Managing by Objectives or Prescribing Behavior: Achieving Soil Protection and Economic Benefits in Forestry

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by

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Abstract

A hierarchical approach to forest planning is formulated, where harvest schedules are first determined, followed by a decision about harvest methods. Choice of harvest methods is particularly important because of concerns about harvest–related soil disturbance. In the decision model developed in this paper determination of a harvest system regime is expressed as a multiple–objective decision incorporating maximization of net present value and minimization of cumulative soil disturbance for different site classes, subject to maintaining high levels of production, an even flow of timber, and avoiding green–up violations. The search for preferred harvest system regimes is performed over a set of non–dominated harvest schedules, with alternative weights placed on the objectives to reflect values of different stakeholders. Based on an application of the model to the Tangier River watershed in south–eastern British Columbia, we conclude that a regulatory approach that restricts the choice of harvest systems is inferior (in terms of both economic and environmental objectives) to one that prescribes performance standards with respect to soil protection without restricting the choice of harvest methods available to the manager.

Key Words: environmental objectives; forest planning; hierarchical and multiple–objective decision making; soil disturbance

1. Introduction

The basic forest decisions are where, when and what treatment should be applied to best meet society's forest management objectives. Published research focused largely on forest management models at the stand level. The stand–level model is relatively simple. In contrast, forest–level planning with complex configurations of possible spatial and temporal location of activities involves combinatorial problems of large dimension when the number of harvest blocks is large.

Recent papers by Brumelle *et al*. (1996), by Weintraub *et al*. (1995, 1994), and by Nelson *et al*. (1991) have addressed spatially–constrained harvest scheduling problems. Harvest schedules specify where and when to harvest. In this paper, we add another important decision, namely, that of choosing harvest methods that are economically efficient and environmentally acceptable. The significance of choice of harvest methods has recently increased because of concerns about harvest–related environmental damage, especially soil disturbance (British Columbia Forest Practices Code 1995; Dykstra and Heinrich 1992; Lewis 1991).

Almost all harvest operations disturb soil to some extent. Soil disturbance is defined as any change in soil properties due to harvest operations that can lead to a reduction of long–term forest productivity (Lewis 1991). It can occur on gentle terrain but is more likely to occur on steeper sites. A range of methods can be used for harvesting a site. They differ by their potential to disturb the soil and by their costs. For example, cable and aerial harvesting are less environmentally harmful than conventional ground–based practices, but their application is more expensive. In this paper, we assume that the principal objective of forest management is to achieve economically effective harvesting while keeping cumulative soil disturbance, especially those of steeper and sensitive sites, to acceptably low levels.

Routledge (1987) studied the long–term stand–level effect of average soil disturbance on future timber volume, while Utzig and Walmsley (1988) estimated the post–logging losses of forest productivity in British Columbia for the ten–year period (1977–1986). Although the stand–level costs and soil disturbance due to harvest operations have been the subject of many studies (see Krag *et al.* 1991 for a review of relevant research in the Pacific Northwest and British Columbia), there is lack of research on the impacts of harvest methods in forest–level planning.

The global forest planning problem can be formulated as determining the time when a forest block should be harvested and the system employed for harvest in order to meet a variety of objectives and constraints. These include economic and soil protection objectives, social objectives such as employment (e.g., by maintaining an even–flow supply of fiber), and environmental constraints, such as green–up constraints that restrict harvesting of a block of forest if adjacent blocks have previously been harvested within the past decade or more.

In this paper, we propose a multiple–objective decision model for determining harvest system regimes that is based on maximization of net present value and minimization of cumulative soil disturbance for different site classes, while maintaining high levels of timber production and an even–flow of fiber. In addition, green–up constraints are to be satisfied, as are specific harvest system regulations. While we consider alternative strategies for regulators, our primary interest is to compare the consequences of restricting harvest systems as opposed to setting performance objectives.

The method of solving the problem is hierarchical. The search for the preferred harvest system regime is performed over a set of non–dominated harvest schedules in terms of the total volume of timber, maintenance of an even flow of fiber and compliance with green–up constraints. This set is determined in the first step of the hierarchical procedure.

The methodology is applied to a harvest plan for the forests of the Tangier River watershed located in south–eastern British Columbia. We proceed in the next section (section 2) to discuss factors determining the choice of a harvest system. Then, in section 3, a formal presentation of the model is provided, followed by a discussion of its application (sections 4 and 5). Our conclusions ensue.

2. Factors Determining the Choice of Harvest System

We define a harvesting system as a set of variables specifying the particular logging equipment and spur roads to be used to access the forest block. In our application, a network of roads already exists and is to be used for transportation—hauling timber to the mill and transporting logging equipment to the harvest site. We explicitly consider only spur roads that link a specific block to the existing branch roads and that need to be constructed before the start of the harvest. The length of the spur road, as a function of harvest system, regulates the maximum skidding distance within a block. While the practice of combining two or more harvesting systems in individual blocks is common, we are assuming that only one feasible alternative is designated for any specific block.

Harvesting cost is mostly determined by the choice of harvesting system and the cutting pattern, although it is also sensitive to other factors (Thibodeau 1994). The present value of total costs depends on the harvest schedule. Harvest–related site disturbance is influenced by the same factors as costs, that is, by the harvesting system and cutting pattern, and also by site conditions (primarily slope) and logging season. Since clearcutting is still the most dominant and ecologically–preferred method of harvest, we assume that harvested blocks are clearcut. However, the approach proposed here is sufficiently general that it could be extended to the choice of a harvesting system that uses partial cutting or thinning.

The factors that have a major and direct impact on the choice of a harvesting system are the original stand conditions, the type of cutting, and the desired end results of harvesting with respect to stand and soil conditions (Howard *et al*. 1993). Physical limitations in determining the feasible systems for harvesting a block are the slope, maximum skid distance and wetness of the site. Other variables, such as volume per hectare or total volume per block, influence harvesting costs. Site sensitivity affects potential future losses of site productivity caused by harvesting. These factors usually determine the choice of feasible harvesting alternatives at the stand–level.

One of the most important decisions regarding the choice of harvesting system is whether a ground–based system can be used or if a cable or aerial system is required. Although ground–based systems are generally less expensive, there are physical and environmental limitations to their use. Equipment with rubber tires for felling and skidding are limited to slopes of less than 45%, while tracked equipment can operate on slopes of up to 60%.[1] The use of a conventional ground–based system might not be possible even when terrain is flat, as in the case of wet soils. Cable or aerial systems must be used on slopes greater than 60%, but their use may be required even on moderate or steep slopes for particularly sensitive sites. The choice of harvest system is especially important when harvesting on slopes between 30% and 60%, where both ground–based and cable–logging systems are potentially feasible options.

Studies of the effects of timber harvesting consistently find that ground–based skidding causes more soil disturbance than cable or aerial yarding (Krag *et al*. 1991; Lewis 1991; Pritchett and Fisher 1987). Most of the soil disturbance occurs in the form of haul roads, landings and skid trails. A harvest system that is designed to work best over short distances will require more roads to harvest a given area than a system that is designed for long yarding distances. Short–

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[1] Standard recommendations on harvest operations prescribe the use of cable or aerial system on slopes greater than 50% (Howard *et al.* 1993; Conway 1982). However, from site surveys, comparative analyses and logging practices, it has been shown that tracked ground–based equipment can be used on slopes up to 60% (Kockx and Krag 1993; Krag and Webb 1987).

distance cable yarding requires a denser truck road network than ground–skidding. On the other hand, cutblocks assigned to mid–distance cable and standing skyline systems have lower average road density because of their longer yarding distance. Cutblocks assigned to helicopter harvesting do not require haul roads as logs are to be yarded to roads outside the block boundaries.

3. Problem Formulation and Model

We employ a hierarchical approach to solve the forest planning problem. In the first stage, priority is given to harvest scheduling. A tabu search method is applied (Brumelle *et al*. 1996). In this initial search for "good" schedules, the even–flow deviation (which is expressed as a function of upper and lower bounds on the volume cut in each period) is minimized, total volume is maximized, and the number of green–up violations is minimized. The three objectives are weighted and their linear combination forms the measure of the overall utility of the schedule. Since total volume is maximized, but even–flow deviation and green–up violations are minimized, the weight on volume is positive while that on the other two measures is negative. The advantage of a multi–criteria approach is that it generates several solutions close to the Pareto surface associated with the three objectives.

In the second stage, harvest system regimes are chosen that have satisfactory net present value of harvest and cumulative soil disturbance levels for different site classes. The search for the preferred harvest system regime—the one that best satisfies the economic and environmental objectives—is to be performed over the set of good harvest schedules generated in the first stage.

For convenience, we employ the same notation as Brumelle *et al*. (1996). Denote by S the set of good schedules generated by the *tabu* algorithm. The characteristic of every schedule $s \in S$ is that it provides satisfactory levels of the total volume $V(s)$, deviation of the even–flow of timber *f(s)*, and the number of green–up violations *n(s)*.[2] Details of the search for a set *S* of acceptable schedules is given in Brumelle *et al*. (1996). Note that it is also possible to derive a set of schedules on the basis of interaction with stakeholders. Such a set of schedules may accommodate a wider range of compromises between conflicting values, as well as other operational considerations.

Let *B* denote the set of blocks in the forest, *T* the set of periods, and *HS* the set of harvesting systems. The set $H(b) \subseteq HS$ is specified for each $b \in B$, and its elements are the feasible systems that can be used for harvesting block b. A harvest schedule defines the period when each block is cut, while a harvest system regime specifies the cutting methods. Each block is cut only once during the planning horizon, and only one system is used. A harvest schedule s is a function mapping blocks in *B* to $T \cup \{0\}$, where $s(b) = 0$ if block *b* is not cut during the planning period. A harvest system regime *h* is a function mapping blocks in *B* to *HS*. Limitations on the use of systems for harvesting block *b* are built into the set $H(b)$. Then the set of feasible harvest system regimes is denoted by $HR = \{h\text{: } h(b) \in H(b),\, b \in B\}$.

The harvest plan that cuts block $b \in B$ under schedule $s(b)$ using system $h(b)$ is represented by $\{(b, s(b), h(b)),\, b \in B\}$. Let $HP = \{(s,h),\, s \in S,\, h \in HR\}$ be the set of feasible harvest plans for the specified set *S* of acceptable schedules. The harvest plan includes temporal and spatial components of harvesting, as well as the method of harvest.

In this phase of the solution, we search for a harvest plan (*s*,*h*) to maximize the net present value of timber harvested over the planning period, and to keep the harvest–related soil disturbance at an acceptable level. Hence, the problem can be formulated as maximization of the net present value from harvest of commercial timber subject to the constraining levels of soil

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[2] Here f(*s*) = Max V(t, *s*) – Min V(t, *s*), where both maximization and minimization are over the set of periods T. One objective, therefore, is to find *s* that minimizes f(*s*).

disturbance for different site classes. But this formulation does not permit tradeoffs between the conflicting economic and environmental objectives. Another possibility which we present is to treat both the net present value and soil disturbance levels as criteria to be optimized simultaneously. This leads to a multi–objective formulation of the given problem. The multi–objective decision making (MODM) approach has been applied to various forest planning problems (Brumelle *et al.* 1996; Kangas 1994; Hof 1993; Howard and Nelson 1993; Howard 1991; Roise 1990; Mendoza *et al.* 1987; Allen 1986; Steuer and Schuler 1978; Schuler and Meadows 1975)

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The harvest system choice model

Let $npv(b, s(b), h(b))$ be the net present value of timber on block *b* cut during period $s(b)$ by the system $h(b)$. Then, the total net present value $NPV(s,h)$ of timber harvested with the system regime *h* and by the schedule $s \in S$ is given by:

$$NPV(s,h) = \sum_{b \in B} npv(b, s(b), h(b)) .$$

The soil disturbance, as a portion of the disturbed area of block *b*, is mainly a function of the harvest method and terrain condition–primarily slope gradient. For purposes of this study, we distinguish zones consisting of the blocks from the same slope class. Let Z_i be the zone of slope class *i, i=1,...,k*, such that Z_1 is the zone with the most gently sloping sites and Z_k is the zone with the steepest sloping sites. The objective is to minimize the cumulative soil disturbance for specific slope classes and, particularly, disturbance of steep and very steep sites because of its effect on future loss of site productivity.

Denote by $sd(b, h(b))$ the portion of the area of the block b disturbed by the use of harvest system $h(b)$. Then

$$sd(b,h(b)) = Area(b) \cdot d(h(b),sl(b)),$$

where $Area(b)$ is the area harvested and $d(h(b),sl(b))$ is the percentage of the block b with slope $sl(b)$ that is disturbed by harvest system $h(b)$. The area of zone Z_i disturbed by activities of harvest system regime h is given by

$$SD_i(h) = \sum_{b \in Z_i} sd(b,h(b)),\ \ i = 1,\dots,k\ .$$

Given the set S of good harvest schedules with respect to three objectives from the first stage of the decision process, the aim is to find the harvest plan from the set $HP = \{\ (s,h),\ s \in S\ \}$ that

(1) $$\max \quad NPV(s,h) = \sum_{b \in B} npv(b,s(b),h(b))$$

(2) $$\min \quad SD_i(h) = \sum_{b \in Z_i} sd(b,h(b)), \quad i = 1,\dots,k$$

subject to

(3) $$h(b) \in H(b),\ b \in B;\ s \in S$$

where $H(b)$ is the set of feasible alternatives for harvesting block b. $H(b)$ takes into account slope and skidding distance of the block.

Considering just the net present value criterion, the system with the lowest harvesting costs would be selected. Then, only the period of harvesting would vary depending on the objective(s) under consideration. After adding soil disturbance concerns, which are generally in conflict with the economic objective, the specification of the system for harvesting each block is not clear anymore.

Usual approaches to solving a multiple–objective optimization problem use parameterization. The problem is transformed into a parametric optimization problem $P(w)$ that depends on the objective functions and weighting parameters w. Then, solutions to the multiple-objective optimization problem are obtained by solving $P(w)$ for different values of w. A parameterization $P(w)$ is based on some scalarizing function, such as a weighted sum of objectives. Another type of scalarizing function measures the distance between a point in the objective space and the ideal point. The usual way of expressing the distance in the Euclidean space is by L_p metrics, with $1 \le p < \infty$. In the case where $p = \infty$, this metric becomes the *max* function.

Denote by $(NPV^*, SD_i^*, i = 1, \ldots, k)$ the ideal point for the problem (1)–(3), where $NPV^*,\ SD_i^*,\ i = 1, \ldots, k$ are specified as

$$NPV^* = \max_{(s,h) \in HP} NPV(s,h), \qquad SD_i^* = \min_{h \in HR} SD_i(h),\ i = 1, \ldots, k \quad . \tag{4}$$

If the distance of a point in the criteria space from the ideal one is expressed as

(5)

$$\max\{NPV^* - NPV(s,h),\ SD_1(h) - SD_1^*, \ldots, SD_k(h) - SD_k^*\}, \quad \mathit{for}\ s \in S\ \mathit{and}\ h \in HR,$$

then at least one solution to the problem

$$\min_{s \in S,\ h \in HR} \max\{NPV^* - NPV(s,h),\ SD_1(h) - SD_1^*, \ldots, SD_k(h) - SD_k^*\} \tag{6}$$

is Pareto optimal. In problem (6), the greatest deviation from the best criteria values is minimized over the set of feasible harvesting plans. Problem (6) is usually modified by introducing weighting factors:

(7)

$$\min_{s \in S, h \in HR} \max\{w_v(NPV^* - NPV(s,h)), w_{s1}(SD_1(h) - SD_1^*), \ldots, w_{sk}(SD_k(h) - SD_k^*)\}.$$

The role of the weights is twofold: to measure the relative importance of objectives and to normalize and scale different criteria. The solution to (7) depends on the weight specification. The weights should combine the internal characteristics of the given problem and the preference structure of the decision maker (DM) or group of decisions makers.

We use the form proposed by Nakayama and Sawaragi (1984):

(8) $$w_v = 1/(NPV^* - \overline{NPV}), \qquad w_{si} = 1/(\overline{SD}_i - SD_i^*), \quad i = 1,\dots,k \ ,$$

where $\overline{NPV}$ is the decision maker's net present value aspiration level, and $\overline{SD}_i$ is the aspiration level of cumulative soil disturbance per slope class *i*. In order for weights to be nonnegative, we need $\overline{NPV} \le NPV^*, \ \ \overline{SD}_i \ge SD_i^*, \ \ i = 1,\dots,k$; so the decision makers' aspirations should be reasonable and not set too high. For the weights given by (8), $w_v(NPV^* - NPV(s,h)), \ w_{si}(SD_i(h) - SD_i^*)$ are the normalized degree of non–attainability of $(NPV(s,h), SD_i(h), i = 1,\dots,k)$ to the ideal point $(NPV^*, SD_i^*, i = 1,\dots,k)$, for every $s \in S \ and \ h.$ The weights specified by (8) reflect the relative importance of objectives through the DM's aspiration levels. The DM expresses her preferences though the aspiration levels. Setting the aspiration level of the specific objective closer to its best value increases the weighted deviation of this objective, and gives it greater importance in (7). Unfortunately, there is no guarantee that the resulting harvest plan $(\tilde{s}, \tilde{h})$, with objective values $NPV(\tilde{s}, \tilde{h}), SD_1(\tilde{h}), \dots, SD_k(\tilde{h})$, will attain the aspiration levels.

Solving the problem

The harvest plan includes temporal and spatial components of harvesting, as well as the method of harvesting. Even with a limited number of harvest schedules in *S*, the number of feasible harvest plans is extremely high because of the various combinations of logging equipment. As an example, where there are *n* cutblocks and between two and four feasible harvesting options, the total number of possible harvest system regimes is between 2^n and 4^n. Rather than finding exact solutions to the forest planning problem, a heuristic approach capable of generating good solutions was used.

Randomized procedures have often been applied to solving combinatorial problems in forest planning (O'Hara *et al*. 1989; Clements *et al*. 1990; Nelson and Brodie 1990). In this paper, good solutions to the problem (7) for various weights (8) were found by a random search procedure similar to that proposed by Conley (1984).

For each harvest schedule *s* from *S*, the procedure generates a set of feasible harvest regimes $HR(s) \subseteq HR$ by assigning randomly a feasible harvest alternative to each cutblock. The regime from $HR(s)$ with the smallest value of weighted distance is accepted as a good harvest system regime for schedule *s*. Among good harvest system regimes for $s \in S$, the best one in terms of (7) is selected. The good harvest plan consists of the selected regime and the corresponding schedule.

4. Timber Production and Environmental Protection in the Tangier Watershed: An Application

The Tangier River watershed is located in the Northern Columbia Mountains of south–eastern British Columbia between Mount Revelstoke and Glacier National Parks. The watershed belongs to the Revelstoke Forest District in the northern part of the Nelson Forest Region (Figures 1 and 2). The watershed has a total area of about 28,000 hectares, of which 10,000 ha are forested. Interior Cedar Hemlock (ICH) occupy valley bottom on the lower elevations, whereas Engelmann Spruce Subalpine Fir (ESSF) is characteristic on the higher elevations. Elevations range form 600 to 1800 m. Primary forest use has been commercial logging, but other values are high, including wildlife (caribou and marten habitat), recreation (heli–skiing, snowmobiling), old–growth preservation and biodiversity. Various studies have examined forestry, wildlife and recreation values in the region (Thompson *et al.* 1993; Brown *et al.* 1994a, 1994b).

The Tangier watershed was selected because there is available a Geographic Information System (GIS) for the region that incorporates a geo–referenced biophysical database consisting of topography, forest inventory and road network information (Brown *et. al.* 1994a). The 5197 hectares of commercial forest were divided into 491 cutblocks ranging from 5 to 20 hectares in area. Cutblock identification was based on topography, forest age and species composition, and harvest guidelines for resource emphasis areas (Price and Blake 1993). The cutblock plan included identification of existing and proposed roads, road construction and maintenance costs, harvesting alternatives within the given constraints, and average harvesting costs for each system.

While the entire watershed was originally projected for multiple use management, a proposed wilderness park, Serenity Peaks, would require the withdrawal of a significant portion of land from commercial logging. The wilderness park would have a total area of 23,636 hectares, constituting about 83% of the Tangier watershed (Figure 2). Since no harvesting would be allowed within Serenity Peaks park, the remaining 17% of the watershed would be available for commercial logging. The operable forest of 2116 hectares contains 219 cutblocks. The current study focuses on this smaller part of the watershed. The operable area has a network of main and branch roads already in place. Only spur roads need to be built and their construction depends on the harvest schedule and the system selected for harvesting.

Site classification

Mountain forests are an important component of the timber supply in the Interior of British Columbia, but harvesting steep slopes is difficult and expensive, and the sites are environmentally sensitive. In comparison to other Interior Forest Regions, the Nelson Forest Region, to which the Tangier watershed belongs, has the highest percent of mature timber on sites with steep and very steep slopes. A distribution of 219 cutblocks by slope classes is presented in Table 1. A dominant forest type is assigned to each block (Thompson *et al.* 1993). Five forest types were identified—Douglas fir, western red cedar, western hemlock, subalpine fir (also referred to as balsam) and Engelmann spruce—and classed into good (G), medium (M), poor (P) and low (L) quality sites. Most of the good and medium sites were allocated to timber cutblocks.

Table 1: Distribution of blocks by slope class

Slope Class	Slope Gradient	Number of Blocks
gentle	0–30%	30
moderate	31–45%	49
steep	46-60%	67
very steep	>60%	73

Tables relating stand attributes to stand age are available from Thompson *et al.* (1993). Volume tables for each combination of age, species and site quality were generated using the forest dynamics simulation model, TIPSY, version 2.0 (Mitchell *et al.* 1992). Projected stand volumes from TIPSY are based upon research plots and represent potential production under most favorable conditions.

Harvesting costs and timber values

Harvest cost and timber value data are available from Thompson *et al.* (1993), although data have been modified for the current study area. Log value (LV) is defined as the price paid for logs at the mill gate and depends upon species, grade and log size. Average values for each species, site quality and age class were estimated from past studies (see Thompson *et al.* 1993). Carrying and administrative costs were estimated to be $8.00 per cubic meter. Harvesting costs consist of three components: tree–to–truck (TTC), spur road building (SRC), and hauling (HC). Tree–to–truck costs ($\$/m^3$) are the costs of felling, de–limbing, and bucking the trees, bringing the logs to roadside, and loading the logs on trucks.

Based on B.C. Ministry of Forests (hereafter MoF) data for the Tangier watershed, one of six harvest systems can be assigned to each of the cutblocks as indicated in Table 2. Constraints in the selection of a harvest system are slope and maximum skidding distance.

Table 2: Harvesting systems used in the study area

Harvest System Class	*Harvest System*	*Description*	*Constraints (slope/skid distance)*	*Cost per* m^3	*Road Cost Adj. Factor*
Ground Skidding	1	Rubber tired skidder	0–45% / ≤300m	\$15.0	1
	2	Small crawler tractor	0–60% / ≤300m	\$17.0	1
Cable yarding	3	Short–distance cable	30–80% / ≤200m	\$22.5	1.3
	4	Mid–distance cable	30–80% / ≤300m	\$24.0	0.8
Aerial	5	Standing skyline[a]	40–100% /≤1000m	\$30.0	0.4
	6	Helicopter	1–100% / off block	\$42.5	0

[a] Although skyline is usually classified as a cable system, it is included in aerial systems because of the total suspension of the log during yarding. This characteristic, together with short spur roads required due to long skid distance, causes significantly lower site disturbance compared to ground–based or cable systems.

The main and branch roads are already in place, so road construction scheduling is not a consideration, with construction of spur roads assumed to occur at time of harvest. In order to calculate the cost of spur roads, the average road building cost is multiplied by the adjustment factor assigned to each harvest system (provided in the last column of Table 2). The road cost adjustment factor is multiplied by an average road cost of \$1.45/m^3 to estimate the cost of accessing the block. The cost of hauling depends on the distance of the block from the valley bottom. The cost of hauling the logs to the bottom of the valley is calculated for each block by multiplying the haul distance (km) by an average cost of \$0.10/m^3/km. The net value of the timber harvested (\$/m^3) can then be calculated as:

$$NV = LV - TTC - HC - SRC - CA,$$

where NV is net value ($\$/m^3$), LV is log value ($\$/m^3$), TTC is the tree–to–truck cost ($\$/m^3$), HC is haul cost ($\$/m^3$), SRC is the spur road building cost ($\$/m^3$), and CA refers to the carrying and administrative costs ($\$/m^3$).

Timber values and the costs of harvesting were calculated for each of the 219 blocks. Economic values (benefits and costs) are in constant dollars, discount rates of 0%, 2% and 5% are used, and it is assumed that there is no change in real costs and prices.

Timber harvesting and soil disturbance

Site or soil disturbance is defined as any abrupt change in the properties of the site by forest management activities. The level of site degradation—reduction of long–term site productivity—depends on the overall sensitivity of a site to forest management activities. A site's sensitivity to degradation is determined by the physical, climatic and biological characteristics of the site. Several site sensitivity classes can be distinguished on the basis of major site factors such as climate, coarse fragments, gullies, slope gradient, complexity, moisture, texture and depth (see Lewis 1991; British Columbia Forest Practices Code 1995). Slope gradient is often the major concern with most degradation processes, with an increase in gradient contributing exponentially to specific degradation hazards (Lewis 1991). Beside the slope factor, sensitivity to degradation is influenced by the actual soil properties, although these are not explicitly considered here except to the extent that they are included in the slope factor. For example, shallow soils that are widespread in British Columbia’s recently glaciated landscape are typically rated as sensitive to degradation, and require the use of special systems for harvesting. Lack of soil mapping makes accurate assessment of site degradation sensitivity impossible and thus we use slope as a prime indicator of sensitivity. Four standard slope classes are used as a proxy for a site’s sensitivity to soil degradation: gentle (slope < 30%), moderate (slope 30–45%), steep (slope 46–60%), and very steep (slope > 60%).

Soil disturbance levels are strongly dependent on a combination of logging season, terrain condition (primarily slope gradient), and harvest system. The sources of soil disturbance are roads, landings, and skid and backspar trails, with disturbance figures given as a percentage of the harvested area. The greatest site disturbance impacts are associated with summer ground–based operations and possible reduction of disturbance by winter logging. We used the average of summer and winter disturbance levels (see Krag *et al*. 1993; Kockx and Krag 1993; Krag 1991; Thompson and Osberg 1991; Froehlich 1988; Utzig and Walmsey 1988; Krag and Webb 1987). Disturbance figures used in this study have been adjusted to reflect the most likely site disturbances (Table 3).

Table 3: Percentage of harvested area disturbed *d(hs,sl)* **by harvest systems** *hs* **on specified slope classes** *sl*

	Slope Class			
Harvest System	Gentle <30%	Moderate 30–45%	Steep 46–60%	Very Steep >60%
1	15	17	–	–
2	12	14.5	18.6	–
3	–	12	15	17.5
4	–	9	10	12
5	–	–	6	9.5
6	–	–	3.5	3.5

Harvest scenarios

We have used the model to assess the consequences of two regulatory strategies, one which focuses on outcomes while the other focuses on means. We defined two regulatory scenarios. The ECON (or net present value) scenario represents the case of management in the absence of soil disturbance constraints. The CONSERVE (or soil conservation) scenario includes restrictions prescribed for each block harvested on the use of harvesting systems to reduce soil disturbance. One of the six harvest systems is designated for any specific block taking into consideration restrictions incorporated in the different scenarios.

The ECON scenario provides flexibility in the choice of cheaper harvest systems by allowing ground–based harvesting on sites with slopes up to 60% (see Table 4). The CONSERVE scenario addresses the choice between ground–based and cable systems on slopes between 30 and 60%, a subject of considerable debate among foresters. The intent of this scenario is to reduce soil disturbance by restricting the use of ground skidding equipment on steep terrain. It modifies the ECON scenario by allowing the use of equipment with rubber tires only on gentle slopes, while timber on moderate slopes can be harvested using small crawler tractors or cable systems; feasible alternatives for harvesting steep slopes are cable systems or skylines (Table 5). Short distance cable cannot be used for logging on very steep slopes because it requires even more spur roads than ground–based harvesting, which makes it environmentally damaging for sensitive sites.

Table 4: Feasible harvest alternatives by slope class for ECON scenario

	Slope Classes				
	gentle	moderate	steep	very steep	
	<30	30–45	46–60	61–80	>80
Harvest System	1(rubber tired skid) 2(small crawl tractor)	1(rubber tired skid) 2(small crawl tractor) 3(short cable)	2(small crawl tractor) 3(short cable) 4(mid cable)	3(short cable) 4 (mid cable) 5 (skyline)	5(skyline) 6(helicopter)

See Table 2

Table 5: Feasible harvest alternatives by slope class for CONSERVE scenario

	gentle	moderate	steep	very steep	
	<30	30–45	46–60	61–80	>80
Harvest System	1(rubber tired skid) 2(small crawl tractor)	2(rubber tired skid) 3(short cable)	3(short cable) 4(mid cable)	4 (mid cable) 5 (skyline)	5(skyline) 6(helicopter)

See Table 2

In order to compare the economic benefits and environmental implications of harvest methods for the two scenarios, we first solve the multiple–objective problem (1)–(2) subject to the following constraint (which replaces (3)):

(9) $$h(b) \in H^{CONS}(b),\ \ b \in B;\ s \in S,$$

where $H^{CONS}(b)$ is the set of feasible alternatives for harvesting block *b* under the CONSERVE scenario (Table 5).

Let (NPV^C, SD_i^C, $i=1,...,k$) be a point on the Pareto surface associated with the k+1 objectives—the net present value and soil disturbance objectives. There is no harvest plan under the CONSERVE scenario that can improve at least one objective value without worsening any of the remaining ones. Suppose that SD_i^C, $i=1,...,k$, are the decision maker's aspirations of the soil disturbance levels. Then, a harvest plan under the ECON scenario is to be found that maximizes the net present value of timber cut over the planning horizon, subject to the upper bounds on soil disturbance for all site classes as in

(10) $$\max \quad NPV(s,h) = \sum_{b \in B} npv(b, s(b), h(b))$$

subject to

(11) $$SD_i(h) \le SD_i^C,\ \ i=1,...,k$$

(12) $$h(b) \in H^{ECON}(b),\ b \in B;\ s \in S\ ,$$

where $H^{ECON}(b)$ is the set of feasible alternatives for harvesting block *b* under the ECON scenario (Table 4). Note that the soil disturbance limits SD_i^C, $i=1,...,k$ in (11) are established by solving (1)–(2) under CONSERVE scenario. The intent is to reach the highest possible net present value of timber by using a range of harvest systems, while keeping the cumulative soil disturbance of various slope classes within acceptable limits.

5. Computational Results

In this section, we describe the results of the application of our model. We consider a 60–year planning horizon, divided into periods of 10 years each, for the southern part of the Tangier watershed, which consists of the 219 blocks. The set *S* of the acceptable harvest schedules is the initial point for further refinement of plans. In this stage of the hierarchical procedure, we chose 15 good harvest schedules out of a set of solutions generated using the *tabu* search algorithm (see Brumelle *et al*. 1996). The criterion for the choice of the schedules was to obtain acceptable non-dominated solutions in terms of timber volume cut, the maintenance of even-flow and the compliance with green-up constraints (Table 6).

Table 6: Harvest schedules and corresponding volume, even–flow and green–up violations

Schedule *s*	Volume *V(s)* m^3	Largest Decadal deviation from even–flow *f(s)* m^3	Green-up violations *n(s)*
1	575,392	827	10
2	577,802	782	15
3	577,541	549	15
4	579,840	792	20
5	583,078	1,643	36
6	582,824	1,089	33
7	555,246	2,462	0
8	555,862	3,073	0
9	554,859	2,095	0
10	568,871	3,201	0
11	595,131	4,017	53
12	594,301	6,432	41
13	585,327	8,348	9
14	581,305	4,836	2
15	595,291	3,861	69

Source: Brumelle *et al*. (1996) and personal communication

The best and worst values of each objective are calculated for both management scenarios, and their pairwise comparisons are presented in Tables 7 and 8. The net present values are calculated for discount rates of 0%, 2% and 5%. The highest net present value is reached when the cheapest harvest alternative is applied to each cutblock; the corresponding soil disturbances are at their maximum (worst) levels. The elements of the *NPV** columns in Table 7 are the maximum net present values (in millions of dollars) calculated for three discount rates under the CONSERVE and ECON scenarios. The schedule column indicates the index of harvest schedule from the set *S* for which the *NPV** are obtained. Maximum net present values are attained with harvest schedules #12 and #15, with the total volume of timber harvested greater than 581,000 m^3 and reasonably low deviations from even–flow. The elements of SD_i , *i=1,....,4,* rows are the levels of soil disturbance of four slope classes corresponding to *NPV**. Since *NPV** is obtained by harvesting with the cheapest system, the corresponding cumulative soil disturbances are at their highest (worst) possible levels.

Table 7: Pairwise Comparison of Scenarios for Maximization of Net Present Value

Discount	CONSERVE Scenario	ECON Scenario	
Rate	NPV* (millions $)		Schedule
0%	4.420	5.627	15
2%	2.398	3.016	12
5%	1.179	1.453	12
SD_1(ha)	56	56	
SD_2(ha)	56	66	
SD_3(ha)	72	89	
SD_4(ha)	75	101	

Table 8: Pairwise Comparison of Scenarios for Minimization of Soil Disturbance

	CONSERVE Scenario	ECON Scenario	Schedule
SD_1* (ha)	38	38	9
SD_2* (ha)	42	42	9
SD_3* (ha)	44	44	9
SD_4* (ha)	48	48	9
Discount Rate	NPV (millions $)		
0%	1.675	1.675	
2%	0.878	0.878	
5%	0.408	0.408	

The ECON scenario allows greater flexibility in the use of cheaper harvest alternatives (ground–based for steep sites and short–distance cable for very steep sites). This flexibility results in an increase in NPV* (maximum of the net present value), but also an increase in the corresponding SD_i compared to the CONSERVE scenario. There is no change in the cumulative soil disturbance of the gentle slope class, since the same harvest alternatives for gentle sites are used in both scenarios.

Minimal cumulative soil disturbances, SD_i *, $i=1,...,4$, are achieved if sites are harvested using the most expensive harvest systems, and are obtained with schedule #9 for both harvest scenarios (Table 8). The corresponding net present values are the lowest possible for various discount rates and established scenarios. Minimal soil disturbance levels and corresponding net present values are the same for both scenarios since the most expensive harvest alternatives are the same for both scenarios.

The results from Tables 7 and 8 make it possible to establish a range of objective values for both scenarios. The worst values for the soil disturbance of the *i–th* class are provided in Table 7, while the lowest values for *NPV* are provided in Table 8. In each case, the * superscript (*viz*., *NPV** and SD_i *) denotes the best possible values.

Comparison of the two regulatory strategies

The problem is first solved for the CONSERVE scenario using discount rates of 0%, 2% and 5%. Different solutions to the problem given by (1), (2) and (9) are generated by varying the weights specified by (8). Setting the aspiration level of the objective closer to its best value increases the corresponding weight. The solution that maximizes net present value is non-dominated solution to (1)–(2) for $w_v = \infty$ (with $\overline{NPV} = NPV^*$) and all other weights equal to zero. Similarly, the solution that minimizes soil disturbance of the *i*th site class is non–dominated for $w_{si} = \infty$ $(\overline{SD}_i = SD_i^*)$, $i=1,...,k$ and $w_v = 0$. Another solution is obtained with similar weights assigned to the net present value and soil disturbance. Thus, three solutions for each discount rate are selected. The soil disturbance levels reached in this stage determine the soil disturbance limits in the next step when the net present value is maximized under the ECON scenario, which is described by (10)–(12).

Starting from the best harvest plan found for the CONSERVE scenario, a random search method can generate harvest plans within the ECON scenario with the objective values not worse than the ones already obtained. Although the quality of this solution relative to the optimal one is hard to verify, the harvest plans that satisfy soil disturbance limits and improve the net present value obtained by the CONSERVE scenario are considered acceptable.

Table 9: Pairwise Comparison of Scenarios for MODM with Maximization of Net Present Value and Minimization of Soil Disturbance for Various Discount Rates

CONSERVE Scenario						ECON Scenario					
NPV (mil.$)	SD_1 (ha)	SD_2 (ha)	SD_3 (ha)	SD_4 (ha)	Sch. (index)	NPV (mil.$)	SD_1 (ha)	SD_2 (ha)	SD_3 (ha)	SD_4 (ha)	Sch. (index)
0%											
						5.627	56	66	89	101	15
4.420	56	56	72	75	15	4.589	55	52	72	75	5
3.606	49	53	60	68	11	3.747	49	51	59	68	3
1.675	38	42	44	48	9	1.675	38	42	44	48	9
2%											
						3.016	56	66	89	101	12
2.398	56	56	72	76	12	2.446	48	56	70	76	3
1.619	50	46	51	62	12	1.636	48	45	51	62	5
0.878	38	42	44	48	9	0.878	38	42	44	48	9
5%											
						1.453	56	66	89	101	12
1.179	56	56	72	76	12	1.210	47	53	72	76	14
0.771	50	46	52	59	13	0.854	47	46	51	59	1
0.408	38	42	44	48	9	0.408	38	42	44	48	9

Two sets of solutions are presented in Table 9. One set consists of good solutions in the objective space obtained for the CONSERVE scenario. Each solution from that group is associated with a solution in the ECON scenario. The only exception is the first solution in the ECON group (for each discount rate) because it has no counterpart in the CONSERVE scenario. The points in the ECON part of the table are obtained by maximizing the net present value subject to the soil disturbance limits. Table 9 presents the pairs of solutions generated for both scenarios as an illustration that it is possible to achieve better values of economic and environmental objectives with the ECON (focusing on outcomes) scenario than with the CONSERVE (regulating means) one. As the soil disturbance limits approach their lowest possible values, random search fails to produce better objective values under the ECON scenario. The tradeoffs between net present value and cumulative soil disturbance are presented in Figure 3 for a discount rate of 0%. The cumulative soil disturbance is determined by assigning equal weights to the soil disturbance of different site classes. Cumulative soil disturbance $\sum_i SD_i$ (in hectares) over the area harvested is plotted on the abscissa, with net present value of timber harvested *NPV* (in million dollars) plotted on the ordinate. From the figure, it is evident that the ECON scenario, which allows flexibility in the choice of harvest systems, can produce better solutions than the CONSERVE scenario in terms of both net present value and cumulative soil disturbance. The ECON scenario not only provides solutions with the greatest net present value, but also lower levels of soil disturbance compared to the values achieved under the CONSERVE scenario.

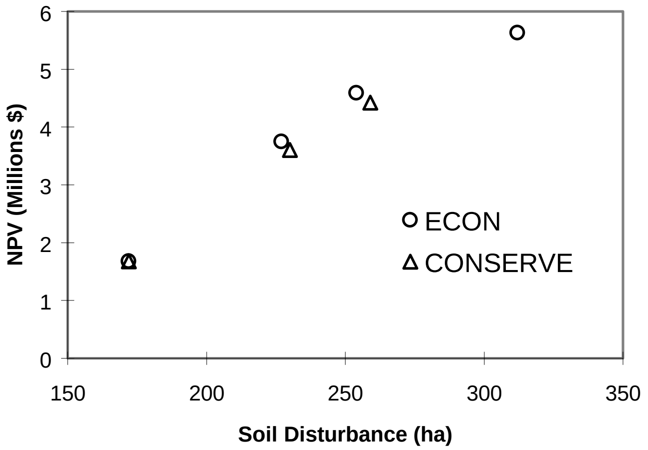

Figure 3: Approximate Pareto Surface in Cumulative Soil Disturbance (ΣSD_i) and Net Present Value (NPV) Space, CONSERVE and ECON Scenarios

The comparison between two scenarios is completed by adding to the analysis the objective values for total volume, the even–flow measure and the number of green–up violations implied by the choice of schedule. Table 10 provides these solutions for the scenarios in Table 9, along with three other objective values from Table 6 for the chosen harvest schedules.

Table 10: Pairwise Comparison of Scenarios for MODM with: Max Total Volume, V(m^3); Min Even–flow Deviation, f(m^3); Min Green–up Violations, g(number of violations); Max Net Present Value, NPV(mil.$); and Min Soil Disturbance, SD_i(ha), i=1,...,4

CONSERVE Scenario								ECON Scenario							
V	f	g	NPV	SD_1	SD_2	SD_3	SD_4	V	f	g	NPV	SD_1	SD_2	SD_3	SD_4
0%								**0%**							
595291	3861	69	4.420	56	56	72	75	583078	1643	36	4.589	55	52	72	75
595131	4017	53	3.606	49	53	60	68	577541	549	15	3.747	49	51	59	68
554859	2095	0	1.675	38	42	44	48	554859	2095	0	1.675	38	42	44	48
2%								**2%**							
594301	6432	41	2.398	56	56	72	76	577541	549	15	2.446	48	56	70	76
594301	6432	41	1.619	50	46	51	62	583078	1643	36	1.636	48	45	51	62
554859	2095	0	0.878	38	42	44	48	554859	2095	0	0.878	38	42	44	48
5%								**5%**							
594301	6432	41	1.179	56	56	72	76	581305	4836	2	1.210	47	53	72	77
585327	8348	9	0.771	50	46	52	59	575392	827	10	0.854	47	46	51	59
554859	2095	0	0.408	38	42	44	48	554859	2095	0	0.408	38	42	44	48

From Table 10, it is clear that the objective values under the ECON scenario are generally not worse than the corresponding values for the CONSERVE scenario. The only exception is total timber harvest volume, which is greater for solutions under the CONSERVE scenario. The decrease of the total volume cut under the ECON scenario in comparison to the CONSERVE scenario does not exceed 3%. Note that this decrease is in the total volume over all periods. Indeed to ensure an “even flow” and compliance with green up constraints the DM may very well sacrifice some of the volume in periods of record cuts.

6. Conclusions

The paper showed the complex nature of trade-offs that must be considered in forest-planning. It suggests that a regulatory strategy aimed at soil protection, which prescribes acceptable levels of outcomes, is likely to dominate a regulatory strategy that attempts to achieve soil protection by restricting harvest methods.

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