Integrating Spatial Aquatic Habitat Goals Into A Planning Process Considering Harvesting System And Road Management Strategies

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ABSTRACT - We developed a scheduling model (LMSCHED) that incorporates stream sediment and stream temperature goals into a forest planning process, allowing one to both evaluate the levels of these measures of aquatic habitat, and to set constraints regarding their upper limit. The scheduling model uses tabu search to identify feasible forest plans with respect to goals and constraints that are specified. Both land management units and road segments are represented by a set of decision variables.

Management units can be assigned a "no-cut" management options as well as harvesting options (both clearcut and partial cut) associated with three logging systems: ground-based, skyline, and helicopter. Road segments can be assigned to their current condition, re-assigned to a paved condition (if not already paved), re-assigned to an obliterated condition, or to a condition where central tire inflation is required. The goal of the scheduling process is to try to identify feasible forest plans that produce the highest net present value without violating constraints related to the aquatic habitat goals. The scheduling model is currently undergoing some revisions, and we discuss how it may be enhanced to address a broader array of logging systems and to attract a wider audience of users.

Keywords: forest planning, heuristic, tabu search, stream sediment, stream temperature

INTRODUCTION

Protection for wild fish stocks has become an important management issue in the Pacific Northwest in the past decade. Fish habitat has been identified as one of the most visible and manageable of the variables that influence the status of certain stock of anadromous salmon, thus much attention has been focused on the development of habitat best suited to these species. Other resource goals are important as well, and we hope not to diminish their importance by excluding them from this analysis.

Three main goals could be used as surrogates for aquatic habitat quality are stream sediment, stream temperature, and pools (Bettinger et al. 1998b). Stream sediment levels are a function of soil type, management activity, road condition and use, and the distance an activity or road is located from the stream system. Stream temperature levels are primarily a function of the quality of riparian vegetation. Management activities upslope from the stream system generally do not influence temperature levels. Pools can be affected by management activities which promote or limit the delivery of large woody debris to the stream system. The spatial location of management activities is therefore quite important in estimating the response of these three measure of aquatic habitat quality. If these goals are deemed important enough that management plans should be developed with some form of their functional relationship(s) in either the objective function or constraints, models to measure their response to management activities can be identified and incorporated into a planning process. The result is that a set of management activities can be developed into a plan of action that is compatible with outcomes desired.

METHODS

We first discuss the planning problem we are addressing, in a general sense. Then we detail the mathematical representation of the planning problem, including the functional relationships that describe how the aquatic goals are being represented. A brief description of tabu search is them provided. Finally, some results from a watershed in eastern Oregon are presented to illustrate outcomes of the planning process. And, a discussion of how the model may be enhanced to address a broader array of logging systems, and to attract a wider audience of users, is provided.

The planning problem we are attempting to solve can be succinctly described as one that maximizes an economic outcome subject to commodity production and environmental constraints:

maximize: net present value

subject to: an even flow of timber volume per time period

an upper limit on stream sediment levels

an upper limit on stream temperature levels

The objective function for this forest planning problem was designed to sum the net revenue from harvesting activities, less the costs of road maintenance associated with the harvesting activities, and the costs of changing road standards.

Maximize:

$$\sum_{k=1}^{n}\sum_{l=1}^{m} r_{k,l}\,\phi_{k,l} - \sum_{k=1}^{n}\sum_{l=1}^{m} c_{k,l}^{m}\,\phi_{k,l} - \sum_{u=1}^{y}\sum_{v=1}^{x} c_{u,v}^{s}\,\varpi_{u,v}$$

Where:

k = a management unit

n = total number of management units

l = silvicultural management regime: a particular arrangement of treatments and logging systems

m = total number of silvicultural management regimes

$r_{k,l}$ = present value of harvest revenue for silvicultural regime l applied to management unit k

$\phi_{k,l}$ = portion of unit *k* assigned to silvicultural management regime *l*

$c^{m}_{k,l}$ = present value of road maintenance costs associated with management unit *k*, silvicultural regime *l*.

u = road segment

y = total number of road segments

v = road management regime

x = total number of road management regimes

$c^{s}_{u,v}$ = present value of costs for road standard changes associated with road segment *u* and road management regime *v*

$\varpi_{u,v}$ = portion of road segment *u* assigned to road management regime *v*

In addition,

$$\sum_{l=1}^{m} \phi_{k,l} = 1 \qquad \forall k$$

$$\sum_{v=1}^{x} \varpi_{u,v} = 1 \qquad \forall u$$

The planning horizon is 100 years long, and there are 10 10-year planning periods in which activities are scheduled. We assume here that the variables $\phi_{k,l}$ and $\varpi_{u,v}$ are integer variables, and can take on the values 0 or 1. Therefore, when a treatment is assigned to a management unit or road segment, it is assumed to have been assigned to the entire management unit or road segment. Since the fixed and variable road costs depend on the road standards employed, the problem takes on a non-linear form.

SHORTEST PATHS IN THE ROAD NETWORK

LMSCHED tracks costs related to the maintenance of roads associated with transporting timber to a mill location. We determine the shortest path from every management unit to a mill location in every time period. Since roads have the possibility of being obliterated during any time period, the path from a management unit to the mill location may not be the same from one period to the next. Dykstra's algorithm (Smith 1982) was used to calculate the shortest paths, based on distance to the mill location. The algorithm determines one of two attributes for each management unit: either the shortest path from the management unit to the mill location, or that there is no path from the management unit to the mill location. Paths do not have to physically touch the management unit. For example, we specified several helicopter landing locations to which timber can be flown from each management unit. Thus the path from the helicopter landing to the mill location may remain feasible while the other paths (facilitating ground-based or skyline yarding) may become infeasible for a specific management unit.

Dykstra's algorithm is formally described by Smith (1982) in three steps:

Step 0: Assign a temporary state *l(I)* = ∞ to all nodes *I* ≠ *s* [*l(I)* is an array of node values]. Set *l(s)* = 0 and set *p* = *s* (*s* is the mill location, and *p* is the last node in the network given a permanent state). Change *l(s)* to a permanent state.

Step 1: For each node *I* with a temporary state assigned to it, redefine *l(I)* to be the smaller of *l(I)* or *l(p)* + *d(p,i)* [*d(p,i)* is an array of distances from node *p* to node *I*]. Find the temporary node *I* with the smallest value and make its status permanent.

Step 2: If any node has a state that is still temporary, repeat Step 1. Otherwise, all shortest paths from all nodes (*I* ≠ *s*) to *s* have been established.

EVEN-FLOW CONSTRAINT

Of the various methods that can be employed to guide planning processes to an even flow of timber volume, we use a form of the following method, which attempts to achieve a non-declining even-flow.

$$\sum_{k=1}^{n}\sum_{l=1}^{m} V_{k,l,a}\,\phi_{k,l} \le \sum_{k=1}^{n}\sum_{l=1}^{m} V_{k,l,a+1}\,\phi_{k,l} \qquad \forall\, a; a = 1, 2, b-1$$

Where:

$V_{k,l,a}$ = timber volume from management unit *k*, managed under silvicultural regime *l*, during time period *a*

a = a single time period

b = total number of time periods

Our implementation can be considered a relaxed version of this formulation. The difficulty in this scheduling process is that when a silvicultural management regime is assigned to a management unit, it may have associated with it several thinnings that contribute timber volume to time periods other than a clearcut time period. To help avoid this scheduling process, we identify the time period with the lowest total timber harvest volume, and only schedule units with initial harvests in that time period, until that time period no longer is the time period with the lowest total timber harvest volume. The intent of the goal, however, is to try to achieve the most even flow of timber volume for all ten time periods.

STREAM SEDIMENT CONSTRAINT

The stream sediment model was developed by the USDA Forest Service (1981), and it was selected because it was an established model and provided the best documentation of the models considered. The units used to describe the delivery of sediment to a stream system are tons km^{-2} yr^{-1}. The one aspect of this model that was not pursued was the sediment generated from mass erosion, since it was not a major problem in the region of Oregon we considered. We altered the sediment model to indicate erosion generated by log truck traffic (0.00297 tons m^{-3} (volume transported) km^{-1}) based on an extreme case from research closest to our region that presented the most complete sediment delivery information (Reid and Dunn 1984). In addition, we reduced the amount of sediment generated via log truck traffic by 60% on rock roads that were assigned central tire inflation (CTI) use, based on conservative results from Foltz (1994).

The levels of sediment produced are routed to the most downstream reach in a watershed, and presented as a single number for the entire watershed. These results should be considered an index of sediment levels, because while the sediment model is widely used, it has not been validated in eastern Oregon using empirical data. Results have shown, however, that the sediment levels are reasonable, and within bounds of those measured in other nearby regions (Bettinger et al. 1998b). In fact, no sediment models have been validated for eastern Oregon. The sediment goal can be described with the following mathematical notation:

$$\sum_{k=1}^{n} natu_{k,a} + \sum_{k=1}^{n}\sum_{l=1}^{m} sedu_{k,l,a}\,\phi_{k,l} + \sum_{u=1}^{y}\sum_{v=1}^{x} sedr_{u,v,a} + \sum_{u=1}^{y}\sum_{v=1}^{x} traffic_{u,v,a}\,\varpi_{u,v} \leq \text{sediment goal}_{\text{a}} \;\forall a$$

Where:

$natu_{k,a}$ = *f* (area of a management unit, and erosion hazard rating). this function represents natural erosion arising from management units.

$sedu_{k,l,a}$ = *f* (harvesting system, logging systems, geologic erosion factor, natural sediment rate, ground slope, slope shape, surface roughness, ground cover, texture of erodible material, water availability, and distance to stream for management unit *k*, managed under silvicultural regime *l*, during time period *a*).

$sedr_{u,v,a}$ = *f* (road standard, road width, road length, slope shape, surface roughness, slope gradient, ground cover, texture of erodible material, water availability, and distance to stream for road segment *u*, with road management option *v*, during time period *a*)

$traffic_{u,v,a}$ = *f* (volume transported across road segment, possible reduction factor for CTI use, for road segment *u*, with road management option *v*, during time period *a*).

STREAM TEMPERATURE CONSTRAINT

The stream temperature model was also developed by the USDA Forest Service (1993), and predicts the 5-day average maximum temperature for a stream system. Solar, stream, and terrestrial conditions are required to operate the model. At the most basic level, this model calculates the area of unshaded stream surface area, and uses established procedures to translate this into an increase in stream temperature over ground water temperature levels. While the temperature at any point in the stream network can be reported with this model, only the temperature at the most downstream reach is reported here. Coincidentally, the USDA Forest Service has an actual stream temperature station at this location in our study watershed. The temperature levels reported here should be considered an index of stream temperature, since the model has not been validated for use in eastern Oregon. However, our results are almost identical to the stream temperature levels measured in our study watershed (Bettinger et al. 1998a). Region 6 of the USDA Forest Service does support the model, and it is used in a variety of locations in the Pacific Northwest. The stream temperature goal can be formulated as such:

$$\sum_{k=1}^{n}\sum_{l=1}^{m} temp_{k,l,a} \leq \text{temperature goal}_a \quad \forall\, a$$

Where:

$temp_{k,l,a}$ = *f* (stream length, stream width, low stream flow, 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 the channel, heat rate, and ground water temperature for management unit *k*, managed under silvicultural regime *l*, during time period *a*). Management units not adjacent to the stream system do not affect the temperature calculations, making this a non-linear model.

HEURISTIC SEARCH PROCESS

Due to the non-linearities associated with this forest planning model, we decided to use a heuristic search process to locate good, feasible solutions (management plans). The heuristic process we use is called tabu search, which has been extensively described in the operations research (Glover 1989, 1990, Glover and Laguna 1993) and forestry literature (Murray and Church 1995, Bettinger et al. 1998b). For our implementation of tabu search, we used 1-opt moves (a change in an attribute of a management unit) to develop a full neighborhood (all possible changes to all management units). The short-term memory was static and chosen based on several trial runs of the heuristic. Aspiration criteria was also used to accept good solutions that may be otherwise considered tabu. Long-term memory controls were not used for diversifying the search, nor were intensification strategies used (such as those proposed by Bettinger et al. 1999) to concentrate the search in a portion of the solution space. Further, strategic oscillation (allowing infeasible solutions to crop up, but incorporating a system of penalties in the objective function to ultimately drive them out) was not utilized to diversify the search, although Richards (1997) indicates that this may be a promising refinement of tabu search. All of these diversification and intensification techniques have been considered, and may be implemented, in future versions of the LMSCHED model.

The heuristic process begins by generating all of the shortest paths from all management units to the mill location (Figure 1). A 1-opt tabu search neighborhood is created of the management units that can be assigned a silvicultural prescription and logging system. A management unit / prescription / logging system is chosen from the neighborhood, representing the choice that could increase the objective function value the most. If this choice is not tabu, and a path exists for the logging system chosen, sediment and temperature responses to the unit / prescription / logging system change are evaluated. If the sediment goal is violated, one of three options can occur: CTI is assigned to a road, the unit / prescription / logging system choice is rejected, or an unused road (to this point in the planning process) is obliterated. The option is chosen at random. CTI is assigned to a list of roads that are being used, and have the highest contribution of sediment per m^3 transported, per km. The tabu process continues for a predetermined number of iterations and subsequently reports the objective function value, the prescriptions and logging systems assigned to each management unit (if any), and the status of each road segment during each time period. A more detailed examination of the operation of this process can be found in Bettinger et al. (1998b).

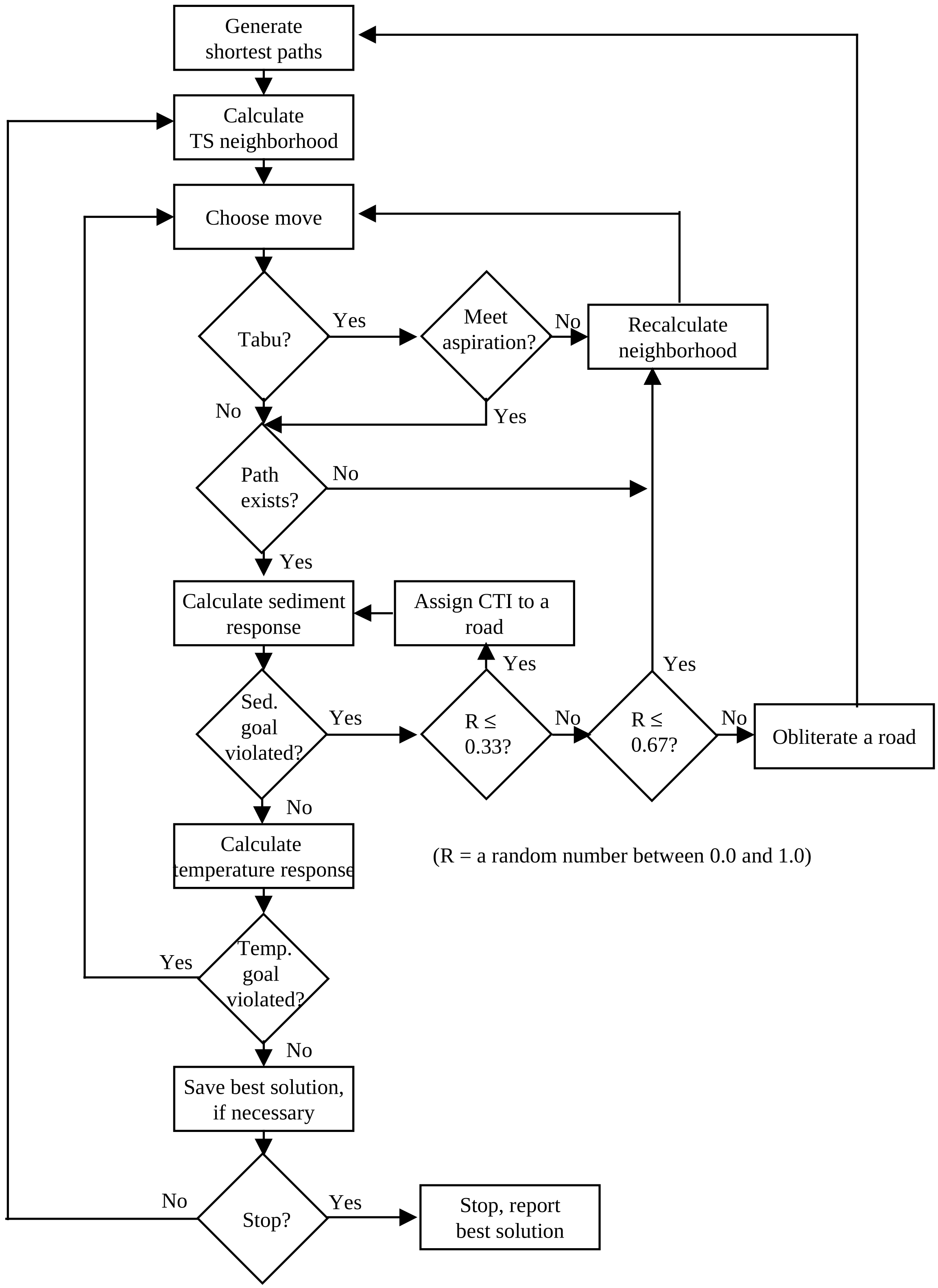

Figure 1. A flow chart of the tabu search process.

CASE STUDY WATERSHED

The case study watershed is a 5,926 ha watershed in the Upper Grande Ronde River watershed of eastern Oregon. The major landowner is the federal government (USDA Forest Service). Geographic information system (GIS) databases were either acquired from the Forest Service or developed specifically for this analysis. Roads, streams, soils, and vegetation were the themes of the major GIS databases. The stream system consisted of 5.54 km km^{-2} of various stream types in the watershed, ranging from the Grande Ronde River itself to intermittent and ephemeral streams. The management units (1,436) and road segments (443), along with the choices available to each, combined to produce a planning model with over 120,000 decision variables.

RESULTS

The LMSCHED model has been verified to produce results consistent with the goals noted above: even-flow of timber harvest volume has been rather closely achieved in each run of the model, and the sediment and temperature constraints are not violated. Bettinger et al. (1998b) detail the performance of the model prior to extensive revisions (currently underway). Many of the objective function values obtained from a number of runs where within 10 percent of an estimated global optimal objective function value. While tabu search cannot guarantee the achievement of an optimal solution, given the complexity of this forest planning model, we felt these results were satisfactory for the initial version of the model. Further, Bettinger et al. (1998a) extended the model to evaluate several alternative scenarios, including reducing sediment and temperature levels over time. These results continue to show the compatibility of timber harvests with aquatic resource goals, although the trade-offs are in some cases rather large.

Two main portions of the LMSCHED model that significantly affected (slowed) the processing time requirements were the computer code in which the model was developed, and the shortest path algorithm. The original computer code in which the LMSCHED model was developed was the BASIC language. We have since begun to convert the code to the C programming language, and hope to significantly (10-20 times) increase the processing time. Dykstra's algorithm was utilized every time a road segment was obliterated, so that every path could be reevaluated given the change in the road system. We are also exploring ways to speed up this portion of the program. For example, one way may be to identify only those management units that would be affected by the road system change, and re-evaluating only the affected paths (rather than all of the paths). Another may be to generate a set of alternative paths at the onset of running LMSCHED, and when one becomes infeasible, quickly replace it with the next-best, and so on.

This research examined a small set of logging systems: ground-based, skyline, and helicopter. Costs associated with these systems were rather general, but were our best estimate for the region and timber conditions that exist in eastern Oregon. Expanding the planning model to allow a wider range of logging systems, and perhaps variations on some of these systems is underway. We envision a user-friendly interface to facilitate a process whereby users can define a logging system, the costs associated with the logging system, as well as the road system requirements. Movement of development towards a more user-friendly system could prompt wider acceptance of the technology among federal and private land management planners.

Further out in the development of LMSCHED is a closer association with digital elevation models (DEMs) and other GIS databases. A variety of data is required to model sediment and temperature, including distance to the stream system, measurements of ground slope on either side of a stream, and orientation of the stream with respect to the Sun. All of this data was compiled manually for the current analysis and results provided in this and previous papers. Automated systems that can extract geographic conditions will undoubtedly make these types of planning models much more open to widespread use, particularly as databases change (as they often do) or are improved.

The debate over which forest planning technique (LP, IP, heuristics) to use to accommodate increasingly complex goals may be becoming moot. Software and hardware technology are increasing at rates many times faster than our knowledge of forest systems. The main concern over the next decade or so may be how closely a given model could be incorporated within a planning technique, or conversely, how many assumptions or generalizations must one make to accommodate a model. We have shown here, for example, that some rather complex aquatic models, developed independently by hydrologists and other scientists, may be incorporated within a heuristic planning technique with little modification. One of the other main challenges in using the aquatic models was in developing the appropriate databases to accommodate them on a large spatial scale.

CONCLUSIONS

The LMSCHED model incorporates stream sediment and stream temperature goals as constraints in a forest planning process, allowing one to both evaluate the levels of these measures of aquatic habitat, and to set limits on their allowable achievement. Both land management units and road segments are represented by a set of decision variables; road segments can be assigned to their current condition, or re-assigned to a paved condition (if not already paved), an obliterated condition, or to a condition where central tire inflation is required. The goal of the scheduling process is to try to identify feasible forest plans that produce the highest net present value without violating constraints related to the aquatic habitat goals. The scheduling model is currently undergoing some revisions, and we have discussed how it may be enhanced to address a broader array of logging systems and to attract a wider audience of users.

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