A Demonstration of SDSS: A Cost Minimization Approach to Silviculture Planning
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by

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1 INTRODUCTION

This report discusses the conceptual and practical aspects of a new model designed to identify the most economically efficient silviculture treatments required to achieve a given biological outcome in a decision-making environment involving uncertainty. This model represents an adaptation of the Silviculture Decision Support System (SDSS) model of McDaniel et al. 1991 and is referred to here as "COSTMIN."

For each forest inventory unit considered, this model generates a minimum-cost silviculture regime that satisfies a specified minimum expected final stocking density requirement. For example, if the minimum expected stocking density requirement is 900 stems per hectare, the model must identify, among all specified silviculture treatment regimes that provide an expected final stocking density of at least 900 stems per hectare, the regime whose expected present value of all treatment costs is minimum. Here, expected final stocking density is measured at a prescribed time after any site preparation and stocking and brushing treatments have been applied. Hence, the model does not consider stand tending treatments such as spacing or fertilization.

1.1 The Present Decision-making Process for Silviculture

Under Chapter 140 of the Forest Act of British Columbia, all "major licensees" are required to submit and have approved by the Minister plans for carrying out "basic silviculture." Basic silviculture is defined as "such harvesting methods and silviculture operations including seed collecting, site preparation, artificial and natural regeneration, brushing, spacing and stand tending and other operations as are prescribed to be required for the purpose of establishing a free growing crop of trees of a commercially valuable species." These plans and, more importantly, the silvicultural effort they describe are a major expense to licensees. Under current legislation, major licensees are to consider these expenses as a cost associated with the harvest of the previous crop rather than as an expense to be capitalized against the future crop. This approach is intended to ensure that all areas are adequately restocked with a productive crop within a specified maximum time period following harvest.

The Silviculture Branch and regional Silviculture Sections of the B.C. Ministry of Forests set regulatory standards that determine what silviculture outcomes constitute compliance. These outcomes are biological measures such as the number of well-spaced, free growing seedlings of an appropriate species per hectare. Target and minimum stocking standards in the form of guidelines are provided on a site-specific basis for each subzone of the provincial ecological classification and are a regulatory requirement of all major licensees. These targets are intended to achieve biologically rather than economically optimal outcomes.

Regeneration costs are the major post-harvest expense incurred by the licensee. These expenses include site preparation, planting (including costs associated with obtaining the planting stock), and brushing and weeding. On any given site, a silviculturist normally has many different options to achieve a given outcome. Decisions on which course to take are generally based on professional experience, local and regional research results, and external factors such as the availability of equipment, planting stock, or appropriate environmental conditions for a given action (e.g., an appropriate fuel loading and fire index for a spring burn).

The complexity of the decision-making process can vary dramatically. On some sites, silviculture decisions might be straightforward with little or no required expense (e.g., natural regeneration with no site preparation required). On other sites, a silviculturist might have two to three possible approaches to site preparation, four to five stock types, and three to four post-planting brushing and weeding treatments and retreatments to consider. The many different treatment combinations and possible biological and economic outcomes on these latter sites make it difficult to identify the optimal approach without analytical support.

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2 "Free growing crop" means a crop of healthy trees, the growth of which is not impeded by competition from plants, shrubs, or other trees.
1.2 Why Cost Minimization?

SDSS evaluated the expected results of silviculture practices within a framework that explicitly accounts for uncertainties. Because the current regulatory approach to basic silviculture requires the establishment of a fully stocked, well-spaced, free-to-grow replacement crop, the main interest of many major licensees is to minimize the cost of achieving the required biological outcome. This approach to silviculture planning is relevant only to basic silviculture practices where a specific biological outcome is required. Expenditures on incremental silviculture practices are more discretionary and normally have maximization of net present value or strategic objectives as their principal aims.

The cost minimization approach to silviculture planning developed in this project offers users the opportunity to examine relationships between inputs (expected silviculture effort) and outputs (outcome density at free growing) across the range of treatment combinations for a given regime, in an environment of uncertainty. This makes it possible to identify both the marginal returns for different levels of silviculture effort and possibly the optimal economic effort. The latter can then be compared with the optimal silviculture effort required to meet a given “hurdle” outcome, such as a target stocking standard to attain free growing status.

2 THE COSTMIN MODEL

2.1 Connection with SDSS

The COSTMIN model is derived from the database and decision analysis components of the SDSS model, which is described in detail in Silviculture Decision Support System: Reports, Documentation, and Software, Volumes I-VI, prepared for Forestry Canada in March 1991. The COSTMIN model adopts SDSS’s structure (inventory breakdown, silviculture treatment types, treatment group structure, etc.), but differs from SDSS in the objective of the decision analysis. While SDSS maximizes an expected net present value of silviculture treatments, the present model minimizes expected silviculture treatment costs subject to the constraint on expected final stocking density.

2.2 Optimization Procedure

Within SDSS’s decision analysis framework, there is no direct means of minimizing silviculture costs that are subject to a constraint on expected final stocking density (or, for that matter, subject to any other type of constraint). However, it is possible to modify the solution procedure in SDSS to produce this information. We do this by defining, for each inventory unit to be analyzed, the following objective to be maximized by the choice of silviculture regimes:

\[ V(k, s) = kd(s) - c(s) \]

where:

- \( k \) = a “scaling factor,” whose units are dollars per stem;
- \( s \) = the silviculture regime (i.e., a policy or set of rules);
- \( d(s) \) = the expected final stocking density resulting from silviculture treatment regimes; and
- \( c(s) \) = the expected present value of silviculture costs for silviculture treatment regimes.

If the decision trees in SDSS are modified to use this objective, solving each decision tree problem for a fixed value of the scaling factor \( k \) will produce an optimal regime, denoted as \( s^* \), with associated expected final stocking density \( d^* = d(s^*) \) and present value of expected silviculture costs \( c^* = c(s^*) \).

---

3 SDSS maximizes the present value of net benefits, employment, or wood supply, or a user-specified weighted average of these three criteria. Net benefit equals the present value of treated stands less the present value of silviculture cost. The present value of treated stands equals the present value of future revenues from the sale of forest products, less harvesting and processing costs. The revenues and costs may be generated by the treated stands themselves, or through an “allowable cut effect,” depending on whether the user elects a “stand” or “forest” perspective for the analysis. Incremental harvest-stage employment and wood supply are determined in a similar manner. None of this is relevant to the present model, since it does not account for harvest-stage effects of silviculture treatments.
It follows that this optimal treatment regime $s^*$ is a minimum-cost treatment regime among all of those that result in an expected final stocking density of $d^*$ or greater. Hence, solving the decision tree problem for a sequence of values for the scaling factor, $k_1, k_2, ... k_n$, generates a sequence of optimal silviculture regimes and associated expected final stocking densities and minimum expected silviculture costs: $(s_1, d_1, c_1), (s_2, d_2, c_2), ... (s_n, d_n, c_n)$. This procedure generates minimum-cost silviculture regimes for a sequence of expected final stocking densities, $d_1, d_2, ... d_n$. If one of these densities, $d_i$, coincidently equals (or nearly equals) the "target" expected final stocking density, the corresponding treatment regime, $s_i$, is an optimal solution to the problem of interest.

It is useful to think of the scaling factor as the present value per stem for stands subjected to silviculture treatments. If the scaling factor equals zero (or is sufficiently small), the optimal solution will be to spend nothing on silviculture treatments, because such treatments would have no or little effect on the "value" of treated stands. Generally, as the scaling factor is increased, the procedure enables more to be "spent" on silviculture treatments to increase the expected final stocking density and therefore the value per hectare of treated stands. One might presume that the expected final stocking density could be made as large as possible if the scaling factor were made sufficiently large.

Figures 1 and 2 show the workings of the solution procedure. Both figures contain identical curves labeled "minimum expected silviculture cost/ha." This relationship between expected final stocking density and the corresponding minimum silviculture cost is, of course, not known before the problem is solved. Indeed, our objective is to identify a treatment regime that corresponds to a single point on this curve, that point where the expected stocking density equals the target density.

Note that the curves in these graphs appear to represent continuous functions of expected density. This is not really the case, since there is only a finite number of silviculture treatment regimes. For this discussion, however, it is convenient to think of these curves as representing continuous functions.

For any given expected stocking density, the expected costs of all treatment regimes that result in this expected density are represented as points on a vertical line extending upward from the "minimum expected silviculture cost/ha" line. For example, silviculture regimes that have an expected final density of 800 stems per hectare have expected costs that range upward from a minimum of $735/ha. This curve represents an "efficient frontier" in the sense that each point on the curve corresponds to a silviculture regime that is a minimum-cost solution for the given expected stocking density.

\[ \text{FIGURE 1. Minimum expected silviculture cost, pseudo value, and net pseudo value per hectare as functions of expected stocking density (scaling factor = $2.45 per stem).} \]

---

Consider any other regime, $s'$, for which $d(s') \geq d^*$. Since $s^*$ maximizes $kd(s) - c(s)$, for fixed $k$, $kd^* - c^* \geq kd(s') - c(s')$. Hence, $c(s') \geq kd(s') - c^* + c^* = c(s^*)$. 

---

4
The value of treated stands is represented by the curve labeled “pseudo value/ha,” which equals the product of the scaling factor and the expected density. For example, in Figure 1, which corresponds to a scaling factor of $2.45 per stem, this pseudo value equals $7.35/ha ($2.45 \times 300$ stems per hectare), at the minimum density of 300 stems per hectare (i.e., the density achieved without any silviculture treatment), and $2450/ha at an expected density of 1000 stems per hectare, the largest expected density shown in the figure.

The “net pseudo value” equals the difference between the pseudo value and the minimum expected silviculture cost. This is the function optimized in the decision tree analysis. When the scaling factor is set to $2.45 per stem, the optimal silviculture regime has an expected stocking density of 800 stems per hectare and an expected silviculture cost of $875/ha, which, for this density, is a minimum expected cost.

As shown in Figure 2, when the scaling factor is increased from 2.45 to 2.73, the slope of the “pseudo value/ha” curve increases, causing the maximum value of the “net pseudo value/ha” curve to increase from 800 to 900 stems per hectare. The optimal treatment regime in Figure 2 has an expected silviculture cost of $1134/ha.

![Graph showing the relationship between expected stocking density and silviculture costs](image)

**FIGURE 2.** Minimum expected silviculture cost, pseudo value, and net pseudo value per hectare as functions of expected stocking density (scaling factor=$2.73 per stem).

Suppose now that the target density is 840 stems per hectare. Since scaling factors of 2.45 and 2.73 are found to generate optimal silviculture regimes with expected stocking densities of 800 and 900, respectively, one might expect that some scaling factor between 2.45 and 2.73 would produce an optimal silviculture regime with an expected density equal, or nearly equal, to the target density of 840. By iteratively optimizing the decision analysis with different scaling factors, we can build up curves such as those shown in Figure 3. Notice that, for the scaling factor equal to 2.45 and 2.73, the values for expected density and minimum expected cost are equal to the corresponding values shown in Figures 1 and 2, respectively.
The optimal solutions for scaling factors of 2.45 and 2.73 can be used to estimate a scaling factor that would result in an expected density of 840 stems per hectare. Using linear interpolation, we estimate the next candidate scaling factor to equal\(^5\):

\[ k = 2.45 + \frac{(840-800)(2.73-2.45)}{(900-800)} = 2.56 \]

This process does not necessarily converge to the target density. One reason for this is that there may be no silviculture regime whose expected density equals the target density. This would certainly be the case if the target density were set so high that it could not be achieved with any silviculture regime. Alternatively, one could have a situation in which there are no silviculture regimes whose expected densities are between two densities that span the target density.

It is in part for this reason that the search procedure ends as soon as a regime is found whose expected density is within a “target density range.” The target density range equals the target density plus or minus a user-specified “tolerance.” For example, if the target density were 825 and the tolerance were set to 5, the target density range would be 820–830 stems per hectare—provided a silvicultural regime that would achieve this density existed.

2.3 A Necessary Assumption

Although this procedure may make sense to us intuitively, there is no assurance that the algorithm will find optimal treatment regimes. For example, suppose the target density range were 900–910 stems per hectare and there was at least one treatment regime with an expected density in this range. What assurance would there be of the algorithm finding this regime?

If the relationships among optimal expected stocking density, minimum expected silviculture cost, and the scaling factor are as shown in Figure 3, then clearly the search procedure would identify an optimal regime. At issue is whether optimal expected stocking density and minimum expected cost are both increasing functions of the scaling factor.

---

5 If the optimal scaling factor is between \( k_x \) and \( k_y \), the next trial scaling factor is set to a value that will be at least \( k_x + \min[q, (k_x+k_y)/2] \), and at most \( k_x + \min[q, (k_x+k_y)/2] \), where \( q \) is a pre-specified minimum step-size. This is necessary to ensure convergence of the scale factor. The process ends if the difference between the last two trial scaling factors is within a pre-specified “cut-off” value before the expected density falls into the target density range.
This assumption can be shown to be true if the envelope of the minimum expected silviculture cost per hectare is a convex function of expected density. A continuously differentiable function with a single argument is convex if the slope of the function increases as the argument increases (i.e., if the second derivative is positive at all points). In other words, the function is convex if incremental silviculture costs become increasingly large as expected density is repeatedly increased by some fixed amount. Intuitively, one would expect this to be the case: large gains in density can be achieved at relatively small additional silviculture costs, whereas further increases in density at already high density levels are relatively costly to achieve. This assumption is also in keeping with assumptions on decreasing marginal productivity of investment, commonly used in economics and evident in practice. Hence, the "net pseudo value" curve, as shown in Figures 1 and 2, is convex.\(^6\)

2.4 Outputs of the Solution Procedure

The solution procedure produces the following outputs for each inventory unit analyzed:

- the optimal silviculture treatment regime (if a regime exists whose expected stocking density falls within the target density range);\(^7\)
- the present value of expected silviculture cost, by treatment category (site preparation, stocking, brushing) for the optimal silviculture treatment regime;
- expected silviculture employment, by treatment category, for the optimal silviculture treatment regime;
- a probability distribution of final stocking density for the optimal silviculture treatment regime; and
- the range of expected density/minimum silviculture cost pairs identified by the search procedure.\(^8\)

All but the first type of output—the optimal silviculture treatment regime—can be computed interactively for individual inventory units, or can be produced in a "batch" run for groups of selected inventory units (ranging from one to all inventory units). In the batch run, pre-selected inventory units are analyzed sequentially, with no requirement for user intervention after the process begins. The optimal silviculture policy is displayed on the screen only, in the form of a series of nested menus corresponding to decision and chance nodes in the decision tree.

2.5 The Role of COSTMIN In Silviculture Planning and Inventory Systems

2.5.1 Data requirements

As described above, COSTMIN is closely connected with SDSS. The reader is therefore referred to SDSS documentation for descriptions of modeling structure and data requirements. Because COSTMIN does not identify yield outcomes under different silviculture regimes, several of the input fields required by SDSS are not required by the COSTMIN model, including:\(^9\)

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\(^6\) To understand the significance of the convexity argument, assume that the minimum expected cost as a function of expected density, c(d), possesses a second derivative, c''(d). Since c is convex, c''(d) > 0 for all d. For fixed k, the decision analysis objective may be expressed in terms of expected density:

\[ V(d) = kd - c(d) \]

Since c is convex, -c is concave; and since kd is linear in d (and therefore concave), V is also concave. Hence, the maximum of V occurs where V'(d) = k - c'(d) = 0, that is, where c'(d) = k. Since c''(d) > 0, c'(d) is a strictly increasing function of d. Hence, there exists an inverse function d(k) that gives the optimal expected density as a strictly increasing function of the scaling factor k. Since c(d) is a strictly increasing function of d, there also exists a function C(k) = c[D(k)] that gives the minimum expected silviculture cost as a strictly increasing function of k. It follows that, for any silviculture regime with expected density d* and minimum expected cost c*(for this density), there exists some scaling factor k* whose corresponding optimal regime will have this expected density and cost.

\(^7\) If no treatment regime has an expected stocking density that falls within the target density range, the model reports on the treatment regime whose expected density is closest to one of the end-points of the range.

\(^8\) This provides information on the trade-off between silviculture cost and stocking density, which potentially may be very useful in setting or revising stocking standards.

\(^9\) COSTMIN has been modified so that none of this unnecessary data can be entered.
• yield tables;
• all data related to harvesting and processing, including: harvest, log hauling and processing costs and employment effects; log size and diameter category definitions; product recovery coefficients; and product prices;
• all data related to stand tending treatments, including the naming of treatments, treatment costs and employment effects, and choices of treatments and outcome probabilities for stand tending treatment groups;
• decision analysis objective weights (for net benefits, employment, and wood supply); and
• yield analysis objective weights and discount rate, and linear programming constraint parameters for harvest scheduling.

The COSTMIN model requires only the following data (for each reforestation and/or brushing treatment group) in addition to that required by SDSS:

• four possible final stocking densities (e.g., 700, 800, 900, and 1000 stems per hectare);
• the desired expected final, or “target,” stocking density (e.g., 900 stems per hectare);
• a stocking density “tolerance” value for terminating the optimization algorithm; and
• optional minimum and maximum “scaling factors” used by the optimization algorithm.

Guidelines for target and minimum free growing stocking standards are published on a site series specific basis by the B.C. Ministry of Forests. These guidelines also identify an allowable regeneration delay and the earliest and latest age of free growing assessment, and define “free growing” as a ratio of crop tree size to competing vegetation. The selection of four possible final stocking densities used in COSTMIN to describe the expected outcome of each silviculture regime is at the discretion of the user and should reflect the full range of likely outcomes across the reforestation and brushing treatment groups (e.g., from a minimum value less than the minimum stocking standard, to some maximum above the target stocking standard). Thus, the four final stocking densities could be viewed as point estimates that constitute the discrete probability density functions for the stocking outcomes on a given site. The desired target stocking density can also be discretionary around the target stocking standard presented in the guidelines. As well, the stocking density tolerance value and scaling factors can be adjusted so that the sensitivity of the optimal silviculture regime can be examined and the program execution time optimized.

The major effort in preparing the COSTMIN database is consumed in defining the reforestation and brushing treatment groups and deciding on inventory characteristics, silviculture treatments, treatment costs, times, and employment associated with each treatment group and silviculture activity. The current design of the model demands that considerable care be put into the naming and constructing of these model elements. Later changes may result in much of the data associated with each treatment group being overwritten. A list of the data elements that cannot be changed without loss of treatment group data is provided in Appendix 1.

To identify the optimal silviculture regime across all reforestation and brushing treatment groups of a complete forest inventory, it is necessary first to identify all possible combinations of the following:

**Inventory characteristics**

- Candidate species groups
- Species groups for treatment options
- Biogeoclimatic subzones or variants affecting treatment options
- Reforestation cover types
- Site groups (site edaphic characteristics affecting treatment options)
- Site class
- Stocking densities (from less than minimum to greater than maximum)
Silviculture treatments
Site preparation options
Natural stocking options
Seedling types
Planted stock options
Brushing options

Treatment groups
Reforestation types
Brushing types

Treatment costs, time, and employment
Site preparation
Seedling production
Planting
Brushing

It would also be necessary to attach probabilities of (1) the likelihood of carrying out each of these activities and (2) the likelihood of success for each procedure, as well as the likely effect of each action on stocking density outcomes, on a treatment group—silviculture regime specific basis. Because there are many ways that these factors can be combined, an extremely large amount of effort can be required to assemble all the information. This reflects the complexity of decisions associated with silviculture choices rather than of the nature of the model per se. Few of these probabilities can be derived empirically because of the lack of site- and treatment-specific response information. It is therefore imperative that “expert” sources of information be used if the optimal solutions identified by the COSTMIN model are to have any value. A useful illustration of the model’s abilities and input requirements is found in the information requirements and COSTMIN outcomes for two reforestation treatment groups that are relatively common to Fletcher Challenge’s fee simple holdings on Vancouver Island.

3 DEMONSTRATION CASE STUDIES OF COSTMIN

The following case studies illustrate (1) the data requirements necessary for successful model execution, (2) the model output, and (3) opportunities for interactively examining the expected costs and stocking density outcomes of optimal and alternative (sub-optimal) silviculture regimes.

Two reforestation treatment groups have been selected in two common site series of the eastern Very Dry Maritime variant of the Coastal Western Hemlock biogeoclimatic zone—the “Douglas-fir—Western hemlock—Salal” and “Redcedar—Lady fern” site series. The names of the model elements required to define the range of silviculture options common to these treatment groups are provided in Appendix 2. Given the large volume of information required to specify silvicultural treatments, the probabilities used in the case study analysis are not included in this report. However, this information has been provided to Forestry Canada.

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10 Subjective probabilities derived from expert judgment are commonly used in decision analysis. The conceptual basis is a personalist or Bayesian view of probability, rather than a frequentist view. Subjective probabilities are required for virtually all important environmental and resource policy decisions. There are well-developed protocols for developing probabilities in these contexts.
3.1 Case I

The first case study is for a treatment group located in the Douglas-fir–Western hemlock–Salal site series. This site series represents a relatively common ecosystem on eastern Vancouver Island that involves very few silviculture decisions to obtain satisfactorily stocked, free-to-grow regeneration of the desired species—Douglas-fir (possibly with a minor component of western redcedar). Figures 4a–c show the range of silviculture options and the expected stocking density outcomes and silviculture costs identified by the COSTMIN model.

Figure 4c shows that the optimal solution for regenerating this treatment group is a fall burn planted with 1+0 bareroot Douglas-fir. This simple case study, involving a treatment group that considered no need for brushing and weeding, only limited need for site preparation, and little choice of planting stock, had a total of 21 different stocking density outcomes and silviculture regimes. The result is an expected silviculture cost of $663/ha and final average stocking density of 779 stems per hectare. Figure 5 shows the COSTMIN output for this optimal solution. The total cost of $613/ha was divided between site preparation—the fall burn ($179/ha)—and planting ($484/ha). The total employment created in site preparation, provision of planting stock, and planting was 1.4 person-days.

The optimal solution identified by the COSTMIN model was not necessarily the most economically efficient. Because the target stocking standard was set at 800 stems per hectare and the tolerance set to 10 stems per hectare, COSTMIN identified the silviculture regime that came closest to the target stocking standard. To identify the most economically efficient silviculture strategy with COSTMIN, the expected silviculture costs of alternative regimes must be examined, along with their expected stocking density outcome.

Figure 6 shows this relationship across the full range of expected silviculture costs for both successful and unsuccessful outcomes. This approach identifies the silviculture regime of no site preparation, followed by planting with 1+0 313 Douglas-fir container stock, as the most economically efficient while still achieving a stocking density very similar (likely not significantly different) to the optimal regime identified by COSTMIN.

---

**FIGURE 4a.** Silviculture options⁴, expected stocking density outcomes (stems/ha)⁵, and silviculture costs⁶ identified by the COSTMIN model for the natural and planted, no site preparation, option.
FIGURE 4b. Silviculture options\(^1\), expected stocking density outcomes (stems/ha)\(^2\), and silviculture costs\(^3\) identified by the COSTMIN model for the spring burn planted option.

FIGURE 4c. Silviculture options\(^1\), expected stocking density outcomes (stems/ha)\(^2\), and silviculture costs\(^3\) identified by the COSTMIN model for the fall burn planted option.
Summary Values for Optimal Treatment Regime When Minimizing Present Value of Silviculture Cost for Reforestation Type Inventory Unit

BGC Zone: CWH-km
Cover Type: Current NSR
Operability: Easy
Hectares in Subunit: 0
Number of Iterations Performed: 8

<table>
<thead>
<tr>
<th>Undiscounted expected silviculture cost and employment per hectare</th>
<th>Cost per hectare</th>
<th>Person-days per hectare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site preparation</td>
<td>179</td>
<td>0</td>
</tr>
<tr>
<td>Stocking</td>
<td>484</td>
<td>1.4</td>
</tr>
<tr>
<td>Brushing</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>663</td>
<td>1.4</td>
</tr>
</tbody>
</table>

PV total expected silviculture cost per hectare: 621

Target Density (stems/ha): 900
Final Density (stems/ha): 779
Density Search Tolerance (stems/ha): 10
Scale Factors: Start Low: 50  Start High: 200  Final: 12,800

Probability Distribution of Final Stocking Density

<table>
<thead>
<tr>
<th>Final density</th>
<th>Chances per 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>37</td>
</tr>
<tr>
<td>600</td>
<td>84</td>
</tr>
<tr>
<td>800</td>
<td>843</td>
</tr>
<tr>
<td>1100</td>
<td>37</td>
</tr>
<tr>
<td>Total</td>
<td>1000</td>
</tr>
</tbody>
</table>

Expected density: 779

Combinations of Expected Final Stocking Density and Present Values of Minimum Expected Total Silviculture Cost

<table>
<thead>
<tr>
<th>Expected density</th>
<th>PV expected silviculture cost/ha ($)</th>
<th>Scaling factors</th>
<th>Number of solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>680</td>
<td>0</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>771</td>
<td>453</td>
<td>800</td>
<td>2</td>
</tr>
<tr>
<td>779</td>
<td>621</td>
<td>3,200</td>
<td>3</td>
</tr>
</tbody>
</table>

FIGURE 5. COSTMIN model output for the optimal solution for the treatment group used in Case Study I.
Expected stocking density (stems/ha)

No site preparation
1+0 313 Fd

Expected silviculture cost ($/ha)

FIGURE 6. Expected silviculture costs and expected stocking density outcomes of alternative silviculture regimes for Case Study I.

3.2 Case II

The second case study is for a treatment group located in the Redcedar–Lady fern site series. This site series represents an ecosystem on eastern Vancouver Island that often involves more complicated regeneration strategies. The main problem in this ecosystem is control of competing vegetation so that satisfactorily stocked, free-to-grow regeneration of the desired species—Douglas-fir, grand fir, and western redcedar—can be attained. This case considered four initial site preparation techniques, six different types of planting stock and species combinations, four kinds of brushing and weeding treatments (including no treatment), and four kinds of brushing and weeding retreatments. An examination of all possible combinations of silviculture treatments considered by COSTMIN (including "successful," "unsuccessful," and "unable to treat" paths) resulted in 13,824 possible outcomes (many silviculture activities of which are very unlikely). The implication is that silviculture choices often encountered in practical contexts can be many orders of magnitude more complex than could be processed intuitively or with a hand-held calculator.

The optimal solution for regenerating this treatment group is a fall burn planted with 1+0 313 Douglas-fir container stock, followed with a minimal amount of brushing using glyphosate in ground applications. This regime has an expected silviculture cost of $580/ha and expected final average stocking density of 758 stems per hectare. Figure 7 shows the COSTMIN output for this optimal solution. The total cost of $621/ha was divided among site preparation (the fall burn at $159/ha), planting ($452/ha), and brushing ($10/ha). The total employment created for the site preparation, provision of planting stock, planting, and brushing was 1.2 person-days.
There are too many treatment regimes to allow us to examine all possible combinations and generate an expected silviculture cost/stocking density outcome trend line. However, Figure 8 does show the trade-offs between silviculture costs and stocking density in the range approaching the target density. This analysis would suggest that the most economically efficient solution would require a silvicultural expenditure of approximately $420. The optimal solution followed is shown in Table 1.

**TABLE 1. Decision pathway for optimal outcome in Case II**

<table>
<thead>
<tr>
<th>Initial site preparation — Fall burn</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful</td>
<td>64%</td>
</tr>
<tr>
<td>Unsuccessful</td>
<td>16%</td>
</tr>
<tr>
<td>Unable to treat</td>
<td>20%</td>
</tr>
</tbody>
</table>

1+0.313 Fd planting stock

Results in outcomes: <360 (10%), 600 (20%), 800 (60%), and 1100 (10%)

<table>
<thead>
<tr>
<th>Brushing required</th>
<th>No brushing required</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>60%</td>
</tr>
</tbody>
</table>

Initial brushing

<table>
<thead>
<tr>
<th>Successful</th>
<th>68%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsuccessful</td>
<td>7%</td>
</tr>
<tr>
<td>Unable to treat</td>
<td>25%</td>
</tr>
</tbody>
</table>

Glyphosate/ground

Final density 758 stems/ha

13
Summary Values for Optimal Treatment Regime When Minimizing Present Value of Silviculture Cost for Reforestation Type Inventory Unit

BGC Zone: CWHxm
Cover Type: Current NSR
Operability: Easy
Hectares in Subunit: 0
Number of Iterations Performed: 8

<table>
<thead>
<tr>
<th>Undiscounted expected silviculture cost and employment per hectare</th>
<th>Cost per hectare</th>
<th>Person-days per hectare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site preparation</td>
<td>159</td>
<td>0</td>
</tr>
<tr>
<td>Stocking</td>
<td>452</td>
<td>1.2</td>
</tr>
<tr>
<td>Brushing</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>621</td>
<td>1.2</td>
</tr>
</tbody>
</table>

PV total expected silviculture cost per hectare: 580

Target Density (stems/ha): 900
Final Density (stems/ha): 758
Density Search Tolerance (stems/ha): 10
Scale Factors: Start Low: 50 Start High: 200 Final: 12 800

Probability Distribution of Final Stocking Density

<table>
<thead>
<tr>
<th>Final density</th>
<th>Chances per 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>60</td>
</tr>
<tr>
<td>600</td>
<td>208</td>
</tr>
<tr>
<td>800</td>
<td>648</td>
</tr>
<tr>
<td>1100</td>
<td>84</td>
</tr>
<tr>
<td>Total</td>
<td>1000</td>
</tr>
</tbody>
</table>

Expected density: 758

Combinations of Expected Final Stocking Density and Present Values of Minimum Expected Total Silviculture Cost

<table>
<thead>
<tr>
<th>Expected density</th>
<th>PV expected silviculture cost/ha ($)</th>
<th>Scaling factors</th>
<th>Number of solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>727</td>
<td>410</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>744</td>
<td>427</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>755</td>
<td>511</td>
<td>800</td>
<td>2</td>
</tr>
<tr>
<td>758</td>
<td>580</td>
<td>3 200</td>
<td>3</td>
</tr>
</tbody>
</table>

FIGURE 7. COSTMIN model output for the optimal solution for the treatment group used in Case Study II.
FIGURE 8. Combinations of expected final stocking density and present values of minimum expected total silviculture costs for outcomes of the treatment group.

4 DISCUSSION

4.1 Advantages of COSTMIN

COSTMIN offers an approach for identifying optimal regeneration strategies with cost minimization as the objective. The opportunity to examine alternative silviculture regimes and their associated stocking density outcomes and expected costs is likely the strongest attribute of COSTMIN. It provides a basis for objectively comparing silviculture strategies that incorporate judgments of the forester, as well as data.

Philosophically, COSTMIN represents an excellent tool for decision-making in an atmosphere of uncertainty. The tremendous complexity of interactions determining the outcome of any given silviculture strategy and the continuing limitations in our ability to make decisions based on empirical evidence make the use of decision theory most appropriate. COSTMIN would also make an excellent teaching tool, allowing students to examine biological and economic trade-offs between silviculture options, and introducing concepts of probability theory.

The optimal results identified for the two case studies do not necessarily represent the “best” overall silviculture strategy, if best is interpreted more broadly than cost minimization. In its present form, COSTMIN examines costs and outcomes in a relatively isolated context. Marrying COSTMIN with SDSS will likely improve this situation. An example of COSTMIN not offering the overall “best” silviculture strategy might be where COSTMIN identifies a fall or spring burn as a site preparation treatment to reduce planting and later brushing costs. This might achieve the minimum cost free-to-grow stocking objective, but might also seriously degrade the future productivity of the site—a factor currently not considered by COSTMIN. The proper way to deal with this situation would be to take great care in considering both the characteristics of each treatment group and the silviculture treatments specified for each treatment group. At the same time, treatments that might have significant negative long-term implications must not be specified for that treatment group.

In essence, these points call for the analysis of term net returns of silviculture investments, in which the analyses consider the effects on productivity and other biological and economic factors. Marrying COSTMIN with SDSS would resolve this problem, although the nature of provincial regulations makes it incumbent upon licensees to plan silviculture regimes that minimize the cost of meeting standards, but do not maximize the long-term returns from silviculture investments. COSTMIN was designed specifically to address the former problem; SDSS addresses the latter.
4.2 Limitations of COSTMIN

In its present form the COSTMIN program has several limitations. These can be classified into two categories: model design and model utility. There are several practical difficulties with the model's design. The first is the method of data entry through nested hierarchical screens. Much of the input data, particularly that for specifying silviculture treatments and outcome probabilities for each treatment group, may be similar among treatment groups. The model currently allows the user to copy the treatments and outcome probabilities of one "model" group to other groups by pressing "Alt-F10." This facility could be greatly improved if the opportunity were offered at a number of different levels of the hierarchy. The model would also be improved by having a "spreadsheet front end" or other full screen editing facility for preparing input data. This would greatly simplify treatment group modifications and offer a better overall picture of the data structure associated with each treatment group. Allowing the user to name the reforestation and brushing treatment group files when creating them and running the COSTMIN model would also improve the model's ease of use. Changes could then be made to the model element structure without losing current settings. Ideally, such an improvement should be designed so that changes to the treatment group structure will not result in loss of other model input data.

An additional improvement of the model's design would be to allow different silviculture regimes within a treatment group to have different target stocking densities. A somewhat extreme example where this situation might occur is in a treatment group representing a moist rich site in the CWHxmx subzone, where the licensee has the option of establishing a stand of (1) Douglas-fir, (2) grand fir and redcedar, or (3) cottonwood. The target stocking density for these stocking options would be 800, 900, and 400 stems per hectare, respectively. The present format of the model allows for only one target stocking density per treatment group, although this target could be respecified during the analysis.

Finally, the current version of COSTMIN has no facilities for output of results—to either a file or printer. The user always has the opportunity to capture an output screen or send output to the printer using "printscreen," but this is cumbersome by conventional software standards. Ideally, the user should be able to print both the complete input data and output data to a file. The opportunity to save the cost and stocking outcomes of all possible scenarios for each treatment unit in a hierarchical format (e.g., as per Figure 4) would provide a powerful tool for analysis of the relationship between expected silviculture costs and stocking density outcomes, allowing construction of cost/outcome functions such as those shown in Figures 6 and 8.

4.3 Future Use

The principal factors limiting the utility of the COSTMIN model are common to virtually all guides, expert systems, and models used to assist in identification of optimal strategies. These factors are not a fault of the COSTMIN model; instead, they relate to how the model is valued and accepted by end users. The first of these factors relates to how well the model might really be able to identify optimal minimum-cost strategies for a real site. Models in which factors important to the decision are not properly captured rarely have the ability to identify optimal solutions on a truly site-specific basis, because most management decisions are influenced by external factors as well as direct cost and outcome information. The decision to plant or not plant a given treatment unit will be partially guided by factors external to the COSTMIN model, such as a local natural seed source, the degree of logging disturbance, the amount of advance regeneration, and the need for rapid "green-up" for non-forest values. These external considerations will always require on-site, professional experience. Blind adherence to the optimal strategies identified by COSTMIN would lead to standardization of the decision-making process rather than optimization. Thus, like all models, the results of a COSTMIN analysis should be viewed as useful insight, but not as the "right" answer. No model could capture all the factors important to these decisions.

The decision theory approach taken by COSTMIN is probably its strongest and most attractive design feature. It makes the model structure extremely adaptive to new information as it becomes available and forces the "expert" specifying treatment groups and silviculture treatments to consider the limitations of current information. However, if the model is to provide truly optimal solutions, this information must be input by expert rather than technician level staff. Treatment group design and data input across even a small inventory is a daunting task and may preclude general acceptance of the COSTMIN model by many industrial and
governmental clients. This final factor limiting the utility of the COSTMIN model is, again, not a direct fault of the model. The most obvious solution to the possibly excessive time required for model preparation is to improve the data input front end. This might make the job of data entry much easier.

5 RECOMMENDATION

The COSTMIN model offers a sophisticated approach to identifying the minimum-cost silviculture strategy to achieve a specified target stocking density. Combining both the COSTMIN and SDSS models would allow the identification of optimal silviculture regimes and, possibly more importantly, the comparison of the cost and yield outcomes of alternative regimes. Forest management decision-making in British Columbia is currently highly regulated, with many decisions made on the basis of standardized guidelines, historical precedent, and ease of administrative compliance. COSTMIN has exceptional value for raising awareness of relationships between biological and economic outcomes.
APPENDIX 1. Data elements that cannot be changed without loss of treatment group data

The two files, CASE.RTG and CASE.BTG, should be backed up before any changes are made to the following data elements in COSTMIN. Changes to these data elements could result in a loss of existing treatment group data.

Reforestation Treatment Group Data

Naming Screens
BGC zones
Cover types
Site groups
Treated species

Treatment Group Aggregations
BGC zone groupings
Cover type groupings
Site group groupings
Access class groupings
Operability class groupings

Brushing Treatment Group Data

Naming Screens
BGC zones
Site classes
Treated species

Treatment Group Aggregations
BGC zone groupings
Treated species groupings
Regeneration method groupings
Site group groupings
Access class groupings
Operability class groupings
APPENDIX 2. Model elements required to define the range of silviculture options common to these treatment groups

Inventory characteristics:

Candidate species groups
FdPl, Fd, FdCw, FdBgCw, Cw, Ac, AcBgCw

Species groups for treatment options
As above

Biogeoclimatic subzones or variants affecting treatment options
CW-I-xm

Reforestation cover types
Current NSR

Site groups (site edaphic characteristics affecting treatment options)
Slightly dry, fresh, moist

Site class
Good, medium, poor

Stocking densities (from less than minimum to greater than maximum, stems/ha)
No stand <380; understocked 600; stocked 800; overstocked 1100

Silviculture treatments:

Site preparation options
Spring burn, fall burn, glyphosate/ground, glyphosate/air

Natural stocking options
Fd, FdCw, AcBgCw

Seedling types
1+0 313 Fd, 1+0 BR Fd, 1+1 BR Fd, 1+1 BR FdCw, 2+0 415 FdCw, 1+0 313 FdBgCw, 2+0 415 FdBgCw, 2+0 415 Cw, Ac whips, and whips + 2+0 AcBgCw

Planted stock options
As in seedling types with target stocking standard of 800 stems per hectare (400 stems per hectare for Ac)

Brushing options
Manual, manual 2x, mechanical scarification, glyphosate/ground, glyphosate/air
Treatment groups:

Reforestation types:
- BGC zone: CWHxlm1
- Cover type: current NSR
- Site group: slightly dry
- fresh: 2
- Access class: all classes
- Operability class: all classes

Total 2

Brushing types:
- BGC zone: CWHxlm1
- Species group: FdPl and Fd
- FdCw and FdBgCw
- Regeneration method: natural and planted
- Site class: all classes
- Access class: all classes
- Operability class: all classes

Total 2

Treatment costs, time, and employment:

Costs ($/ha):

Site preparation
- Spring burn: $200
- Glyphosate/ground: $250
- Mechanical scarification: $600
- Fall burn: $200
- Disc trench: $750

Seedling production:
- 1+0 313 Fd: $.21
- 1+1 BR Fd: $.27
- 1+0 313 FdBgCw: $.28
- 2+0 415 FdCw: $.29
- Ac whips: $.25
- 2+0 415 Cw: $.28
- Whips + 2+0 AcBgCw: $.27

Planting:

<table>
<thead>
<tr>
<th>Stock type</th>
<th>No treatment</th>
<th>Spring burn</th>
<th>Fall burn</th>
<th>Glyphosate/ground</th>
<th>Disc trench</th>
<th>Mechanical scarify</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+0 313 Fd</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
<td>.30</td>
<td>.22</td>
<td>.25</td>
</tr>
<tr>
<td>1+0 BR Fd</td>
<td>.40</td>
<td>.35</td>
<td>.35</td>
<td>.35</td>
<td>.25</td>
<td>.30</td>
</tr>
<tr>
<td>1+1 BR Fd</td>
<td>.45</td>
<td>.35</td>
<td>.35</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
</tr>
<tr>
<td>1+1 BR FdBgCw</td>
<td>.45</td>
<td>.35</td>
<td>.35</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
</tr>
<tr>
<td>2+0 415 FdCw</td>
<td>.40</td>
<td>.35</td>
<td>.35</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
</tr>
<tr>
<td>1+0 313 FdBgCw</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
<td>.30</td>
<td>.25</td>
<td>.25</td>
</tr>
<tr>
<td>2+0 415 FdBgCw</td>
<td>.40</td>
<td>.35</td>
<td>.35</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
</tr>
<tr>
<td>2+0 415 Cw</td>
<td>.40</td>
<td>.35</td>
<td>.35</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
</tr>
<tr>
<td>Ac whips</td>
<td>.25</td>
<td>.20</td>
<td>.20</td>
<td>.20</td>
<td>.15</td>
<td>.20</td>
</tr>
<tr>
<td>Whips + 2+0 AcBgCw</td>
<td>.35</td>
<td>.35</td>
<td>.30</td>
<td>.30</td>
<td>.25</td>
<td>.25</td>
</tr>
</tbody>
</table>
Brushing:
- Manual: $490
- Mechanical scarification: $850
- Glyphosate/air: $200
- Manual 2x: $900
- Glyphosate/ground: $350

Treatment times:
All 1 year except planting with no site preparation (2 years) and brushing (3 years)

Access and operability cost factors:
All costs set equal to 100%

Silviculture employment:
- Site preparation (pdays/ha):
  - Spring burn: 0.2
  - Glyphosate/ground: 0.8
  - Mechanical scarify: 0.2
  - Fall burn: 0.1
  - Disc trench: 0.1

- Seedling production (pdays/1000 seedlings):
  - All container stock: 0.2
  - All bareroot stock: 0.3
  - Cottonwood whips: 0.3

- Planting (pdays/ha):
  - All 313 container stock: 1.0
  - All bareroot stock: 1.2
  - Whips: 0.8

- Brushing (pdays/ha):
  - Manual: 3.0
  - Glyphosate/air: 0.1
  - Glyphosate/ground: 0.8
  - Manual 2x: 6.0
  - Mech. scarify: 0.2

Access and operability factors: all equal to 100%

Target density parameters:
- Target density: 800 stems per hectare
- Tolerance: 10 stems per hectare
- Starting scale factors: high: 200 low: 50

Decision analysis discount rate was selected to be 4%
APPENDIX 3. Operating instructions for the Silviculture Decision Support System (SDSS) silviculture Cost Minimization module (COSTMIN)

Installation

The cost minimization module of SDSS is installed in the same manner as SDSS. The user should create a new directory (say, "C:\COSTMIN") and copy all the files COSTMIN.EXE, SDSS.* and CASE.* from the distribution disk to this directory. The files with prefix "SDSS," together with the file COSTMIN.EXE, are the program files. They include:

- COSTMIN.EXE: Executable file
- SDSS.INL: List of lists
- SDSS.INM: List of menus
- SDSS.INS: List of screens
- SDSS.KEY: List of keywords
- SDSS.SC1: Screen image file, part 1
- SDSS.SC2: Screen image file, part 2
- SDSS.SC3: Screen image file, part 3
- SDSS.MNU: Menu image file
- SDSS.HLP: Help file
- SDSS.DBF: dBASE IV template for batch runs

The data are stored in the following files with filename prefix "CASE":

- CASE.MAI: Main data file
- CASE.REI: Reforestation type inventory
- CASE.BRI: Brushing type inventory
- CASE.RTG: Reforestation treatment group data
- CASE.BTG: Brushing treatment group data

These data files are a subset of the SDSS data files, but are slightly different in size and structure from the SDSS data files of the same name."

In future, SDSS will be integrated with the cost minimization module in such a way that the same database can be used for either a standard value maximization analysis (the original purpose of SDSS) or a cost minimization analysis. At present, however, this integration is not complete. The cost minimization module program and data files are incompatible with SDSS program and data files, and therefore must be kept in a separate directory and used only for cost minimization.

Running COSTMIN

To run COSTMIN, simply make C:\COSTMIN (or whichever directory contains the program and data files) the current directory, and execute COSTMIN.EXE.

COSTMIN's database is, for the most part, a subset SDSS's database. The differences between the two are detailed in the body of the report.
Once the data are entered, the user can analyze selected inventory units to identify silviculture treatment regimes that minimize the present value of expected silviculture costs subject to achieving a specified minimum expected final stocking density.\(^{12}\)

As with SDSS, the user can analyze inventory units one at a time, or analyze groups of inventory units in a batch process. The procedures for both options are the same as for SDSS. A dBASE IV template has been provided (SDSS.DBF) to read the batch output into a dBASE IV database (one record per inventory unit). To create the dBASE IV database, execute the following commands on the dBASE command line after completing the batch COSTMIN run:

```
SET PATH TO C:\COSTMIN
USE SDSS.DBF
ZAP  (to delete any existing records in the dBASE file)
APPEND FROM CASE.DBA SDF
```

The fields written to the file CASE.DBA are evident from the field names in the dBASE template. They consist of fields that identify the inventory unit (exactly as in the batch file produced by SDSS) and output fields. These output fields include:

- Number of hectares
- Site preparation cost and employment per hectare
- Stocking cost and employment per hectare
- Brushing cost and employment per hectare
- Present value of silviculture cost per hectare
- Target stocking density
- Target density tolerance
- Expected final stocking density
- Final scaling factor
- Possible final stocking densities (four)
- Probability distribution of final stocking density
- Combinations of trial expected stocking densities and minimum expected silviculture cost (i.e., stocking density/cost trade-off)

As in analyzing multiple data sets with SDSS, the CASE.* files must be copied to a different file name prefix after COSTMIN is exited (e.g., COPY CASE.* CASE1.*). When a previously created case is to be modified or analyzed, the data files must first be renamed CASE.*, or copied to files with a “CASE” prefix (e.g., COPY CASE1.* CASE.*).

\(^{12}\) This procedure differs from that for SDSS in that SDSS is a two-step procedure, the first being to compute tables of marginal values of treated stands (by solving a harvest scheduling linear program, if a “forest” perspective is taken, or by optimizing one or an infinite number of rotations if a “stand” perspective is elected). Only after the marginal values are computed can the decision tree problems be solved for individual inventory units.