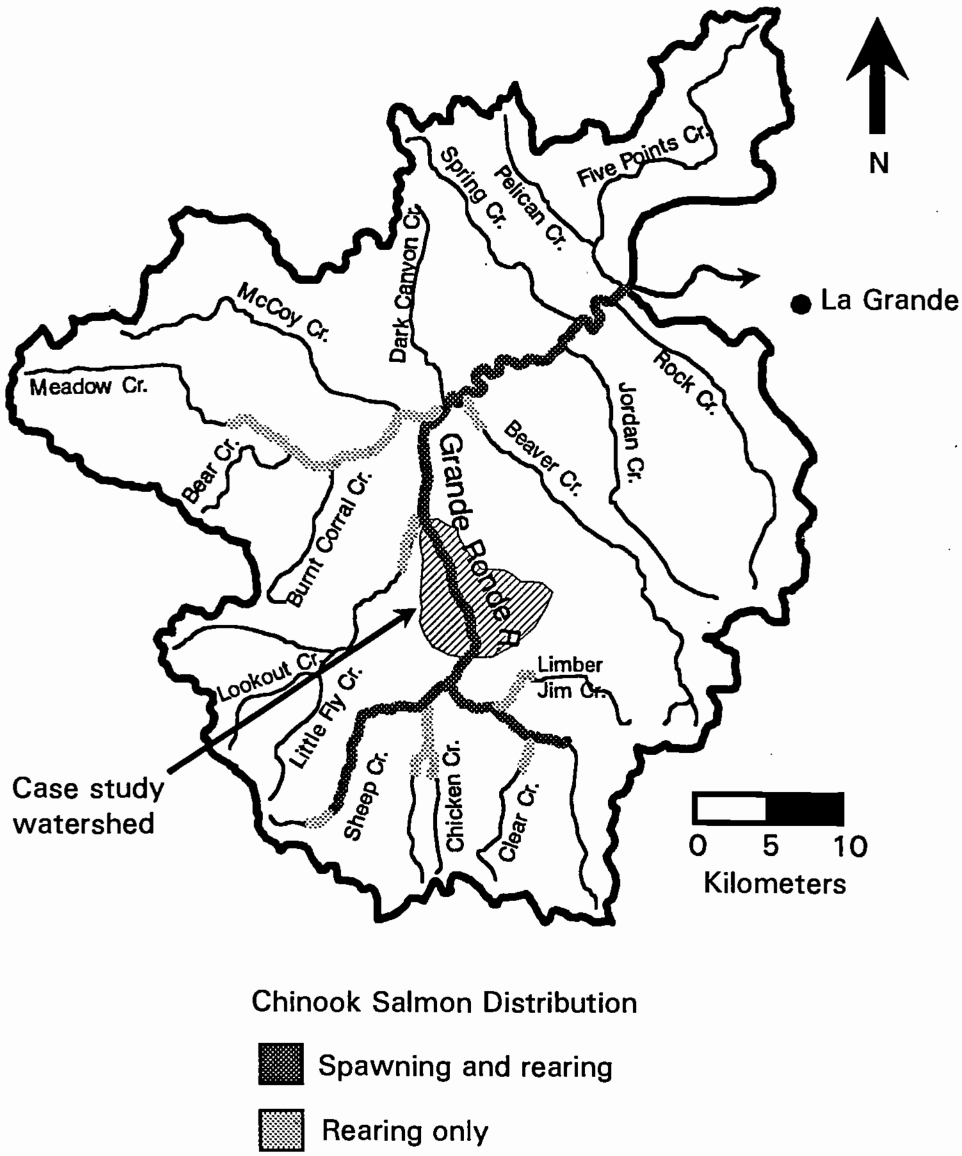
Methods

I first describe the case study watershed and the GIS processes used to develop the land units, then provide an overview of the land management scheduling model formulation and goals of interest. Finally, I discuss the sampling techniques used to evaluate the differences in model results.

Case Study Watershed, Empirical Data Used, and Estimation of Constraints.

A 14,643 acre watershed in eastern Oregon (Figure 5.2) was used as a case study for the application of the model. My decision to use a large landscape to test the model was based on my desire to use the land management scheduling model to emulate an operational tactical planning process, and to evaluate cumulative effects at a watershed scale. GIS databases depicting the road system, stream system, and vegetation and soils resources were developed

Figure 5.2. The Upper Grande Ronde River basin in eastern Oregon, and the 14,643 acre case study watershed.



in ArcInfo (ESRI 1995). The road network for the watershed consists of 474 road segments, 443 of which are physically located within the watershed, and for which the effects of sediment produced by the roads will be evaluated. Roads were classified into three categories: obliterated, paved, and rock. Empirical data included average road widths, road slope percent, and the shortest distance from each road segment to a U.S. Forest Service class 1-4 stream. These data were derived from a sample of roads within the watershed, topographic maps, and GIS processes.

The stream system (Figure 5.3) consists of 9.6 miles of U.S. Forest Service class 1 streams (namely the Upper Grande Ronde River); however stream density varies by stream class (Table 5.1). Empirical data for the stream network include: stream widths by stream class, tree overhang percent, shade density, tree-channel distance, stream orientation, and terrain slope percent. These data were derived from a sample of streams within the watershed, topographic maps, and aerial photographs. Average flow rates the downstream reach in the watershed were obtained from an actual monitoring station. Riparian areas were developing using the PACFISH guidelines (USDA Forest Service and USDI Bureau of Land Management 1995).

Empirical data for the vegetation and soils databases included: average merchantable volume per acre, average basal area per acre, average age of dominant trees, dominant tree species, average height of dominant trees, ground slope percent, soil type, texture of erodible material, erosion hazard rating, and other site-specific variables. These data were accumulated from files located at the La Grande Ranger District (La Grande, OR) of the Wallowa-Whitman National

Figure 5.3. Stream classification, based on U.S. Forest Service stream guidelines, for a 14,643 acre case study watershed in eastern Oregon.

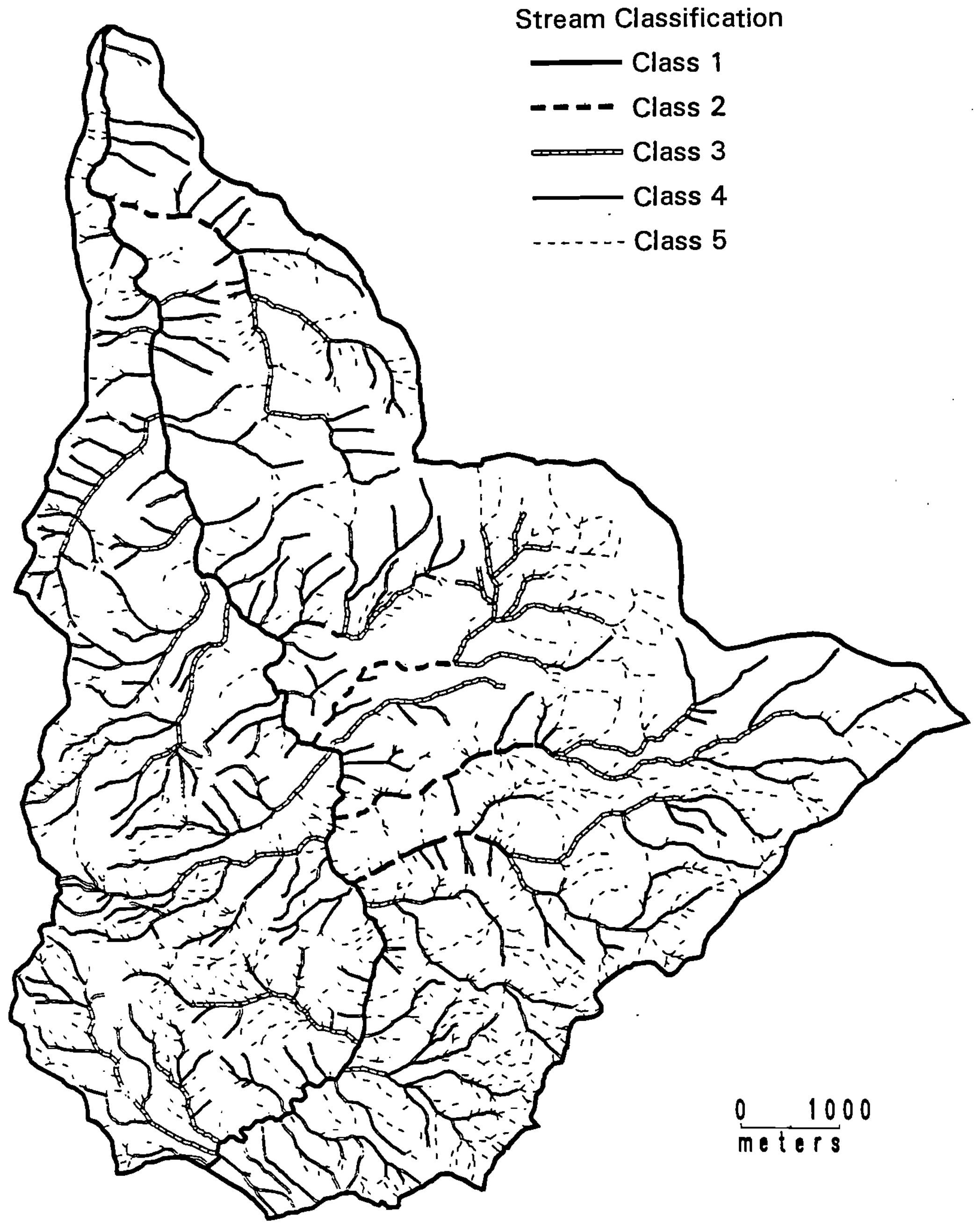


Table 5.1. Stream density in the 14,643 acre case study watershed, by U.S. Forest Service (USFS) stream class.

USFS stream class	Stream density (mi/mi^2)
1 - Perennial, used by anadromous fish and resident fish	0.42
2 - Perennial, used only by resident fish	0.25
3 - All other perennial streams not classified	0.94
4 - All intermittent streams	3.66
5 - All ephemeral streams	3.65
Total	8.92

Forest, the Wallowa-Whitman National Forest Supervisor's Office (Baker City, OR), and from aerial photographs taken from 1984-1989.

All revenues and costs were assumed to occur in the mid-point of a period, and were discounted by 4 percent per year in calculating the net present value (NPV). No stumpage price appreciation was used in this analysis. Empirical data used in the forthcoming case study includes stumpage prices, harvesting costs, road maintenance costs, and road standard change costs for the Blue Mountains region of eastern Oregon. Harvesting and road costs were accumulated from recent sale proposals developed for the La Grande Ranger District timber sale program.

The stream sediment index and stream temperature index goals I used were obtained by estimating the extent and location of harvest activity during the previous 10 years in the case study watershed, and evaluating the impact of those activities on the stream sediment and temperature indices. The sediment (28.7 tons/square mile/year) and temperature (77.0°F) index levels I estimated were then used as goals not to be exceeded during the analysis.

GIS Processes

GIS techniques were used to create three representations of land units (hereafter called "scenarios"): (1) those defined by the dominant vegetation, (2) those defined by the dominant soils type, and (3) those defined by a combination of vegetation and soils types. A riparian area coverage was first created by buffering stream various widths according to stream class, using PACFISH guidelines (USDA Forest Service and USDI Bureau of Land Management 1995). Riparian areas were given special protection in the land management scheduling model in that only partial cutting activities could occur inside them. To create scenario 1 (polygons defined by the dominant vegetation), I first unioned the vegetation coverage with the riparian area coverage. I then eliminated polygons that were less than 2 acres in size and outside riparian areas. Those polygons inside the riparian areas were not altered to retain the geographical integrity of the riparian areas. Data required by the land management scheduling model (for example, area, timber volume per acre, tree species) were then exported to an ASCII file. The vegetation coverage was subsequently unioned with the soil coverage, and data concerning soil characteristics (for example, erosion hazard rating) were exported to an ASCII file. I developed a Quick BASIC program to calculate a weighted average of the soils characteristics for each vegetation unit.

The resulting watershed represented by scenario 1 consists of 1,436 land units (mean size = 10.2 acres, coefficient of variation (CV) = 174.9).

To create scenario 2 (polygons defined by soil type), I unioned the soils coverage with the riparian area coverage, and then eliminated all polygons less than 2 acres and outside of riparian areas. Data concerning the soils units were then exported to an ASCII file. I unioned the soils coverage with the original vegetation coverage, and exported the vegetation data to an ASCII file. I again developed a Quick BASIC program to calculate a weighted average of vegetation characteristics for each soils unit.

One limitation in my land management scheduling model is that it assumes only one tree species is dominant for each land unit. Therefore calculating a weighted average tree species became difficult. Species types in the model are coded using numerical values, and thus taking an average of these values may completely misrepresent the type of tree species that dominates (for example, averaging species 2 and species 6 would produce species 4). Since stumpage prices vary by tree species, this seems unrealistic. I developed a Quick BASIC program to determine the dominant tree species based on total timber volume, and use that species as the dominant tree species for the soils units. This process produced more land units defined by a tree species as compared to scenario 1, as many meadow polygons were combined with tree species polygons, resulting in tree species polygons. All other weighted averages of vegetation data in my analysis are based on land area and required no special treatment. The resulting landscape described by scenario 2 consists of 1,106 land units (mean size = 13.2 acres, CV = 127.1).

Scenario 3 consists of the unioned vegetation and soils coverage created when developing scenario 1. This representation of the landscape consists of 2,945 land units (mean size = 8.5 acres, CV = 171.0).

For all three scenarios, the entry point for each land unit into the road network (for transporting timber volume harvested to a mill) was determined using the NEAR command in ArcInfo. This technique was used to locate the shortest distance between the polygon label of each land unit and nodes from the road system. For estimating sediment levels I also needed to locate the shortest distance between each land unit and the stream system. To do so the unit coverages for each scenario were converted to point coverages using the ARCPOINT command; then the NEAR command was used to calculate the shortest distance between the points representing unit boundaries and stream arcs. I exported data regarding the left- and right-polygons for each point along the distance to the closest stream, and in a Quick BASIC program sorted the data and determined the single shortest distance from each unit to the stream system.

These are the most unbiased processes to determine the landings and distances to streams, but have their limitations. First, locating the shortest distance between polygon labels and road nodes assumes that polygon labels are somewhere near the centroid of a polygon, which may not actually be true. Even then, the road node (landing) selected may not be the most appropriate, based on operational considerations. Second, by converting polygons to points, for determining the shortest distance to the stream system, some accuracy in polygon boundary location may be lost. For example, polygons explicitly crossing a stream may not be represented as such, because a point representing a polygon boundary must lie exactly on a stream arc to be reported as having "zero distance to stream." In addition, I am ignoring subtle influences of topography, since the shortest distance may not be the route that surface erosion will follow to the stream system.

Model formulation

The problem we attempt to solve with this research can be formulated as such:

maximize:	net present value (NPV)
subject to:	an even-flow of timber harvest volume
	an upper limit on stream sediment levels
	an upper limit on stream temperature levels

The decision choices consist of:

Harvesting systems:

- Partial cutting on a 30-year return interval, all tree species, no cutting before age 50 or after age 150.
- Partial cutting on a 50-year return interval, all tree species, no cutting before age 50 or after age 150.
- Clearcutting and thinning. If thinning is the first harvesting activity, it can occur between the ages of 50 and 100. Clearcutting follows 20 years later. If clearcutting is the

first harvesting activity, it can occur between the ages of 101 and 150. After a clearcut has occurred, thinning occurs at subsequent age 50, and clearcut at age 70. Lodgepole pine stands only.

- Not harvesting a unit.

Logging systems:

- Ground-based
- Skyline
- Helicopter

Road standard changes:

- Standard rock to central tire inflation (CTI) use
- Standard rock to obliterated
- No change in road standard

It is important to note that some of these decision choices involve land allocation issues (e.g., timber harvesting, road obliteration), while one of the choices (requiring lower log-truck tire pressures on certain roads, via CTI) involves changes in management practices. Here, the state of the road is not changed when CTI use is assigned to the road. In addition, sediment and temperature index levels utilize spatial information and are constrained in the analysis, while a measure of landscape use, equivalent clearcut acres (ECA), uses non-spatial information and is unconstrained.

Objective Function

The land management scheduling model uses an objective function that maximizes the net present value of all harvesting and road management-related activities. The objective function is formulated as:

maximize:

$$\sum_{m=1}^{n}\left(\frac{\sum_{k=1}^{u}((P_m - H_m) * V_{km}\Phi_{km}) - \sum_{k=1}^{u}(FC_{km}\Phi_{km} + (VC_{km} * V_{km}\Phi_{km}))}{(1 + i)^{(m-1)+5}}\right)$$

$$- \sum_{m=1}^{n}\left(\frac{\sum_{s=1}^{q}(RC_{sm}\omega_{sm})}{(1 + i)^{(m-1)+5}}\right)$$

Where: m = Period

n = Total number of periods

k = Unit

u = Total number of units

ϕ_{km} = Variable indicating the extent to which unit k is harvested in period m

P_m = Stumpage price ($/MBF) in period m

H_m = Harvesting cost ($/MBF) in period m

V_{km} = Total volume (MBF) within unit k during period m

FC_{km} = Fixed road maintenance cost ($/mile) for the path associated with unit k in period m

VC_{km} = Variable road maintenance cost ($/MBF) for the path associated with unit k in period m

s = Individual road segment

q = Total number of individual road segments

RC_{sm} = Road standard change cost ($/mile) for road segment s in period m

ω_{km} = Variable indicating the extent to which a road standard has changed in period m

i = discount rate (percent)

In formulating the objective function for a linear programming (LP) problem, one would assume $1 \geq \phi_{km} \geq 0$ and $1 \geq \omega_{km} \geq 0$. For integer programming (IP) problems, ϕ_{km} and ω_{km} equal 0 or 1. This approach utilizes the IP formulation of the objective function. A fixed road maintenance cost is applied on a per-unit basis.

Even-flow constraint

There are various methods for ensuring an even-flow of timber harvest volume over time for a forest management problem. Classical timber management scheduling techniques address how many acres (area control) or how much volume to harvest (volume control). Area control can achieve a regulated forest in one timber rotation, yet often at the expense of near-term harvest level stability; volume control ensures near-term harvest level stability, yet may not achieve a regulated forest after one rotation (Davis and Johnson

1987). We are attempting to achieve a non-declining even-flow of timber harvest volume:

$$\sum (V_{km}\phi_{km}) \leq \sum (V_{km+1}\phi_{km+1})$$

Our approach to ensuring an even-flow of timber harvest volume, however, is not as strict as the constraint above. Our process adds incremental silvicultural management regimes, defined by a series of harvests over time, to the solution, by only considering those management regimes that can start with a harvest in the period that has the lowest harvest volume. So during the operation of our model, we examine the harvest rates over time, select the period with the lowest harvest volume, and select a management regime that can start in that period. We then are assured that the period with the lowest harvest volume will have volume added to it. It is a constraint in the sense that the set of potential decision choices is confined to those that can start with a harvest in the period with the lowest harvest volume.

Stream sediment goal

A formal declaration of the sediment goals is:

$$\textit{sediment goal for period } m \geq \sum_{k=1}^{u}(natu_{km}\phi_{km}) + \sum_{k=1}^{u}(sedu_{km}\phi_{km}) + \sum_{s=1}^{q}(sedr_{sm}\omega_{sm})$$

$$+ \sum_{s=1}^{q}(traffic_{sm}\omega_{sm})$$

Where: $natu_{km}$ = f (area, erosion hazard rating for unit k in period m)

$sedu_{km}$ = f (harvesting system, logging system, geologic erosion factor, natural sediment rate, ground slope, slope shape, surface roughness, ground cover, texture of erodible material, water availability, distance to the stream system for unit k in period m)

$sedr_{sm}$ = f (road standard, road width, road length, slope shape, surface roughness, slope gradient, ground cover, texture of erodible material, water availability, distance to the stream system for road segment s in period m)

$traffic_{sm}$ = f (volume transported across road, possible reduction factor for using CTI for road segment s in period m)

In formulating this constraint for an LP problem, $1 \geq \phi_{km} \geq 0$ and $1 \geq \omega_{sm} \geq 0$. For IP problems, ϕ_{km} and ω_{sm} equal 0 or 1. My implementation of the sediment constraint follows the IP formulation. Since road construction is not an option in this problem, typical road trigger constraints (see Kirby et al. 1982) are not utilized.

The procedures used to evaluate stream sediment levels are derived from the "Guide to predicting sediment yields from forested watersheds" (USDA Forest Service 1981), known here as the Region 1 / Region 4 (R1/R4) sediment model. This model was selected because it is an established model, and because it provided the best documentation of the models that were considered. The R1/R4 model separates erosional and delivery processes and considers them individually for each land unit and road. There are four major parts to the R1/R4 model: natural sediment yield, sediment from surface erosion, sediment from mass erosion, and routing of sediment to a critical reach.

The R1/R4 model was altered to evaluate surface erosion from road traffic resulting from logging activities, and to reduce sediment from road traffic by assigning CTI use to particular road segments. A factor of 0.0338 tons of sediment / thousand board feet (MBF) - mile was developed using the extreme case from Reid and Dunne (1984), and is applied to all roads which are scheduled to be used to haul timber volume. Although Reid and Dunne's research was from western Washington, it presented the most complete information (sediment produced per MBF transported across road segments) available for use in this study. In addition, a reduction of 60% in surface erosion from road traffic is assumed when CTI is assigned to a road, based on conservative results obtained from Foltz (1994).

The estimation of sediment from mass erosion is highly variable, and since it is not currently a major problem in the case study watershed (R. Beschta, Department of Forest Engineering, Oregon State University, Corvallis, OR, pers. comm.), it is not included in the estimation of stream sediment impacts from land management activities. Finally, stream sediment index levels are only measured at the downstream reach in the watershed. Sediment from all sources is routed to the downstream reach using a coefficient developed by Roehl (1962) that is based on watershed size. The amount of sediment routed to the downstream reach is considered here an index of sediment levels because the R1/R4 model has not been validated in eastern Oregon using empirical data. In fact, no sediment estimation models have been validated for forested watersheds in eastern Oregon.

Stream temperature goal

The stream temperature goal is a function of timber harvesting activities can be formulated as follows:

$$\textit{temperature goal for period } m \geq \sum_{k=1}^{u} (temp_{km})$$

for all {k | k is a unit adjacent to the stream}

Where: $temp_{km}$ = f (stream length, stream width, low flow (cfs), latitude of watershed, declination of watershed, ground slope, shade density, tree overhang percent, tree height, number of skyroads, percent canopy removed during harvest, stream orientation, distance from trees to channel, heat rate (BTU/square foot-minute), ground water temperature for unit k in period m)

The procedures to evaluate stream temperature levels were derived from the SHADOW model (USDA Forest Service 1993). This model calculates the area of unshaded streams, using stream orientation, solar angles, and other reach-specific data. Reach-specific data are spatial in nature in that they include only data (e.g., average tree height, terrain slope) associated with land units which are adjacent to a U.S. Forest Service class 1-3 stream. An equation developed by Brown (1969) is used with SHADOW to predict the increase in stream temperature (as a result of solar heating) over groundwater temperature levels. The resulting estimated temperature is considered here as an index because SHADOW has not been validated in eastern Oregon using empirical data. Only one stream temperature model has been validated for use in eastern Oregon (Bohle 1994), and then only for small stream reaches. SHADOW, however, has been applied to large watersheds, and is supported by Region 6 of the U.S. Forest Service.

Equivalent Clearcut Acres

The ECA concept is defined as a watershed index of the snowmelt and evapotranspiration rates relative to a baseline condition where tree stands are completely canopied. ECA is used to estimate a change in magnitude of the highest 6-day peak flow from a watershed (Wallowa-Whitman National Forest 1991). Changes in peak flow are important where there exists objectives for maintaining or improving stream channel stability. In addition, it has been used as an index of watershed use, where a threshold level is set, and once exceeded, no further activities can occur. Threshold ECA levels are used by the National Marine Fisheries Service (NMFS) in considering the effect of land management activities on aquatic habitat quality in the Columbia River basin. The general rule of thumb is that once an ECA for a watershed gets above 15 percent of a potentially forested area, a watershed analysis must be performed prior to initiating any action that would increase ECA (National Marine Fisheries Service

1995). After watershed analysis, actions that would increase ECA can proceed only if there is no more than a *de minimis* risk of adversely affecting aquatic habitat. While neither uses of ECA provide a direct linkage of land management activities to resource impacts, the one imposed by NMFS seems to be the most constraining given the current legal situation.

The most influential factor in measuring ECA is the amount of area altered by nature or by land management activities (Belt 1980). The amount of area which can be described as being in a clearcut condition is defined in terms of the density of residual vegetation. Each particular land use area (e.g., roads, timber stands) is given a "clearcut-equivalent factor" (CEF), which is subsequently multiplied by the area disturbed to arrive at an equivalent clearcut acre value. For example, clearcuts and roads are generally given a CEF of 1.0, while partial cuts are given a value from 0 to 1, depending on the density (basal area) of residual vegetation (Table 5.2). The more open a unit is, the closer it emulates the snowmelt and evapotranspiration characteristics of a similar stand that is completely clearcut.

An implicit recovery factor is employed in ECA calculations, and is determined by the growth rates used in models to estimate vegetative regrowth of a particular site. Thus the effects of land management activities over space and time are aggregated and standardized into a single measure (ECA). ECA can then be compared to a threshold level that corresponds with the onset of an undesirable change in the environment (McGurk and Fong 1995).

The ECA model used here does not represent factors which add variability to the amount of degradation from a disturbance, such as proximity to the stream

Table 5.2. Clearcut equivalent factors used in equivalent clearcut acres calculations.

	Clearcut Equivalent Factor						
Species	1.00	0.90	0.70	0.50	0.30	0.10	0.00[a]
	Range of basal area (ft²/acre)[b]						
Subalpine fir	0	1-6	7-14	15-28	29-46	47-75	76+
Lodgepole pine	0	1-9	10-17	18-25	26-38	39-50	51+
Grand fir	0	1-12	13-24	25-46	47-73	74-103	104+
Douglas-fir	0	1-13	14-24	25-46	47-64	65-89	90+
Ponderosa pine	0	1-8	9-15	16-23	24-32	33-42	43+

[a] Assumed hydrologically recovered at this point.
[b] Post-harvest basal areas, and basal areas during recovery. Basal areas after clearcutting are an explicit function of stand age.

system. Menning et al. (1996) have proposed an alternative model which utilizes spatial zones around riparian areas. The ECA model also does not take into account other sources of degradation, such as cattle grazing or fire. ECA is not used as a constraint in the model, although the model could be formulated to constrain ECA. The mathematical formulation for estimating ECA is:

$$ECA \text{ for period } m = \left(\frac{\sum_{k=1}^{u} (CEF_{km} Area_{km}) + \sum_{s=1}^{q} (CEF_{sm} Area_{sm})}{\text{Total landscape area}} \right)$$

Where: CEF_{km} = a clearcut equivalent factor for unit k during period m, based on tree species and average basal area

$Area_{km}$ = the area of land covered by unit k during period m

CEF_{sm} = a clearcut equivalent factor for road s during period m

$Area_{sm}$ = the area of land covered by road s during period m

A CEF for an individual unit may vary through time, based on harvest intensity and growth rates of residual tree stands, however CEFs for roads are assumed not to vary in the model. One may assume (although I did not) that abandoned or obliterated roads may eventually become revegetated with tree species. Under this assumption, an area of land formerly represented by a road may, in the future, be represented by a stand of trees which has a basal area of a certain level that would require the use of a CEF lower than 1.0.

Sampling Techniques

ECA, the stream sediment and stream temperature indices, and timber harvest levels are estimated using a land management scheduling algorithm which schedules timber harvest and road standard choices the case study watershed. Twenty solutions were generated for each scenario, each a result of the algorithm starting with an initial, randomly defined set of management alternatives for timber harvests. Each solution is considered to be independent; the results obtained include ECA, stream sediment and temperature index levels, and timber harvest volume levels for each of ten 10-year periods in a 100-year planning horizon. From the 20 independent solutions, there are 200 ECA-aquatic habitat index-timber harvest volume sets for each scenario:

Solution #1:	X_{11},	X_{12},	X_{13},	....,	$X_{1,10}$
Solution #2:	X_{21},	X_{22},	X_{23},	....,	$X_{2,10}$
"	"	"	"	"	"
"	"	"	"	"	"
Solution #20:	$X_{20,1}$,	$X_{20,2}$,	$X_{20,3}$,	....,	$X_{20,10}$

Where: X_{ij} = a set containing ECA, stream sediment index, stream temperature index, and timber harvest volume data for solution *i*, period *j*

To evaluate the differences among scenarios I considered two options: an analysis of variance (anova), and a non-parametric technique (Kolmogorov-Smirnov [K-S] test). The anova was the first choice, but I had to determine whether it was appropriate and whether the test of significance was reliable using the data. I assume that each run is independent, since each was started from a random point in the solution space (Golden and Alt 1979, Los and Lardinois 1982). Thus the error term for the expected value of each variate is assumed to be a random normal variable, therefore it is assumed that the error terms are independent and identically distributed. With no transformation of the sample data, most of the distributions were slightly skewed to either the left- or right-hand sides of their respective distributions, yet most resembled a normal distribution. Several transformations (e.g., log normal, inverse, square root) were attempted, but I was unable to produce better distributions, based on box-plots.

Although there are no variables in the calculation of each measurement that require estimated levels from previous periods, and many activities take place during each period - the location and timing determined by many factors (e.g., violation of a goal, even flow constraints), one may argue that perhaps some temporal autocorrelation among X_{ij} sets, as many units simply grow from one period to the next. So I assume that by sampling X_{ij} pairs that could theoretically be 60-70 years apart may alleviate the temporal correlation concern. Thus a sample size of 30 of the 200 Xij pairs seems appropriate.

I also needed to assure myself that the error terms have identical variances. I used Hartly's F_{max}-test, which evaluates the ratio of largest to smallest sample variances (e.g., scenario 3 NPV variance / scenario 1 NPV variance), to determine whether the variances were homogenous. All of the variances used here were found to be heterogenous, violating the assumption of equal variances. Even when transformations were applied the variances were considered heterogenous. Bartlett's test for homogeneity may have been used, yet it is sensitive to departures from normality (Sokal and Rohlf 1995).

As a result, a non-parametric test (the Kolmogorov-Smirnov [K-S] test) is used to examine the differences between scenarios. The hypotheses I tested were that the sample data (NPV, length of road obliterated per period, length of road assigned a CTI use per period, stream sediment index levels, stream temperature index levels, and timber harvest levels) are distributed identically.

The K-S test is based on differences between the cumulative frequency distribution of each of the paired samples.

I use bootstrapping, a method of resampling data to infer the variability of an estimate (Felsenstein 1985), to sample 30 X_{ij} pairs from the original set of 200 pairs. Bootstrapping is most useful when either the distribution of the sample data X_{ij} is unknown, or when the method of statistical estimation is so complicated that its standard error is difficult to compute (Felsenstein 1985). The justification for using this technique is that one can view each data point as having evolved independently from the others according to a stochastic process, and one can consider each as a random sample from the distribution of all possible configurations of sample data. The configuration of sample data drawn randomly can then be seen as drawn independently and identically distributed (Felsenstein 1985).

I carry out a random resampling procedure by sampling with replacement using the 200 sets of data generated from the 20 independent runs. The resampling process produces a resampled set of n points from the original data points, and for each the estimate t^* is computed, where t^* can be one of many statistics (here it is the K-S statistic). I then have a collection of estimates (t^*) of a parameter which has a distribution that approximates the distribution of the actual estimate t. Averaging the collection of t^* produces a bias-corrected estimate of the parameter t. It has been shown that the mean of the estimated statistics from these bootstrapped samples approximates the mean of the population (Sokal and Rohlf 1995). Further, the variance of t can be inferred by computing the variance of the collection of t^* values, and confidence intervals can be produced using the approximate upper and/or lower percentiles of the distribution of t^* values. The standard deviation of these bootstrapped samples also approximates the standard error of the estimated statistic, just as if I had repeatedly sampled from the unknown population without replacement. A Quick BASIC program was written specifically to evaluate the K-S statistic using the bootstrapping technique. To produce these results, 1000 bootstraps were utilized, each taking a 30 samples with replacement from the 200 original samples.

Results

In terms of NPV, a significant difference ($p<0.01$) among all three scenarios was observed, with scenario 2 having a 45.7 percent higher average NPV ($3,752,554) than scenario 1 ($2,575,872), and scenario 3 having a 15.7 percent lower average NPV ($2,171,110) than scenario 1. No significant difference ($p>0.05$) was observed among scenarios in terms of the length of road obliterated per period. Here, an average of 2.61 miles of road were obliterated under scenario 2, while scenarios 1 and 3 averaged 1.24 and 1.13 miles, respectfully. While more roads may have been obliterated in the first two periods of scenario 2 than the other two scenarios, by randomly selecting periods to sample these data, no significant differences were observed.

Two significant differences were observed regarding the length of road assigned to CTI use per period. Scenario 3 (average 5.48 miles of CTI per period) was significantly different ($p<0.02$) than scenario 1 (average 8.43 miles of CTI), and scenario 2 (average 7.17 miles of CTI) was significantly different ($p<0.01$)

than scenario 1. There was no significant difference ($p > 0.05$) observed between scenarios 2 and 3. Table 5.3 lists the average miles of obliterated and CTI roads per road standard over the ten 10-year projection periods for all three scenarios.

While stream sediment and temperature index levels were constrained to upper threshold levels in the land management scheduling model, the K-S test for sediment index values revealed a significant difference in index levels among the three scenarios. Scenario 2 (average sediment index level = 28.22 tons per square mile per year) was found to be significantly different than scenario 1 ($p < 0.02$; average sediment index level = 28.42), but not scenario 3 (average sediment index level = 28.40). No significant difference ($p > 0.05$) between scenarios 1 and 3 was observed. Stream temperature index levels also were found to be significantly different among scenarios. Here, scenario 2 (average temperature index level = 74.79°F) was significantly different ($p < 0.01$) than both scenario 1 (average temperature index level = 75.71°F) and scenario 3 (average temperature index level = 75.66°F). No significant difference ($p > 0.05$) was observed between scenarios 1 and 3.

ECA was not constrained in the land management scheduling model, however significant differences were observed among all three two-way comparisons of scenarios were observed. Scenario 2 had the highest average ECA (15.65%) and was significantly different ($p < 0.01$) than scenario 1 (12.67%) and scenario 3 (average = 11.49%). And, scenario 1 was found to be significantly different ($p < 0.02$) than scenario 3. Finally, timber harvest volume levels were found to be significantly different among the three scenarios. As with the ECA results, all three two-way comparisons were significantly different

Table 5.3. Average miles of road by road standard for ten 10-year periods in a 14,643 acre case study watershed in eastern Oregon. Results are derived from an average of 20 independent runs of a land management scheduling model which maximizes net present values subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

	Period									
	1	2	3	4	5	6	7	8	9	10
	(miles)									
Scenario 1										
Obliterated	5.9	1.0	0.5	0.1	0.0	2.3	0.4	0.0	0.4	1.7
	(2.1)	(1.4)	(0.9)	(0.3)	(0.1)	(1.8)	(0.8)	(0.0)	(0.9)	(1.9)
Central tire inflation	10.0	6.9	7.1	2.2	1.4	15.8	10.1	0.0	10.8	20.0
	(4.3)	(4.7)	(5.0)	(2.8)	(2.2)	(5.9)	(5.6)	(0.1)	(6.8)	(9.2)
Scenario 2										
Obliterated	16.8	8.7	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	(2.8)	(3.8)	(0.6)	(0.1)	(0.1)	(0.1)	(0.0)	(0.0)	(0.1)	(0.0)
Central tire inflation	19.7	30.0	13.2	4.0	2.0	0.5	0.2	0.4	0.5	1.2
	(5.6)	(5.6)	(5.0)	(2.7)	(2.6)	(1.0)	(0.5)	(0.8)	(0.9)	(2.0)

[a] standard deviations are in parentheses.

Table 5.3 (cont.). Average miles of road by road standard for ten 10-year periods in a 14,643 acre case study watershed in eastern Oregon. Results are derived from an average of 20 independent runs of a land management scheduling model which maximizes net present values subject to even-flow of timber harvest volume, stream sediment, and stream temperature constraints.

	Period									
	1	2	3	4	5	6	7	8	9	10
	(miles)									
Scenario 3										
Obliterated	4.3	1.4	0.8	0.0	0.1	3.6	0.0	0.0	0.0	1.1
	(1.3)	(1.4)	(1.0)	(0.1)	(0.1)	(1.3)	(0.0)	(0.0)	(0.0)	(1.4)
Central tire inflation	7.6	5.5	6.8	1.2	2.5	17.2	3.2	0.0	0.0	10.8
	(3.6)	(4.4)	(4.0)	(1.6)	(2.7)	(2.7)	(4.2)	(0.0)	(0.0)	(9.4)

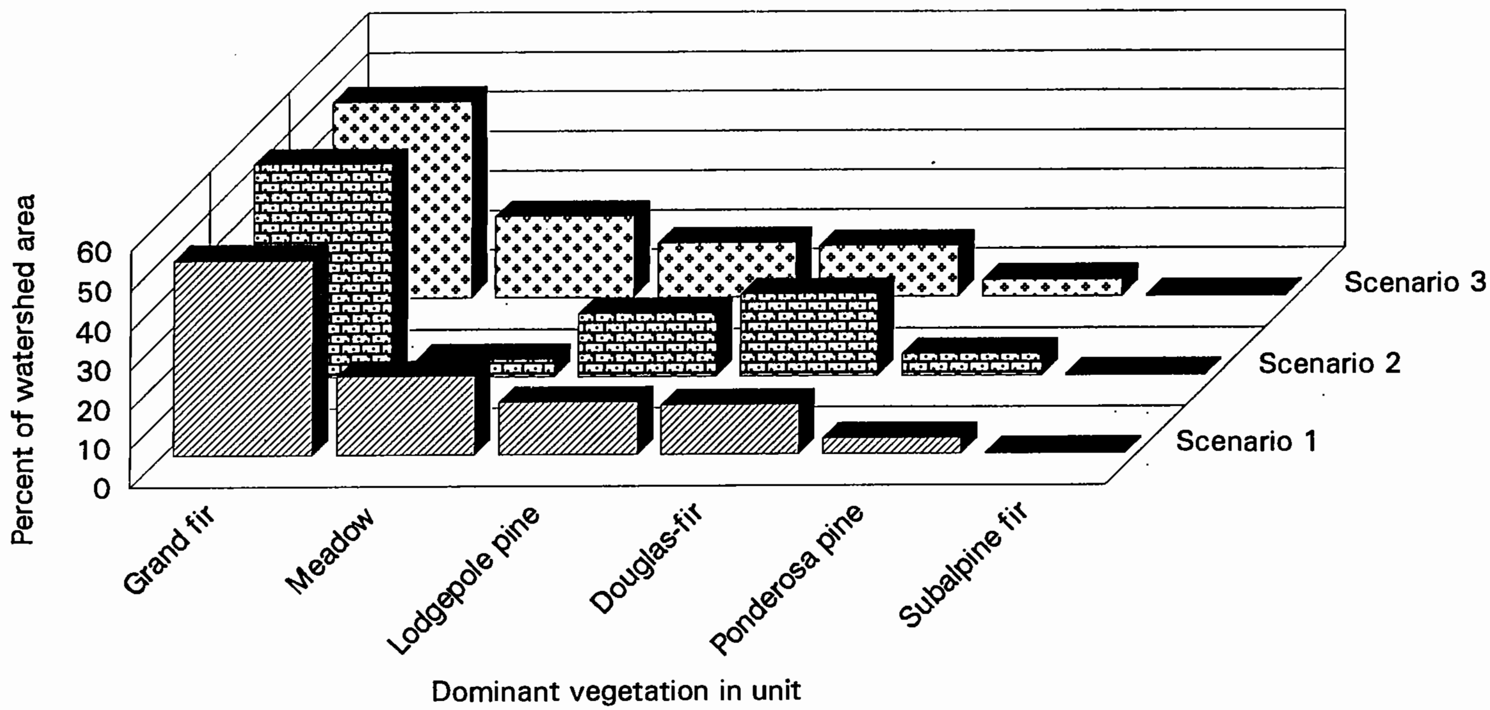
[a] standard deviations are in parentheses.

($p<0.01$). Scenario 2 had the highest average timber harvest volume levels per period (9,388 MBF per period), followed by scenario 1 (6,379 per period) and scenario 3 (5,295 MBF per period).

Discussion

On the surface, the results seem to indicate that using soil units can provide solutions with higher average net present values and lower sediment and temperature index levels. However, the results are an artifact of the solution-generation process, as assumptions regarding the representation of the landscape and regarding transportation costs play a large factor in these results. The landscape represented by scenario 2 had: (1) larger land units, on average, and (2) more units represented by tree species rather than meadows (Figure 5.4). This second fact provided the land management scheduling model with more opportunities to schedule harvest activities, within the constraints of the model, than those afforded to scenarios 1 or 3. In addition, larger harvest units produced larger sediment fluxes, requiring more sediment alleviation, specifically via road obliteration. Many of the road obliteration choices were realized in the first period of the analysis, which provided some relief in terms of sediment produced for all subsequent periods. And since each unit is assumed to be represented by only one type of tree species, the difference in species types between scenarios 1/3 and scenario 2 may eventually higher (or lower) stumpage prices for the same supply of timber. This may have also contributed to a higher average NPV in scenario 2.

Figure 5.4. Percent of area by dominant vegetation in units, as described by three representations of a 14,643 acre case study watershed in eastern Oregon.



Scenario 2 also probably reached the upper limit of sediment produced sooner in the operation of the model, due to scheduling larger units. Therefore scenario 2 could rely on more road obliteration than the other two scenarios, since only unused roads could be obliterated, although this was not found to be significant. So since scenarios 1 and 3 may have taken longer to reach the upper limit on the sediment goal, more individual units were scheduled, thus more roads were being used at the time the sediment goal was violated, perhaps reducing the potential number of individual road segments that could be obliterated. In order to reduce sediment index levels and allow more harvesting activities to occur, scenario 1 had to rely on more CTI choices than scenario 2. Scenario 3 did not require as much CTI since this scenario was constrained by the interaction of the size of the land units and the transportation costs that were incurred on a per-unit basis.

Implicit in the transportation cost structure of the land management scheduling model are both fixed and variable costs associated with harvest units. Variable costs are dependent on the amount of volume harvested, but fixed costs are based on the length of non-paved road used, and are assumed in the model to be incurred on a per-unit basis. Thus smaller land units become economically unattractive to harvest as haul routes on non-paved roads become longer. Larger units, conversely, may not ever become economically unattractive if the proceeds from the volume harvested can offset the logging costs and both the fixed and variable haul costs. Scenario 2 has larger land units than in either scenario 1 or scenario 3, possibly allowing the selection of more units to harvest, and subsequently allowing higher harvest volumes and higher net present values.

Since scenario 2 had larger units (on average) than scenarios 1 and 3, it became apparent that the upslope units in scenario 2 were larger than the riparian units, whereas in scenarios 1 and 3 the difference in sizes of upslope and riparian units was not as obvious. Therefore the scheduling model may have concentrated more on scheduling upslope units than riparian units in scenario 2. As a result, stream temperature index levels were slightly different among scenarios, although the difference was indeed significant. The occurrence of larger land units in scenario 2, and the opportunity to schedule more harvest activities also resulted in higher ECA levels. Conversely, the smaller land units in scenario 3 resulted in fewer land units being scheduled for harvest activities, and thus average ECA levels were lower.

Operationally, scenarios 2 and 3 would be more difficult to implement than scenario 1. For scenarios 2 and 3 one would need to be able to delineate soil unit boundaries on the ground in order to accommodate harvest activities. This may not pose much of a problem where abrupt changes in soil types occur, however, where soil characteristics only subtly change, this may be a major problem. In addition, it may be unreasonable to combine vegetation types from a variety of age classes and structures into one land unit, as was done in scenario 2. Developing silvicultural management regimes and logging systems for these types of land units may prove to be very difficult. Finally, by averaging vegetation characteristics for each soil unit in scenario 2, we may be misrepresenting the resources required to evaluate the effectiveness of land management plans for other species. For example, fewer meadows are being represented under scenario 2 than under scenarios 1 and 3, possibly affecting measurements required to evaluate elk habitat effectiveness.

Scenario 3 is composed of many small land units because I simply combined the vegetation and soils GIS databases. While the measurement of sediment may be more precise here than in scenario 1, considering each of these land units individually for harvest activities may prove to be economically unreasonable due to the fixed transportation costs. A better approach may be to schedule activities where many small land units may be grouped together, and then applying a single fixed transportation cost to the group.

Conclusions

The development of land units for use in forest planning (on a watershed or smaller level) requires a thorough evaluation of the goals of the planning problem. When planning is directed by ecosystem management or watershed analysis, a wide variety of goals may be considered important. For planning problems where both land management (timber harvests and road management) and aquatic habitat quality goals are important, a balance must be struck between the geographic representations of environmental response variables used in evaluating these goals.

Planning for timber harvest alone seems relatively simple from an operational point of view: timber units can usually be delineated easily by both planners and ground personnel; growth and yield models have been developed for a wide variety of commercial timber species (e.g., ORGANON [Hester et al. 1989], FVS [Wykoff et al. 1982]); and many harvest scheduling techniques have been developed using linear programming (Benninghoff and Ohlander 1978, Bottoms and Bartlett 1975, Kent 1980, Leuschner et al. 1975), integer programming (Hof and Joyce 1992, Jones and Schuster 1985), non-linear programming (Roise 1990), or heuristic approaches (Hoganson and Rose 1984, Murray and Church 1993, Sessions and Sessions 1993, Yoshimoto et al. 1994). The addition of aquatic habitat quality goals to a timber production model usually requires some relaxation or generalization in the variables used for input into these models. For example, scenario 1 required averaging the soil characteristics for each timber unit.

If aquatic habitat quality goals are perceived to be more important than timber goals, and timber goals therefore a by-product of activities which are allowed after meeting aquatic habitat quality goals, then perhaps land units that better describe units of analysis for aquatic habitat quality goals should be used. Operationally this poses several problems; for example, locating these units on the ground may be impossible, and combining pieces of land which contain several ages and species of commercially useful tree resources may be unreasonable from a silvicultural point of view.

Modeling both commodity production goals and wildlife goals may require using a combination of the two definitions of land units. For example, in scenario 3 a combination of timber and soils units is used. Thus the response of sediment production to land management activities may be more precisely measured, as may the calculation of the commodity production goals. However, this produces land units which may be too small to be harvested on their own. Many of these units may have to be grouped together in a single timber sale package to be profitable for both logging contractor and landowner, as well as being considered operationally efficient on spatial and temporal scales. My analysis did not take these considerations into account.

What I have shown is that the definition of land units does significantly affect some of the results (e.g., NPV, timber harvest levels) in this case study. Other factors (i.e., institutional or operational) not quantified in this study may be more important to an organization charged with managing land for multiple goals within the context of ecosystem management or watershed analysis.

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Chapter 6

Conclusions

Protection of wild fish on federal forests has become increasingly important recently in the Pacific Northwest as many fish stocks have become listed as threatened or endangered under the Endangered Species Act. Without assurance of protection, forest management activities on the National Forests, designed to achieve the multiple goals of the recently adopted Forest Plans, cannot go forward. In identifying goals for management of key resources in the Upper Grande Ronde River basin, it has become clear that three fisheries-related goals are important: reduce stream sediment, reduce stream temperatures, and increase the number of pools. This research focused on two of these goals: stream sediment and temperature.

Stream sediment and temperature importance asserted in this research come from three sources: 1) guidance for protection of listed fish from the National Marine Fisheries Service, 2) guidance for protection of aquatic habitat from the Conservation Strategy for the Upper Grande Ronde River (USDA Forest Service 1994), and 3) concurrence from an expert panel comprised of hydrology and fisheries experts familiar with the Upper Grande Ronde River basin. Since goals for reducing sediment and temperature levels are unclear, I chose to develop a land management scheduling model which uses constraints to maintain them at recent levels (although incorporating a reduction over time is possible). In addition, this research focused on two community stability goals (even-flow of timber harvest volume and efficiency). The decision variables included land allocation choices (harvesting and road obliteration) and choices that involve changing management practices (requiring lower tire pressures for log trucks, via central tire inflation devices).

The major challenge of this research was to address the need for a planning model which can produce feasible and efficient solutions to problems with both aquatic habitat goals and commodity production goals. Successfully meeting this challenge represented required an original contribution to forest science. The specific objectives were to 1) develop a mathematical programming technique to produce feasible and efficient solutions to problems with aquatic habitat quality goals, 2) to compare the correlation between equivalent clearcut acres, stream sediment and temperature indices, and timber harvest volume, and 3) to compare the sensitivity of the mathematical programming technique to alternative definitions of land unit decision variables.

Development of the Mathematical Programming Technique

The first objective was to develop a land management scheduling model to produce feasible and efficient solutions to problems with both aquatic habitat goals (stream sediment and temperature) and two commodity production goals (timber production and efficiency). This involved combining core theory (GIS, remote sensing, forest management, economics, and hydrology) and deductive scientific methodology to produce a scheduling model that can produce feasible and efficient land management plans. The hypothesis that was tested was whether the land management scheduling model will produce feasible and efficient forest management plans that incorporate the aquatic goals and their relationships to land management activities. This hypothesis was tested by estimating a global optimum from an asymptotic distribution of best feasible and efficient solutions, and then comparing these solutions against the estimated global optimum.

The land management scheduling model was applied to a subwatershed of the Wallowa-Whitman National Forest in eastern Oregon. In terms of net present value, 80 percent of the solutions were found to be within 10 percent of the estimated global optimum, and all were within 15 percent. In ensuring the compatibility of commodity production and aquatic habitat goals, it was important to consider both timber harvest and road standard choices, since generally speaking harvesting may produce increases in temperature and sediment index levels (as a function of spatial location), while changing road standards can either increase or decrease sediment index levels. Here we have used road standard choices to alleviate the increases in sediment from harvesting activities.

I have demonstrated that a Tabu search model can be developed to simultaneously meet aquatic habitat and commodity production goals with each decision choice. Therefore, I ensure that land management activities are compatible with aquatic habitat goals by always staying in the feasible region of solutions. In developing a plan of forest activities, I feel this approach shows promise for efficiently and explicitly incorporating aquatic habitat goals into forest plans.

Evaluating the Correlation Between Equivalent Clearcut Acres, Stream Sediment and Temperature Indices, and Timber Harvest Levels

A second objective was to evaluate the correlation between a measure of landscape use (ECA), two surrogates of aquatic habitat quality (stream sediment and temperature), and timber harvest volume levels. The hypotheses tested were: 1) that ECA was not correlated with stream sediment and temperature indices, and timber harvest volume levels, 2) that timber harvest volume levels were not correlated with stream sediment and temperature indices, and 3) that the stream sediment index was not correlated with the stream temperature index. A correlation analysis and a bootstrapping technique were used was used to test these hypotheses. If p-values fell below 0.05, we assumed a significant difference existed between two variables.

The results showed that ECA was not significantly correlated with stream sediment index and timber harvest volume levels, however, ECA was found to be significantly negatively correlated with the stream temperature index. In addition, timber harvest levels were not significantly correlated with the stream sediment and temperature indices. No correlation was observed between the stream sediment and stream temperature indices. Our results are limited to situations where only the stream sediment and temperature index levels are constrained in the land management scheduling model. If ECA had been also been constrained, one might expect to find positive correlation among these measures. If ECA was the only goal constrained, one might find no correlation at all among the measures.

We found a wide variation in ECA, stream sediment index, and stream temperature index levels with corresponding timber harvest levels, due to the spatial and temporal arrangement of activities across the landscape. Two of the measures (sediment and temperature) required spatial information, while ECA was a function of residual basal area levels. It may be unreasonable to expect that ECA levels would be positively correlated with stream sediment and temperature index levels. The lack of positive correlation between ECA and stream sediment and temperature index levels observed here is mainly a factor of the functional relationships that are used to estimate each measure, and the assumptions we have made with respect to model specification and problem formulation.

Comparing the Sensitivity of the Model to Alternative Definitions of Land Unit Decision Variables

The final objective of this research was to compare the sensitivity of the mathematical programming technique to alternative definitions of decision variables that are used to describe land units. Three types of decision variables were used to describe land units: 1) vegetation units, 2) soil units, and 3) a combination of vegetation and soil units. For each type of land unit, a number of solutions (samples) were developed. The hypothesis that was tested was that the definition of land unit decision variables does not significantly affect the results (stream sediment and temperature levels, long-term timber harvests, etc.). This hypothesis was tested using a non-parametric technique (the Kolmogorov-Smirnov test) to determine whether there were significant differences in the solution results. If p-values fell below 0.05, we assumed a significant difference existed between two definitions of land units. Results showed that the definition of land units did significantly affect the economic, commodity production, and aquatic habitat results, mainly due to the size of the resulting land units, and assumptions regarding aggregation of data when developing the land units.

The landscape defined by soils units had significantly higher net present values than the other two definitions of land units, because land units were larger, and there were more opportunities for harvesting, as more of the landscape was represented by tree species rather than by meadows. All three definitions of land units showed results which had most of the road obliteration choices being made in the first few periods of the ten-period analysis. Road obliteration levels were higher when using soils units to define the landscape (but not significantly different than the other landscape representations) because the sediment threshold was reached with fewer harvesting choices, therefore more roads were available (unused) to obliterate. The other two land unit scenarios had fewer obliteration options once the sediment threshold was reached, thus relied more heavily on the other option to alleviate sediment concerns (central tire inflation assigned to road segments). However, the landscapes defined by soils units and by a combination of vegetation and soils units may pose several operational challenges.

Summary

Tactical forest management plans derived using spatial-analysis techniques should at least provide feasible alternatives at the watershed scale, a first step in evaluating cumulative effects. The simultaneous evaluation of forest goals with each decision choice is more efficient than relying on posterior evaluations of plan suitability. One such technique was demonstrated here.

The Contribution of This Research to Ecosystem Management

With this research I expected to develop spatial analysis techniques which can be used to form feasible and efficient land management plans in eastern Oregon by laying out a conceptual foundation for incorporating aquatic habitat and commodity production goals into quantitative landscape planning. The Society of American Foresters (SAF 1993) task force on sustaining long-term forest health and productivity list three criteria that forest planning methodologies should possess in order to represent ecosystem management goals: 1) models need to be more probabilistic and less deterministic, 2) models need to represent spatial configurations and operate at a landscape level, and 3) models need to represent ecological processes and desired future conditions. The land management scheduling model developed in this research has no probabilistic device to model such events as fire, but represents spatial configurations, operates on a landscape scale, and represents ecological processes (aquatic habitat quality responses to land management activities).

While I did not explicitly examine the use of a new planning model in a hierarchical context, the results of this research should contribute to the broader theoretical framework of forest planning with the calculation of aquatic habitat goals occurring simultaneously with decision variable choices, thus potentially controlling the spatial and temporal scheduling of land management activities. Forest-wide goals, however, can be passed down to watershed-level analysis, and watershed results can be fed back up to evaluate the feasibility of forest-wide goals.

Forest managers need integrated spatial models to quantitatively portray many resource goals because the goals may act as constraints in developing land management plans, and because spatial and temporal constraints make many forest planning efforts impractical due to the prevalence of piece-meal planning efforts. Aquatic goals may then be used as goals to achieve within the analysis, rather than relying on a posterior measurements. In addition, the results of the research show that a plan can be developed to meet the multiple goals of stream sediment, stream temperature, and timber production, while maximizing net present value.

The land management scheduling model developed here has the potential to incorporate both social values and ecological goals into a single mathematical programming structure. With this type of planning model one could ensure the feasibility of maintaining ecological processes within natural ranges of variability (to the degree that the models are accurate), and plan management regimes over long periods of time while perhaps accommodating human use of the landscape. It is hoped that an integrated model such as this will allow managers and decision-makers to develop policies which maintain or restore ecological integrity to a landscape, while providing for some human uses.

Future Directions for Ensuring the Compatibility and Land Management Activities and Aquatic Habitat Goals in Eastern Oregon

The mathematical programming technique developed here has several areas for improvement, as noted in Chapter 2. In addition, assumptions regarding the aquatic habitat goals can be varied to estimate the implications of different management assumptions. Two areas of research not covered by this dissertation, yet important to the management of federal land in eastern Oregon, are evaluating the impacts of 1) livestock grazing, and 2) fire (natural and prescribed) on aquatic habitat. Future efforts for ensuring the compatibility of land management activities and aquatic habitat goals may want to incorporate some or all of these improvements.

Model Improvements and Variations in Goals

Several areas for improvement in the mathematical programming technique were identified in Chapter 2, and include: 1) generate a starting solution which schedules the best silvicultural management regimes / harvest choices (in terms of net present value) first, rather than using a random starting solution, 2) allow more road management choices, including the reconstruction of obliterated roads, 3) allow the obliteration of roads which are (in the operation of the model) considered to be used, rather than considering only unused roads for obliteration, and 4) allow the assumption that obliterated roads can be revegetated to tree species, possibly to alleviate ECA levels.

The goals for sediment and temperature that I identified from the literature were to *reduce* these levels over time. Since there was some uncertainty in the amount of reduction required for each goal over time, I developed a model to *maintain* recent levels of each goal. The model could be adjusted to incorporate some sort of reduction in sediment and temperature levels over time, and to locate a solution to provide the maximum amount of reduction in these goals. In future runs of the model one might also adjust the constraints to include ECA (by itself or in conjunction with sediment and temperature levels), and one might also want to assume that obliterated roads can be revegetated with tree species, and therefore be used to reduce ECA levels over time.

Finally, incorporating a model to measure the amount of pools produced (or lost) over space and time as a result of land management activities is needed. Although I did not identify a pool model from the literature which included the functional relationships required to incorporate such a model into a land management scheduling model, one may be able to make various assumptions regarding these relationships. For example, one could include decision choices which involve directional felling of trees into the stream system, from units adjacent to the stream system, and then assume some stochastic (or deterministic) relationships regarding pool formation (and subsequent loss) and movement.

Livestock Grazing

Livestock grazing can degrade riparian environments and fish populations (Meehan 1991). Streambank vegetation and stability generally decline when livestock concentrate near water. Erosion from livestock-compacted soils, and the breakdown of streambanks, causes streams to become wider but more shallow (Meehan 1991). The effects of livestock grazing have been extensively studied in eastern Oregon. Bohn and Buckhouse (1985) studied the recovery of riparian areas after grazing, and found that rest-rotation grazing strategies led to recovery, while deferred rotation and season-long grazing strategies did not lead to recovery. Short-rotation, high intensity grazing in September probably had no effect on recovery. Recovery was defined as an increase in infiltration and decreases in compaction and sedimentation. Bohn and Buckhouse (1985) also state that these results hold regardless of big game accessibility.

Gillen et al. (1985) studied the movement of cattle due to various grazing regimes. In early grazing seasons, cattle were found to exert less occupancy in riparian areas than in late grazing or season-long regimes. Early and continuous regimes, however, were found to be most detrimental to meadow plants. Cattle were found to be attracted to riparian areas due to large amounts of nutritious palatable herbage, moderate slope gradients, reliable water supply, and a more favorable microclimate.

Kauffman and Krueger (1984) summarize the effects of cattle grazing on stream environments. Four components of stream environments are affected by grazing: stream channel morphology, shape of the water column, quality of the water column, and structure of the soil portion of the streambank. Morphology changes include widening and shallowing of the streambed, and gradual channel trenching or braiding. Shape and quality effects include increased water temperatures, nutrients, sediment, and bacterial counts. Sloughing of the streambanks and sediment are the major effects of the changes in Streambank structure. Kauffman and Krueger (1984) suggest several rehabilitation practices, including exclusion, alternative grazing schemes, changes in the type of animals grazed, in-stream structures, and basic range management practices (salting, alternative water sources, fencing, etc.).

The functional relationships between livestock grazing and stream sediment and temperature index levels have not been formally formulated, thus to model these processes, one would have to make several general assumptions. For example, one could assume: 1) that grazing produces soil and vegetative cover situations similar to certain harvesting systems, then utilize an approach to estimating the sediment impact that is similar to estimating impacts from harvesting activities, and 2) that grazing reduces stream shading levels, and perhaps widens stream channels over time, then utilize these relationships in the stream temperature estimation model for affected stream reaches.

Natural and Prescribed Fire

Almost universally, burn intensity, whether a prescribed fire or a wildfire, has a major impact on the yield of sediment from upland areas (Campbell et al. 1977, Shahlaee et al. 1991, Robichaud and Waldrop 1994). Lower-intensity burns leave some of the original forest floor intact, producing lower sediment yields. After fire, sediment yields can increase due to increased overland flow due to reduced infiltration capacity, and mass soil movement (Helvey 1980), exposed soil and decreased canopy protection, and an induced water-repellant layer in sandier soils (Campbell et al. 1977). Prescribed fires have been used, however, to eliminate Douglas-fir regeneration in ponderosa pine stands

(Kalabokidis and Wakimoto 1992), possibly contributing to a return to favorable forest health conditions.

To model fire effects on stream sediment and temperature levels, we could take similar approaches as discussed above regarding the effects of cattle grazing. Here, however, fire effects are not predictable, unless of course one is modeling prescribed fire. So to model the effects of wildfires, one would have to assume a that it is a stochastic process. In addition, we would have to consider the role of fire on a larger landscape, as our case study watershed is certainly smaller than the upper range of the area encompassed by natural variability of wildfires. In either case functional relationships could possibly be developed to estimate the effects on stream sediment and temperature levels; with fire probability based on vegetative characteristics, topographic characteristics, and assumptions regarding weather patterns.

At a minimum, one would need to address the potential for large destructive fires and their effects on aquatic habitat, and the resulting forest structure and composition under different management regimes. Fuel condition for each forest type, and weather patterns could be incorporated into a planning model which uses stochastic processes to estimate fire behavior. Land management activities can be used to: 1) alter the fuel composition of a landscape, and 2) create fuel breaks. The goals would then be to achieve some type of forest structure over time while meeting aquatic habitat goals and achieve some level of commodity production.

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APPENDIX

Model Specification

The land management scheduling model incorporates ASCII tables, derived from a geographic information system (Figure A-1), with goals developed for aquatic habitat maintenance (or restoration) and commodity production, to produce a schedule of activities over a 100-year planning horizon. The model accesses several files, and processes data in several subroutines of a Quick BASIC program. Below I describe the file structure, then the structure of the model itself, and finally describe a few variables that are not intuitively obvious. Figure A-2 illustrates a simplified flow of the Tabu search process. A copy of the program itself is located on the attached diskette.

File Structure:

The following four files are required in the operation of the Tabu search algorithm. Each line of each file includes all of the variables listed for that file, and they must appear in the order of the list. See discussion of variables for specifics on the range of values.

UNITS.PRN

This is the basic ASCII data file required for units (polygons).

Unit number (numeric)
Area (acres)
Erosion hazard rating (0-100)
Potential harvest system - logging system (1-8)
Geologic erosion factor (1-8)
Ground slope percent (0-100)
Tree species (1-6)
Basal area (square feet per acre)
Age of dominant trees
Volume (merchantable MBF per acre)
Distance to nearest USFS Class I-IV stream (feet)
Riparian (0 = not in riparian zone, 1 = in riparian zone)
Average K factor for soils (0-100)

ROADS.PRN

This is the basic ASCII data file required for road segments. This file needs to start with from-node 0 (mill), after which the order does not matter.

From-node (numeric)
To-node (numeric)
Road standard (0-3)
Length (feet)
Geologic erosion factor (0-8)

Figure A-1. Operations flow of the geographic information systems processes used to create input files.

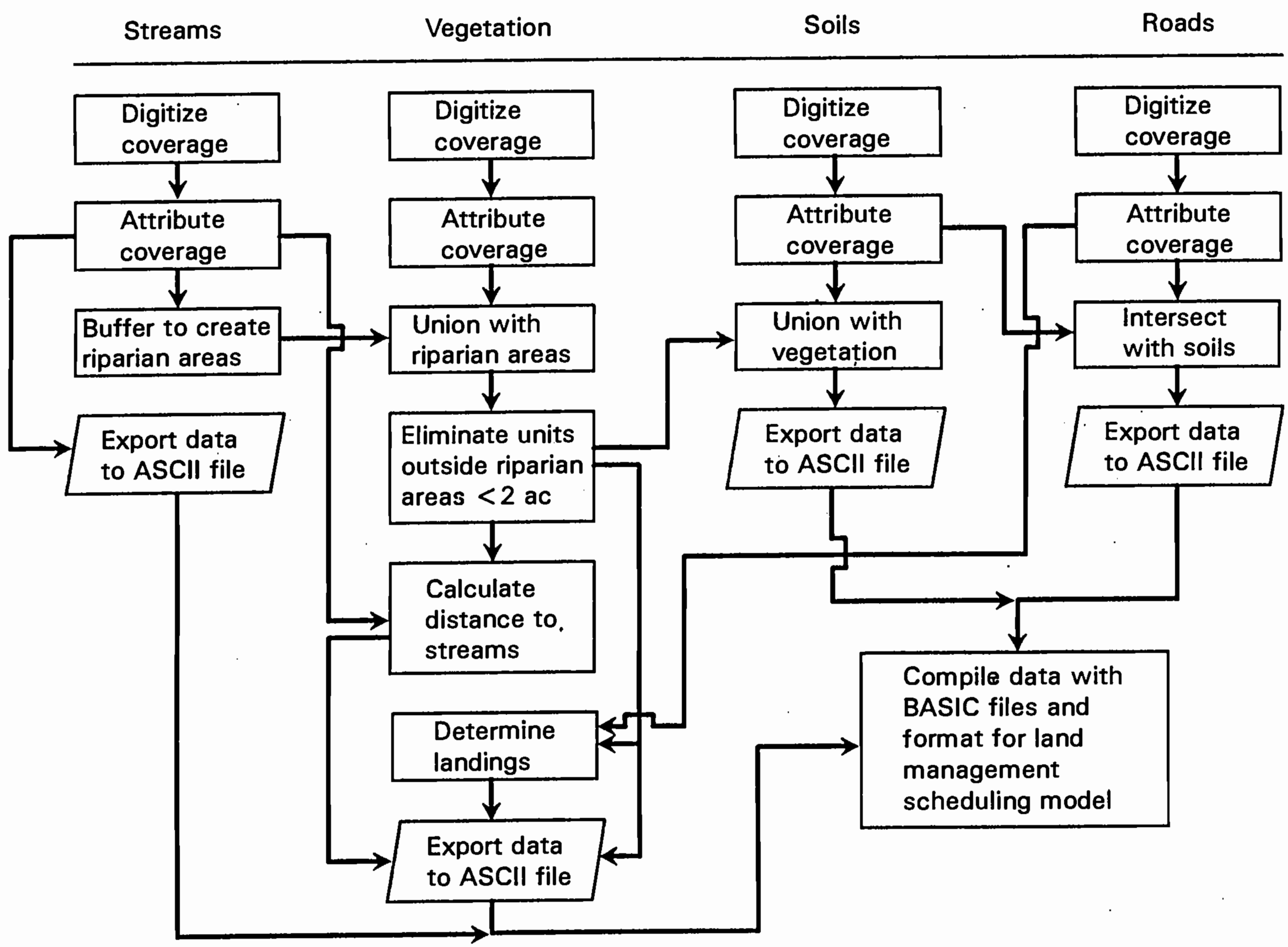
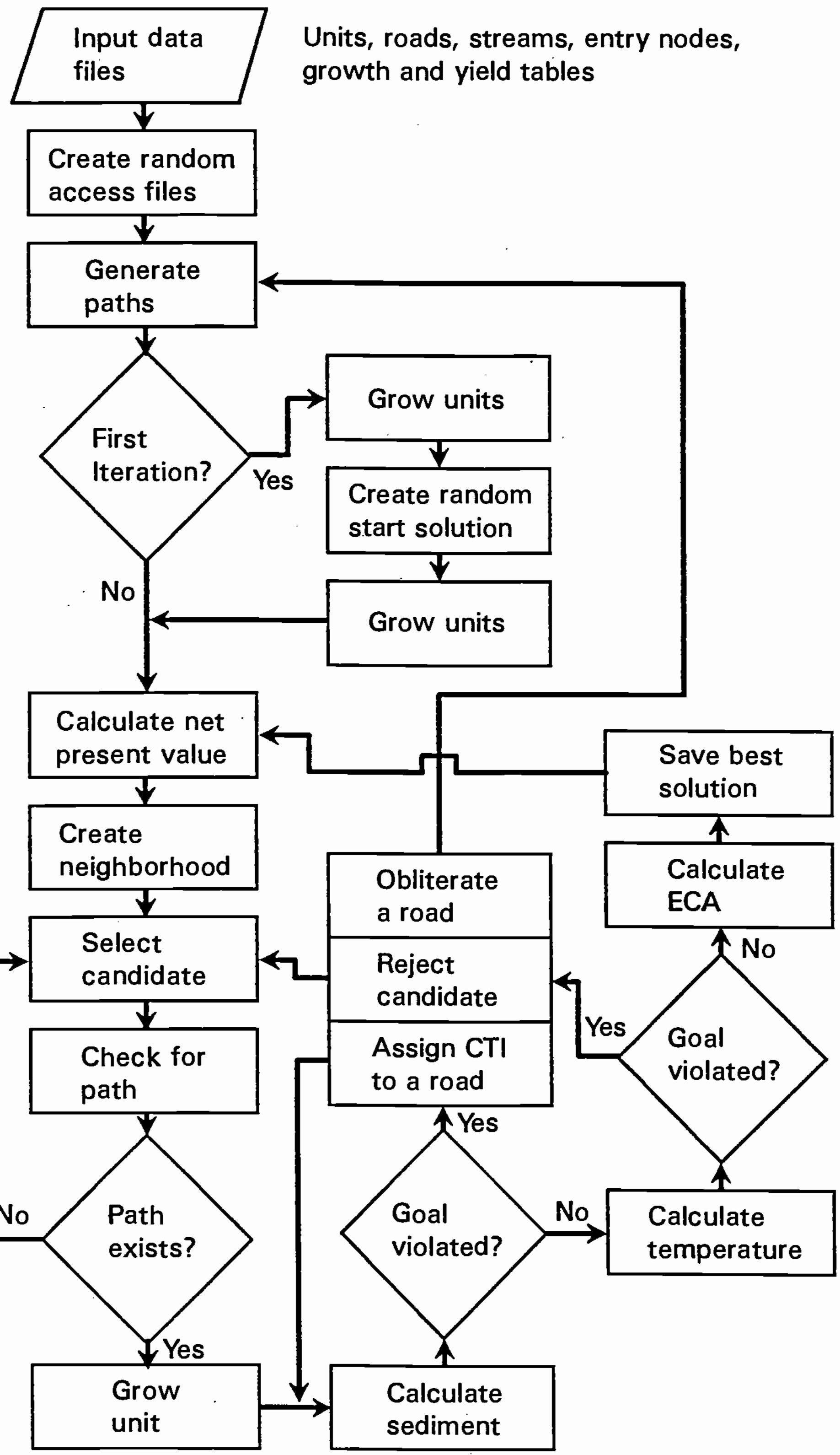


Figure A-2. Operations flow of the land management scheduling model.



Distance to nearest USFS Class I-IV stream (feet)
In watershed? (0 = no, 1 = yes)
Average K factor for soils (0-100)
Ground slope percent (0-100)

STREAMS.PRN

This is the basic ASCII data file required for streams. The last upstream - downstream node combination in the file should be the one for which (at the downstream node), temperature is to be evaluated.

Upstream node (numeric)
Downstream node (numeric)
Stream class (USFS I-V)
Length (feet)
Orientation (-90 to +90 degrees)
Polygon number
Stream reach slope percent (0-100)
Tree channel distance (feet)
Shade density (0-100)
Tree overhang percent (0-100)

ENTRY.PRN

This is the basic ASCII data file required to specify entry nodes for units into the road network, by harvest system - logging system combination. Each unit must have an entry node specified for all 8 combinations, whether or not they are to be used.

Unit number (numeric)
Harvest system - logging system (1-8)
Entry node in road network (numeric)

Growth and yield files

ASCII Growth and yield files must be specified for all 6 tree species.

Age (10-year intervals, from age 0 to 300)
Average number of trees per acre
Average basal area per acre (square feet)
Basal area growth rate (per decade)
Merchantable volume (MBF)
Merchantable volume growth rate (per decade)
Average height of dominant trees (feet)
Tree height growth rate (per decade)

The remaining files are created during the operation of the Tabu search algorithm. Each line of a file contains the variables listed for that file.

BA.PRN

A random access file that contains the average basal area for each unit by period. Each row corresponds to a unit number.

Basal area (square feet per acre) by period (1-10)

BESTCUT.PRN

An ASCII file that contains the volume harvested by period for the best solution found during the Tabu search process.

Unit number (numeric)
Tree species (0-6)
Volume harvested (total MBF) by period (1-10)

BESTHARV.PRN

An ASCII file that contains the unit harvest choices by period for the best solution found during the Tabu search process.

Unit number (numeric)
Silvicultural management regime (0-3)
Harvest system - logging system (0-8) by period (1-10)

BESTROAD.PRN

An ASCII file that contains the road standards by period for the best solution found during the Tabu search process.

From-node (numeric)
To-node (numeric)
Length (feet)
Road standard (0-3) by period (1-10)

CANDIDAT.PRN

A single line of data in an ASCII file describing a candidate unit choice.

Unit number (numeric)
Silvicultural management regime (0-3)
Harvest system - logging system (0-8) by period (0-10)

CUT.PRN	A random access file that contains the merchantable volume harvested from each unit by period. Each row corresponds to a unit number. Tree species (1-6) Volume harvested by period (1-10)
DATA.PRN	An ASCII file that contains numeric data (sediment levels, temperature level, ECA levels and volume harvested) by iteration of the Tabu search process.
DISTANCE.PRN	A random access file that contains the distance and sediment contribution (by period) for each road segment. From-node (numeric) To-node (numeric) Distance (feet) Sediment contribution (tons/MBF) by period (1-10)
DUMP.PRN	A temporary ASCII storage file
ENTRYRND.PRN	A random access file that contains the entry nodes for each unit by harvest system - logging system. Unit number (numeric) Harvest system - logging system (1-8) Entry node (numeric)
HARVEST.PRN	A random access file that contains the harvest system - logging system choices by period for each unit. Each row corresponds to a unit number. Harvest system - logging system (0-8) by period (1-10)

HAULCOST.PRN	A random access file that contains the current discounted haul costs incurred by the management regime for each unit. Each row corresponds to a unit number. Haul cost (NPV)
HEIGHT.PRN	A random access file that contains the average tree heights for dominant trees in each unit, by period. Each row corresponds to a unit number. Average tree height (feet) by period (1-10)
INSOL.PRN	A random access file that contains data regarding the current status of each unit in the solution. Each row in the file corresponds to a unit number. Period that management regime starts (0-10) Silvicultural management regime (0-3) Harvest system - logging system (0-8) used first
LINKCOST.PRN	A random access file that contains fixed and variable costs for each road segment by period. From-node (numeric) To-node (numeric) Distance (feet) Fixed cost ($/mile) by period (1-10) Variable cost ($/MBF) by period (1-10)
MNTCOST.PRN	A random access file that contains the fixed and variable costs for each path in PATHS.PRN by period. Start-node (mill, numeric) Terminus (all nodes in the network, numeric) Period (1-10) Fixed cost ($/mile) for path Variable cost ($/MBF) for path

NOCUTAGE.PRN

A random access file that contains the average age of dominant trees in the unit, by period, assuming each unit will never be harvested. Each row in the file corresponds to a unit number.

Unit age by period (0-10)

NOCUTVOL.PRN

A random access file that contains total merchantable volume in the unit, by period, assuming each unit will never be harvested. Each row in the file corresponds to a unit number.

Volume (total MBF), by period (0-10)

OUTPUT.PRN

An ASCII file that contains descriptive data regarding the flow of the program, for each iteration.

PATHS.PRN

An ASCII file that contains the paths from each node in the road network to the mill node (0), by period (10).

Start-node (mill location, numeric)
Terminus (any other node in the network, numeric)
Period (1-10)
Sediment contribution from path (tons/MBF)
Number of nodes in path (n)
Length of path (feet)
$Node_1$ ... $Node_n$

REGIMES.PRN

An ASCII file that contains the potential management regime for each candidate choice in the neighborhood.

Unit number (numeric)
Silvicultural management regime (0-3)
Period (0-10)
Harvest system - logging system (0-8) by period (1-10)

REVENUE.PRN	A random access file that contains the current revenue generated by each unit. Each row corresponds to a unit number. Revenue (NPV)
ROADTYPE.PRN	A random access file containing the road standards for each road segment by period. Each row represents a road segment as described in order in ROADS.PRN. Road standard (0-3) by period (1-10)
ROADUSE.PRN	A random access file containing the total merchantable volume (MBF) transported over each road segment, by period. Each row represents a road segment described in order in ROADS.PRN. MBF by period (1-10)
SEDRND.PRN	A random access file that contains the variable sediment contribution for each path. Start-node (mill location, numeric) Terminus (all nodes in the network, numeric) Period (1-10) Sediment contribution (tons/MBF) for path
TABUROAD.PRN	A random access file containing the Tabu state (0-50) for each road segment. Each row in the file represents a road segment as described in order in ROADS.PRN. Tabu state (0-50)
TABUUNIT.PRN	A random access file containing the Tabu state (0-50) for each unit. Each row in the file corresponds to a unit number. Tabu state (0-50)

TEMP.PRN	A random access file to temporarily store harvest choices. Uses the same file format as HARVEST.PRN
TEMPBA.PRN	An ASCII file that contains one line of data corresponding to the average basal area of the candidate unit by period, given the potential silvicultural management regime the candidate will utilize. Unit number (numeric) Basal area (square feet per acre) by period (0-10)
TEMPCUT.PRN	An ASCII file that contains one line of data corresponding to the merchantable volume harvested from the candidate unit by period, given the potential silvicultural management regime the candidate will utilize. Unit number (numeric) Tree species (1-6) Volume harvested by period (0-10)
TEMPHT.PRN	An ASCII file that contains one line of data corresponding to the average tree height of dominant tree in the candidate unit by period, given the potential silvicultural management regime the candidate will utilize. Unit number (numeric) Tree height (feet) by period (0-10)
TEMPPATH.PRN	A temporary ASCII file storing the paths. Same file structure as PATHS.PRN.
UNITNPV.PRN	An ASCII file that contains the potential NPV for unit choices is listed, and from which a candidate will be selected. Unit number (numeric) Period (0-10) that management regime starts Silvicultural management regime (0-3) NPV for using harvest system - logging system (8)

Model Structure:

Main Program - Declares subroutines, determines number of units and roads, declares structure of random access files, identifies main program structure, and writes output to files.

Input:	UNITS.PRN	Output:	OUTPUT.PRN
	ROADS.PRN		DATA.PRN
	ROADTYPE.PRN		
	TABUROAD.PRN		
	ROADUSE.PRN		

Subroutines

ALTNEIGH - Alters the neighborhood for rejected unit choice candidates.

Input:	UNITNPV.PRN	Output:	UNITNPV.PRN

ALTTABUR - Alters the Tabu file for roads. Tabu state for obliterated roads is 50 moves, Tabu state for CTI roads is 5 moves.

Input:	TABUROAD.PRN	Output:	TABUROAD.PRN

ALTTABUU - Alters the Tabu state for units. Tabu state is 50 moves.

Input:	TABUUNIT.PRN	Output:	TABUUNIT.PRN
	INSOL.PRN		

CHECKPATH - Checks PATHS.PRN to see whether a path exists for a candidate unit choice over the entire management regime for that choice.

Input:	CANDIDAT.PRN	Output:	Variable indicating existence of path
	MNTCOST.PRN		
	ENTRYRND.PRN		

DIJKSTRA - Calculates the shortest path from a mill node to all other nodes in the road network, based on distance. Calculates the variable and fixed costs for each road, and calculates the variable sediment contribution (tons/MBF) for each path.

Input:	ROADS.PRN	Output:	PATHS.PRN
	ROADTYPE.PRN		TEMPPATH.PRN
			LINKCOST.PRN
			MNTCOST.PRN
			SEDRND.PRN
			DISTANCE.PRN

ECA - Calculates the equivalent clearcut acres from roads and units.

Input:	UNITS.PRN	Output:	ECA (period)
	ROADS.PRN		
	ROADTYPE.PRN		
	BA.PRN		

ECON - Calculates the net present value of the management plan. Writes to file the current revenue per unit and haul cost per unit for all units in the solution.

Input:	UNITS.PRN	Output:	REVENUE.PRN
	ROADS.PRN		HAULCOST.PRN
	HARVEST.PRN		
	ROADTYPE.PRN		
	CUT.PRN		
	MNTCOST.PRN		
	ENTRYRND.PRN		

FLIP - Flips the candidate unit's data into the main files to be used in other algorithms in assessing sediment, temperature, etc. Stores the old data for the candidate unit choice in temporary files.

Input:	HARVEST.PRN	Output:	HARVEST.PRN
	BA.PRN		BA.PRN
	HEIGHT.PRN		HEIGHT.PRN
	CUT.PRN		CUT.PRN
	CANDIDAT.PRN		CANDIDAT.PRN
	TEMPBA.PRN		TEMPBA.PRN
	TEMPHT.PRN		TEMPHT.PRN
	TEMPCUT.PRN		TEMPCUT.PRN

FLIPBACK - If the candidate unit choice is rejected, the old data for that unit is flipped back into the main files.

Input:	CANDIDAT.PRN	Output:	HARVEST.PRN
	HARVEST.PRN		BA.PRN
	BA.PRN		HEIGHT.PRN
	HEIGHT.PRN		CUT.PRN
	CUT.PRN		
	TEMPBA.PRN		
	TEMPHT.PRN		
	TEMPCUT.PRN		

GROWTH - Grows the ages, heights, basal area, volume, and calculates the harvested volume for all units in the analysis area. At the beginning of the program, it calculates the age and volume over time for each unit under the assumption that the unit will never be harvested. These "no cut" files are used in the neighborhood algorithm to assess management alternatives.

Input:		Output:	
	UNITS.PRN		HEIGHT.PRN
	HARVEST.PRN		BA.PRN
	growth and yield files		CUT.PRN
			NOCUTAGE.PRN
			NOCUTVOL.PRN

INITIAL - Generates random access files from the base ASCII files.

Input:		Output:	
	UNITS.PRN		HARVEST.PRN
	ROADS.PRN		TABUUNIT.PRN
	growth and yield files		ROADTYPE.PRN
			TABUROAD.PRN
			ROADUSE.PRN
			DISTANCE.PRN
			LNKCOST.PRN
			growth files (random access)

MINGROWTH - Essentially the same as GROWTH, except it only performs operations on the candidate unit choice.

Input:		Output:	
	UNITS.PRN		TEMPBA.PRN
	CANDIDAT.PRN		TEMPHT.PRN
	growth and yield files		TEMPCUT.PRN

NEIGHBOR - Calculates the neighborhood for unit choices, and writes the candidate unit choices and potential management regimes to files.

Input:		Output:	
	UNITS.PRN		REGIMES.PRN
	CUT.PRN		UNITNPV.PRN
	NOCUTVOL.PRN		
	NOCUTAGE.PRN		
	REVENUE.PRN		
	HAULCOST.PRN		
	MNTCOST.PRN		
	ENTRYRND.PRN		
	INSOL.PRN		
	growth and yield files		

R1R4 - Uses the Region 1 / Region 4 sediment model (USDA Forest Service 1981) to estimate the effects of a management plan of activities on sediment yield for an analysis area.

Input:		Output:	
	UNITS.PRN		Sediment (Period)
	ROADS.PRN		
	HARVEST.PRN		
	ROADTYPE.PRN		

RANDOMSTART - Sets the initial, randomly-defined solution, which includes harvesting 5% of the analysis area in the first period using any harvest prescription (clearcut, thinning, etc.), and assigns a management regime for the remaining periods to those units being harvested.

Input:		Output:	
	UNITS.PRN		HARVEST.PRN
	ENTRY.PRN		TABUUNIT.PRN
			ENTRYRND.PRN
			INSOL.PRN

ROADCHANGE - Changes ROADTYPE.PRN after a road standard has been chosen to be changed.

Input:		Output:	
	ROADS.PRN		ROADTYPE.PRN

ROADUSE - Calculates the usage (MBF) for each road segment, as each unit is brought into, or taken out of, the solution. Only checks the road segments associated with the path for a particular unit, and only during the period(s) of harvest.

Input:		Output:	
	PATHS.PRN		ROADUSE.PRN
	ENTRYRND.PRN		

SAVEBEST - Saves the best solution to ASCII files

Input:		Output:	
	ROADS.PRN		BESTCUT.PRN
	HARVEST.PRN		BESTHARV.PRN
	ROADTYPE.PRN		BESTROAD.PRN
	CUT.PRN		

SHADOW - Uses the SHADOW (USDA Forest Service 1993) procedures to calculate the effects of management activities on stream temperature.

Input:	STREAMS.PRN HARVEST.PRN HEIGHT.PRN	Output:	Temperature (period)

TABUTESTR - Determines whether road choices are Tabu. No aspiration criteria.

Input:	TABUROAD.PRN	Output:	Variable defining Tabu state

TABUTESTU - Determines whether unit choices are Tabu. Tests aspiration criteria if a unit choice is Tabu.

Input:	TABUUNIT.PRN CANDIDAT.PRN	Output:	Variable defining Tabu state

UNITCHOICE - Chooses a unit / harvest system - logging system / silvicultural management regime from the neighborhood to become a candidate unit choice.

Input:	REGIMES.PRN UNITNPV.PRN	Output:	CANDIDAT.PRN

Model Variables:

The following is a brief description of data required for variables that are not obvious upon first inspection.

Average K factor: Required by the R1R4 sediment model, used here as a surrogate for the texture of erodable material. Range 0-100.

Erosion hazard rating: Required by the R1R4 sediment model, a debris avalanch, debris flow, or slump eathflow hazard rating. Range 0-100.

Geologic erosion factor: Required by the R1R4 sediment model, and based on the underlying rock type. Range 0-1.05.

1. Acid igneous	1.00
2. Basic igneous	0.42
3. Serpentine	0.35
4. Misc. metamorphic	0.39
5. Schist	0.75
6. Hard sediments	0.52

7. Soft sediments 0.66
8. Alluvium 1.05

Harvest system - logging system combinations: Range 1-8.

1. Clearcut - ground-based
2. Clearcut - cable (jammer)
3. Clearcut - skyline
4. Clearcut - helicopter
5. Partial cut - ground-based
6. Partial cut - cable (jammer)
7. Partial cut - skyline
8. Partial cut - helicopter

Orientation: Required by the SHADOW stream temperature model. Range -90 to +90. This is the orientation of each stream segment. See SHADOW (USDA Forest Service 1993) for further description and calculation of this variable.

Shade density. Required by the SHADOW stream temperature model. Range 0-100. It relates to the quality of a shadow cast by the shading vegetation. See SHADOW (USDA Forest Service 1993) manual for further description and calculation of this variable.

Tree channel distance: Required by the SHADOW stream temperature model. This is the distance from the base of riparian tree vegetation to the edge of the stream channel, in feet. See SHADOW (USDA Forest Service 1993) manual for further description and calculation of this variable.

Tree overhang percent: Required by the SHADOW stream temperature model. It is the percent of tree shading over a stream reach, based on the type of overhanging vegetation, the density or stocking, and stream channel width. See SHADOW (USDA Forest Service 1993) manual for further description and calculation of this variable.

Tree (or vegetation) species: Range 1-6.

1. Meadow
2. Grand fir
3. Lodgepole pine
4. Subalpine fir
5. Douglas-fir
6. Ponderosa pine