# Potential financial returns from alternative silvicultural prescriptions in second-growth stands of coastal British Columbia

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**Abstract**: This paper reports the findings from a study made of the potential financial returns from nine alternative silvicultural prescriptions applied to four case-study stands of second growth in coastal British Columbia. The objectives were to compare prescriptions based on partial cutting with conventional clear-cutting and to explore the effects of harvesting costs and harvesting systems on potential returns. Inventory data were obtained for four case-study second-growth stands representing a wide range of both stocking and species composition. Prescriptions based on shelterwood, uneven-age management, and intermediate commercial thinnings followed by clear-cutting were specified. The PROGNOSIS growth and yield simulation program was used to model stand responses. Logging costs and timber gross and net values were estimated using a timber harvesting simulation model. Discounted cash flow analysis was used to compare the prescriptions. The findings showed that prescriptions based on partial cutting were more profitable than conventional clear-cutting in only a few cases, but competitive in most. Integrated design of individual treatments and whole prescriptions involving both silvicultural objectives and the economics of timber harvesting was recommended.

**Résumé** : Cet article présente les résultats d'une étude du rendement financier potentiel de neuf prescriptions sylvicoles alternatives appliquées à quatre peuplements côtiers de seconde venue en Colombie-Britannique. L'objectif consistait à comparer des prescriptions de coupes partielles à la coupe à blanc conventionnelle et à examiner les effets des coûts de récolte et des systèmes d'exploitation sur le rendement potentiel. Des données d'inventaire ont été obtenues pour quatre peuplements de seconde venue représentant une large gamme de densités et de compositions en espèces. Des prescriptions basées sur la coupe progressive, l'aménagement inéquienne ou encore l'éclaircie commerciale suivie de la coupe à blanc ont été élaborées. PROGNOSIS, le programme de simulation de la croissance et du rendement, a été utilisé pour modéliser la réaction des peuplements. Les coûts d'exploitation de même que les valeurs nettes et brutes des bois ont été estimés à l'aide d'un modèle de simulation de la récolte. L'analyse des liquidités actualisées a servi à comparer les prescriptions. Les résultats montrent que les prescriptions de coupe partielle sont plus rentables que la coupe à blanc conventionnelle uniquement dans quelques cas, mais qu'elles sont compétitives dans la majorité des cas. La conception intégrée de traitements individuels et de prescriptions globales considérant à la fois des objectifs sylvicoles et la rentabilité de la récolte des bois est recommandée.
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## Introduction

Alternative harvesting methods for partial cutting in commercial thinnings or seed tree, shelterwood, and selection management silvicultural systems have yet to be proven as either operationally or economically feasible in the majority of second-growth stands of coastal British Columbia (B.C.). Successful design of treatments requires that available equipment options and alternative engineering practices be carefully matched to silvicultural and site requirements to ensure both operational and economic viability. The potential financial returns from alternative silvicultural treatments and prescriptions is one measure that can be used to guide decision making among options. Important factors largely ignored in past studies of comparative returns from alternative cutting strategies are the effect of tree size on harvesting costs, net periodic cash flows, and long-term returns.

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This paper reports the findings from a study made of the potential financial returns from nine alternative silvicultural prescriptions applied to four case-study stands of second growth in coastal B.C. The study had two primary objectives. First, potential financial returns from a range of silvicultural prescriptions based on partial cutting was compared with conventional clear-cutting when applied to second-growth stands. Second, the effects of the harvesting system for individual cuttings and the detailed modeling of logging costs including the effect of tree size on potential returns were explored. We begin by describing the data and methods used in the study. Next, the results are presented and discussed, and finally conclusions are offered.

## Data and methods

### Case study stands

Four stands were used in the study, all of which are second-growth between 53 and 60 years old on medium growing sites. Stands I and III are located in the Campbell River area and were marked and sold for commercial thinning by the B.C. Ministry of Forests (MoF) under the Small Business Forest Enterprise Program. These stands are dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and have site indices of 34 and 30 m for Douglas-fir respectively.

 

**Table 1.** Silvicultural prescriptions.

| Prescription | Abbreviation | Description |
|---|---|---|
| 1 | $CC_0$ | Clear-cutting immediately |
| 2 | $CC_{30}$ | Clear-cutting in 30 years |
| 3 | $TH1_0CC_{30}$ | Thinning from below (B grade) immediately, clear-cutting in 30 years |
| 4 | $TH2_0CC_{30}$ | Thinning from below (C grade) immediately, clear-cutting in 30 years |
| 5 | $BA_{0/15}CC_{30}$ | Thinning from below to a residual basal area of 25 $m^2$ (B grade) immediately, similar thinning to 30 $m^2$ in year 15 (C grade), clear-cutting in year 30 |
| 6 | $NT_{0/15}CC_{30}$ | Thinning from below to a residual 400 trees/ha immediately (B grade), similar thinning to 300 trees/ha in year 15 (C grade), clear-cutting in year 30 |
| 7 | $SW1_{30}$ | Shelterwood consisting of a preparatory thinning from below immediately (B grade), regeneration cutting in 15 years (50% removal), overstory removal in 30 years |
| 8 | $SW2_{30}$ | Shelterwood consisting of a preparatory thinning from below immediately (C grade), regeneration cutting in 15 years (50% removal), overstory removal in 30 years |
| 9 | $UE_{0/15/30}$ | Individual tree selection combined thinning removing 20% of trees 13.5 cm DBH and larger up to 64 cm, and all trees larger than 64 cm (sites I and III) or 70 cm (sites II and IV) immediately, in 15 years, and in 30 years |

Stand II is located on private land owned by Canadian Forest Products Limited (CANFOR), near Port McNeill and is dominated by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carrière), and amabilis fir (*Abies amabilis* (Dougl.) Forbes) with a site index of 30 m (Sitka spruce). Stand IV is located on the University of British Columbia Research Forest in Maple Ridge, B.C., and contains a mixture of western hemlock, western redcedar (*Thuja plicata* Donn ex D. Don), and Douglas-fir with a site index of 28 m (Douglas-fir). Summary statistics on the initial stocking for the stands are given in Tables 4 to 7. These stands were selected to represent a relatively wide range of initial stocking and species composition. The terrain found at all sites is gentle with slopes generally below 15%, suggesting that both ground-based and cable systems are potentially usable; however, soils are sensitive to compaction and rutting, particularly under wet conditions.

### Silvicultural prescriptions

Nine different silvicultural prescriptions were specified for use in the simulation study, all of which covered a period of 30 years, which corresponds roughly to the conversion phase from the unmanaged to managed state for the majority of the options explored (see Table 1). The first ($CC_0$) and second ($CC_{30}$) prescriptions were simply variations on the timing of clear-cutting, in one case immediately, and in the other after 30 more years of growth. The third ($TH1_0CC_{30}$) and fourth ($TH2_0CC_{30}$) prescriptions involved commercial thinnings from below of different grades as described by Smith (1986) applied immediately followed by clear-cutting in 30 years. The fifth prescription ($BA_{0/15}CC_{30}$) was taken from a recent study of the financial viability of various thinning options for a sample of stands located on the Oregon State University Research Forest (Bishaw 1995). The sixth prescription ($NT_{0/15}CC_{30}$) involved commercial thinnings of specified intensities based on the residual number of trees per hectare followed by clear-cutting (Stone 1993). The seventh ($SW1_{30}$) and eighth ($SW2_{30}$) prescriptions were shelterwood systems, differing only in the nature of the initial (year 0) preparatory cuttings. The first employed a light thinning from below (grade B), identical with that used in prescription 3, and the second began with a heavier cutting (grade C) identical with the one made initially in prescription 4. The ninth prescription ($UE_{30}$) employed intensive selection management (Smith 1986), which leads to the development of uneven-age stands. Three cuttings were prescribed over the 30-year planning period spaced at 15-year intervals, all of which were a combination of individual tree selection and thinning.

### Growth and yield

Growth and yields were modeled using the Pacific Northwest Variant of the PROGNOSIS computer model developed by the U.S. Forest Service (Wykoff et al. 1982). Cruise data for the four case study stands obtained from the MoF, CANFOR, and staff at the U.B.C. Research Forest were entered as required by PROGNOSIS to create the initial inventory. Each of the nine silvicultural prescriptions were modeled separately by applying the appropriate options for cuttings available in the simulation model. With the exception of prescriptions 8 and 9, all commercial cuttings were required to produce a minimum of 50 $m^3$/ha in trees with diameter at breast height (DBH) larger than 15.0 cm. Prescriptions 8 and 9 involved commercial thinnings with strict specifications on either the residual basal area or number of trees per hectare, and these were adhered to independent of the resulting yield. For all cuttings, the option within PROGNOSIS for creating a file containing a detailed listing of the trees removed, including DBH and species, was chosen. This file is required as input to the timber harvesting simulation model used to estimate harvesting costs and gross and net revenue.

### Harvesting costs and log values

Harvesting productivity and costs, and gross and net values for trees and logs, were simulated using a timber harvesting simulation model developed by Howard (1987). This model is a Windows-based simulation program designed to predict the cost of harvesting individual tracts of timber using a wide range of harvesting systems. The model requires inventory data for the trees to be cut (DBH, height, species, and number of trees), harvest layout information for the stand, and cost information and production equations for the harvesting systems of interest. It also requires log prices by grade and tree bucking preferences, including lengths and minimum small-end log diameters.

**Table 2.** Costs per scheduled machine hour (SMH) by harvesting phase and system.

| | Harvesting phase – system ($/SMH) | | | | |
|---|---|---|---|---|---|
| | Felling | | Skidding–forwarding–yarding | | |
| Cost class | Hand felling | Single-grip harvester | Line skidder | Shortwood forwarder | Swing yarder[a] |
| Labor | 46.56 | 31.00 | 31.00 | 31.00 | 131.51 |
| Equipment | | | | | |
| Variable | 2.00 | 91.61 | 50.77 | 81.01 | 91.18 |
| Fixed (new[b]) | na | 61.56 | 24.62 | 61.56 | 73.87 |
| Fixed (used[c]) | na | 30.78 | 12.31 | 30.78 | 38.47 |
| Totals (new) | 48.56 | 184.17 | 106.39 | 173.57 | 296.56 |
| Totals (used) | 48.56 | 153.39 | 94.07 | 142.79 | 261.16 |

[a]Includes mobile backspar for clearcuts or skidder for swinging wood in partial cuts.
[b]Three years old, purchased new.
[c]Six years old, purchased used.

**Table 3.** Tree bucking specifications, mill-gate log prices (July 1996), and relative yields from second-growth stands, by species and log class.

| Specification, species | Log class 1 | Log class 2 | Log class 3 |
|---|---|---|---|
| % by BCFS log grade[a] | 80% I, 20% H | 100% J | 90% U, 10% pulp |
| Small-end diam. (cm) | 38 | 20 | 10 |
| Preferred lengths (m) 1st, 2nd, 3rd | 12.5, 10.7, 8.2 | 10.7, 8.2, 4.2 | 5.6, 5.0, 3.2 |
| Weighted avg. prices ($/m$^3$) | | | |
| Douglas-fir | 129 | 100 | 19 |
| Hemlock–spruce–balsam | 76 | 60 | 10 |
| Redcedar | 108 | 65 | 10 |
| Alder | 20 | 10 | 5 |

[a]British Columbia Forest Service letter grades (B.C. MoF 1989).

The harvesting simulation model functions as follows. The listing of harvested trees from each commercial cutting produced by PROGNOSIS is read automatically. Trees are first bucked into logs using the preferences provided and then four phases of logging (felling, yarding or skidding, processing at the landing, and transport with self-loading trucks) are simulated using the data and models for the harvesting equipment and crews chosen. Gross values are computed as the product of the log volume and the appropriate price given the grade. Log grades are assigned according to species and log dimensions only. Defects are not considered. Net log values are calculated by subtracting harvesting costs from gross value. These are totaled for all logs produced from the cutting and then divided by the total volume to give the net value or cash flow per unit volume.

Three harvesting systems were modeled, one of which (the swing yarder) required two sets of production equations, one for clear-cutting and one for partial cutting. The systems are described below with the sources for the production equations shown in parentheses:

(1) Line skidder: manual felling with chainsaws and ground skidding with line skidders (Howard and Coultish 1991; Whitwell 1990).
(2) Harvester–forwarder: machine felling and processing with a single-grip harvester and transport to landings with a bunk forwarder (McNeel and Rutherford 1994).
(3) Cable yarding: (*a*) for partial cuts, manual felling with chainsaws, and cable yarding with a swing yarder rigged to backspars (trees) and equipped with a drop-line carriage for lateral yarding; trees are swung from the landing using a line skidder (Howard and Coultish 1991; Howard et al. 1995); (*b*) for clearcuts, manual felling with chainsaws and cable yarding with a swing yarder rigged with grapples and a mobile backspar (Howard and Coultish 1991; MacDonald 1987).

For all sites and systems an average skidding or yarding distance of 125 m was assumed, while for partial cutting with the swing yarder an average lateral yarding distance of 20 m was used.

In the harvesting simulation model the production equations are used to predict the time it takes to process individual trees in each phase of logging. The time per tree is then converted to a production rate (m$^3$/h) by dividing by the volume of the tree. Cost per cubic meter is determined by dividing the combined hourly cost of equipment and labor for the phase ($/h) by the production rate for the tree ($\$/h \div m^3/h = \$/m^3$). The average cost per cubic meter for each cutting is computed by weighting the individual estimates of cost per cubic meter for each diameter class in the listing of cut trees by the total volume for the class.

A fixed contract rate of $9.00/m$^3$ for a 50-km haul for log transportation with self-loading trucks was determined by telephone survey of local contract log haulers in the Campbell River area. Equipment and crew cost data were taken from a combination of recently published studies, telephone surveys of equipment dealers, and the 1994–1997 International Woodworkers Association Coastal Master Agreement (International Woodworkers Association 1994) (see Table 2). Standard hourly rates for woods workers were inflated by 40% to account for benefits. Depreciation was calculated using the declining balance method, with an annual rate of 30%. Fixed costs also included a margin for profit calculated using the annual average investment method (Miyata 1980) and an alternative rate of return of 10%.

Two equipment cost scenarios were used as a means for exploring the sensitivity of the findings to changes in harvesting equipment costs. In the base-line case, all equipment was assumed to be 3 years old, but purchased new. These costs were applied to all prescriptions and stands. In the second scenario we assumed that equipment was

**Table 4.** Growth and yield statistics for nine silvicultural prescriptions applied to stand I.

| | | Initial conditions | | | | Removals | | | | Residual conditions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prescription | Year | Trees/ha | BA ($m^2$/ha) | Vol. ($m^3$/ha) | Vol. growth[a] ($m^3 \cdot ha^{-1} \cdot year^{-1}$) | Trees/ha | BA ($m^2$/ha) | Vol. ($m^3$/ha) | Vol. ($m^3$/trees) | Trees/ha | BA ($m^2$/ha) | Vol. ($m^3$/ha) |
| $CC_0$ | 0 | 790 | 32.0 | 280 | | 790 | 32.0 | 280 | 0.35 | | | |
| $CC_{30}$ | 0 | 790 | 32.0 | 280 | | | | | | 790 | 32.0 | 280 |
| | 30 | 643 | 61.0 | 722 | 14.7 | 643 | 61.0 | 722 | 1.12 | | | |
| $TH1_0CC_{30}$ | 0 | 790 | 32.0 | 280 | | 428 | 9.7 | 66 | 0.15 | 362 | 22.3 | 215 |
| | 30 | 321 | 45.0 | 573 | 12.0 | 321 | 45.0 | 573 | 1.79 | | | |
| $TH2_0CC_{30}$ | 0 | 790 | 32.0 | 280 | | 237 | 10.0 | 84 | 0.35 | 553 | 22.0 | 196 |
| | 30 | 479 | 50.0 | 574 | 12.6 | 479 | 50.0 | 574 | 1.20 | | | |
| $BA_{0/15}CC_{30}$ | 0 | 790 | 32.0 | 280 | | 373 | 8.0 | 52 | 0.14 | 417 | 24.0 | 228 |
| | 15 | 396 | 36.6 | 411 | 12.2 | 218 | 10.0 | 139 | 0.64 | 178 | 22.8 | 272 |
| | 30 | 168 | 30.6 | 405 | 8.9 | 168 | 30.6 | 405 | 2.41 | | | |
| $NT_{0/15}CC_{30}$ | 0 | 790 | 32.0 | 280 | | 373 | 8.5 | 56 | 0.15 | 400 | 23.5 | 224 |
| | 15 | 379 | 36.6 | 404 | 12.0 | 79 | 4.9 | 38 | 0.48 | 300 | 31.7 | 366 |
| | 30 | 282 | 41.9 | 533 | 11.1 | 282 | 41.9 | 533 | 1.89 | | | |
| $SW1_{30}$ | 0 | 790 | 32.0 | 280 | | 428 | 9.7 | 66 | 0.15 | 362 | 22.3 | 215 |
| | 15 | 341 | 34.0 | 388 | 11.6 | 272 | 21.6 | 232 | 0.85 | 69 | 12.4 | 155 |
| | 30 | 69 | 16.8 | 235 | 5.3 | 69 | 16.8 | 235 | 3.40 | | | |
| $SW2_{30}$ | 0 | 790 | 32.0 | 280 | | 237 | 10.0 | 84 | 0.35 | 553 | 22.0 | 196 |
| | 15 | 516 | 35.6 | 378 | 12.1 | 156 | 10.6 | 113 | 0.73 | 360 | 25.0 | 264 |
| | 30 | 341 | 35.4 | 423 | 10.6 | 341 | 35.4 | 423 | 1.24 | | | |
| $UE_{30}$ | 0 | 790 | 32.0 | 280 | | 158 | 6.7 | 56 | 0.35 | 632 | 25.3 | 224 |
| | 15 | 588 | 39.8 | 420 | 13.6 | 119 | 8.5 | 91 | 0.76 | 336 | 31.3 | 329 |
| | 30 | 440 | 39.1 | 454 | 8.3 | 89 | 8.0 | 94 | 1.06 | 351 | 31.1 | 363 |

[a]Growth rates in Tables 4 to7 are periodic annual increments.

purchased used 3 years previously at one-half the original purchase price used in the first scenario. This scenario was applied to stand I only. Fixed costs associated with developing access, equipment moving, and setup were held constant for all stands at $600/ha. Overhead costs (supervision, administration) were estimated as $75/shift.

Delivered log prices for July of 1996 were obtained from a local sawmill in the Campbell River area (Table 3). The timber harvesting simulation model permits the use of up to three log grades for each species. The log buyer for the mill provided estimates of the proportion of B.C. Forest Service log grades (B.C. MoF 1989) that typical second-growth stands in the area yield by species. For the most part, log grades are determined by the small-end diameter of the logs and can be aggregated into three broad classes, each of which contain a number of Forest Service letter grades. Additional factors that affect the grade of any given log within a small-end diameter class include knot sizes and distribution, and other defects were not available from the inventory data from the case-study stands, nor does the PROGNOSIS model provide for predicting the future quality of trees. Consequently, aggregate log grades were assigned to all harvested trees based on the scheme shown in Table 3.

Sensitivity analysis was also applied to delivered log prices. In March 1995 prices for pulp and utility grade logs at the Campbell River mill were $70/m^3$ for Douglas-fir and $82/m^3$ for hemlock, amabilis fir, and Sitka spruce compared with $10/m^3$ for the same grades and species in July 1996. Prices for the log class 3 shown in Table 3 were increased by $20/m^3$ for all species to explore the impact on the ranking of the nine prescriptions.

### Financial returns

The potential financial returns from each of the nine prescriptions applied to the four case-study stands were computed using discounted cash flow analysis. Net cash flows, excluding stumpage payments, were computed as follows. Per unit volume net revenue ($/m^3$) from each commercial treatment was computed by subtracting all logging costs from the gross product value, both of which are calculated using the timber harvesting simulation model. Net cash flows for each cutting were computed as the product of the total per hectare yield and the per unit volume net revenue minus timber marking costs (all treatments involving partial cutting with the exception of overstory removal in the shelterwood prescriptions) or planting costs (all harvests employing clear-cutting). For all prescriptions involving clear-cutting, planting was assumed to occur in the same year as harvesting. Planting costs of $438/ha and timber marking costs of $185/ha were assumed based on data from recent contracts provided by the B.C. MoF. Net cash flows were then discounted for the appropriate time using a discount rate of 4% (Heaps and Pratt 1989). The short-term net present value (NPV) for each prescription was computed as the sum of the discounted net revenues over a 30-year planning horizon. Soil expectation values (SEV) were also computed as a means for resolving differences in ending inventories among the various options by assuming that each prescription would be applied in perpetuity. For uneven-age management, we assumed that timber yields and values from the third cutting would be repeated at 15-year intervals. Both taxes and inflation were ignored. All NPV and SEV figures were expressed in $/ha.

## Results and discussion

### Growth and yield

The results of the growth and yield simulations are shown in

**Table 5.** Growth and yield statistics for nine silvicultural prescriptions applied to stand II.

| | | Initial conditions | | | | Removals | | | | Residual conditions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prescription | Year | Trees/ha | BA (m$^2$/ha) | Vol. (m$^3$/ha) | Vol. growth (m$^3$·ha$^{-1}$·year$^{-1}$) | Trees/ha | BA (m$^2$/ha) | Vol. (m$^3$/ha) | Vol. (m$^3$/trees) | Trees/ha | BA (m$^2$/ha) | Vol. (m$^3$/ha) |
| $CC_0$ | 0 | 1001 | 69.0 | 708 | | 1001 | 69.0 | 708 | 0.71 | | | |
| $CC_{30}$ | 0 | 1001 | 69.0 | 708 | | | | | | 1001 | 69.0 | 708 |
| | 30 | 820 | 85.0 | 1043 | 11.2 | 820 | 85.0 | 1043 | 1.27 | | | |
| $TH1_0CC_{30}$ | 0 | 1001 | 69.0 | 708 | | 626 | 20.5 | 138 | 0.22 | 375 | 48.5 | 570 |
| | 30 | 334 | 63.9 | 878 | 10.3 | 334 | 63.9 | 878 | 2.63 | | | |
| $TH2_0CC_{30}$ | 0 | 1001 | 69.0 | 708 | | 302 | 20.3 | 212 | 0.70 | 699 | 48.7 | 464 |
| | 30 | 598 | 66.8 | 825 | 12.0 | 598 | 66.8 | 825 | 1.38 | | | |
| $BA_{0/15}CC_{30}$ | 0 | 1001 | 69.0 | 708 | | 568 | 16.8 | 106 | 0.19 | 433 | 52.2 | 602 |
| | 15 | 405 | 60.4 | 759 | 10.4 | 195 | 18.1 | 191 | 0.98 | 210 | 42.3 | 568 |
| | 30 | 203 | 48.5 | 695 | 8.5 | 203 | 48.5 | 695 | 3.42 | | | |
| $NT_{0/15}CC_{30}$ | 0 | 1001 | 69.0 | 708 | | 601 | 18.6 | 123 | 0.20 | 400 | 50.4 | 585 |
| | 15 | 378 | 58.2 | 739 | 10.3 | 78 | 6.4 | 69 | 0.89 | 300 | 51.8 | 670 |
| | 30 | 284 | 58.4 | 812 | 9.4 | 284 | 58.4 | 812 | 2.86 | | | |
| $SW1_{30}$ | 0 | 1001 | 69.0 | 708 | | 626 | 20.5 | 138 | 0.22 | 375 | 48.5 | 570 |
| | 15 | 354 | 56.6 | 721 | 10.1 | 257 | 30.6 | 350 | 1.36 | 97 | 26.0 | 371 |
| | 30 | 94 | 30.4 | 456 | 5.7 | 94 | 30.1 | 456 | 4.86 | | | |
| $SW2_{30}$ | 0 | 1001 | 69.0 | 708 | | 302 | 20.3 | 212 | 0.70 | 699 | 48.7 | 464 |
| | 15 | 647 | 58.1 | 657 | 12.8 | 195 | 17.5 | 197 | 1.01 | 452 | 40.6 | 460 |
| | 30 | 425 | 49.1 | 606 | 9.8 | 425 | 49.1 | 606 | 1.43 | | | |
| $UE_{30}$ | 0 | 1001 | 69.0 | 708 | | 200 | 13.3 | 141 | 0.71 | 801 | 55.7 | 567 |
| | 15 | 736 | 65.1 | 735 | 11.2 | 150 | 17.7 | 223 | 1.49 | 586 | 47.3 | 512 |
| | 30 | 536 | 56.3 | 674 | 10.8 | 109 | 11.9 | 148 | 1.35 | 427 | 44.3 | 526 |

**Table 6.** Growth and yield statistics for nine silvicultural prescriptions applied to stand III.

| | | Initial conditions | | | | Removals | | | | Residual conditions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prescription | Year | Trees/ha | BA (m$^2$/ha) | Vol. (m$^3$/ha) | Vol. growth (m$^3$·ha$^{-1}$·year$^{-1}$) | Trees/ha | BA (m$^2$/ha) | Vol. (m$^3$/ha) | Vol. (m$^3$/trees) | Trees/ha | BA (m$^2$/ha) | Vol. (m$^3$/ha) |
| $CC_0$ | 0 | 354 | 27.4 | 241 | | 354 | 27.4 | 241 | 0.68 | | | |
| $CC_{30}$ | 0 | 354 | 27.4 | 241 | | | | | | 354 | 27.4 | 241 |
| | 30 | 321 | 46.6 | 561 | 10.6 | 321 | 46.6 | 561 | 1.75 | | | |
| $TH1_0CC_{30}$ | 0 | 354 | 27.4 | 241 | | 193 | 8.3 | 59 | 0.31 | 161 | 19.1 | 182 |
| | 30 | 149 | 33.6 | 432 | 8.3 | 149 | 33.6 | 432 | 2.90 | | | |
| $TH2_0CC_{30}$ | 0 | 354 | 27.4 | 241 | | 106 | 8.4 | 73 | 0.68 | 248 | 19.0 | 169 |
| | 30 | 230 | 35.4 | 431 | 8.7 | 230 | 35.4 | 431 | 1.87 | | | |
| $BA_{0/15}CC_{30}$ | 0 | 354 | 27.4 | 241 | | 168 | 6.9 | 49 | 0.29 | 186 | 20.5 | 193 |
| | 15 | 176 | 28.3 | 317 | 8.3 | 92 | 10.4 | 105 | 1.14 | 84 | 17.9 | 212 |
| | 30 | 82 | 23.0 | 301 | 5.9 | 82 | 23.0 | 301 | 3.67 | | | |
| $NT_{0/15}CC_{30}$ | 0 | 354 | 27.4 | 241 | | | | | | 354 | 27.4 | 241 |
| | 15 | 339 | 38.0 | 394 | 10.2 | 39 | 2.7 | 12 | 0.31 | 300 | 35.7 | 382 |
| | 30 | 287 | 44.2 | 532 | 10.0 | 284 | 44.2 | 532 | 1.87 | | | |
| $SW1_{30}$ | 0 | 354 | 27.4 | 241 | | 193 | 8.3 | 59 | 0.31 | 161 | 19.1 | 182 |
| | 15 | 154 | 26.2 | 300 | 7.8 | 119 | 15.4 | 170 | 1.43 | 35 | 10.8 | 129 |
| | 30 | 47 | 14.0 | 187 | 3.9 | 47 | 14.0 | 187 | 3.97 | | | |
| $SW2_{30}$ | 0 | 354 | 27.4 | 241 | | 106 | 8.4 | 73 | 0.68 | 248 | 19.0 | 169 |
| | 15 | 237 | 27.3 | 219 | 3.4 | 72 | 8.2 | 88 | 1.22 | 165 | 19.1 | 132 |
| | 30 | 161 | 22.5 | 310 | 11.9 | 161 | 22.5 | 310 | 1.93 | | | |
| $UE_{30}$ | 0 | 354 | 27.4 | 241 | | 72 | 5.3 | 49 | 0.68 | 282 | 22.1 | 178 |
| | 15 | 269 | 30.8 | 328 | 10.0 | 57 | 8.3 | 90 | 1.58 | 212 | 22.5 | 237 |
| | 30 | 203 | 29.9 | 356 | 7.9 | 50 | 9.3 | 118 | 2.36 | 153 | 20.3 | 238 |

**Table 7.** Growth and yield statistics for nine silvicultural prescriptions applied to stand IV.

| | | Initial conditions | | | | Removals | | | | Residual conditions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prescription | Year | Trees/ha | BA ($m^2$/ha) | Vol. ($m^3$/ha) | Vol. growth ($m^3 \cdot ha^{-1} \cdot year^{-1}$) | Trees/ha | BA ($m^2$/ha) | Vol. ($m^3$/ha) | Vol. ($m^3$/trees) | Trees/ha | BA ($m^2$/ha) | Vol. ($m^3$/ha) |
| $CC_0$ | 0 | 567 | 50.2 | 408 | | 567 | 50.2 | 408 | 0.72 | | | |
| $CC_{30}$ | 0 | 567 | 50.2 | 408 | | | | | | 567 | 50.2 | 408 |
| | 30 | 482 | 69.6 | 833 | 14.2 | 482 | 69.6 | 833 | 1.73 | | | |
| $TH1_0CC_{30}$ | 0 | 567 | 50.2 | 408 | | 358 | 15 | 93 | 0.26 | 209 | 35.2 | 317 |
| | 30 | 190 | 51.1 | 682 | 12.2 | 190 | 51.1 | 682 | 3.59 | | | |
| $TH2_0CC_{30}$ | 0 | 567 | 50.2 | 408 | | 171 | 15.3 | 122 | 0.72 | 396 | 34.9 | 291 |
| | 30 | 346 | 53.7 | 649 | 11.9 | 346 | 53.7 | 649 | 1.87 | | | |
| $BA_{0/15}CC_{30}$ | 0 | 567 | 50.2 | 408 | | 326 | 12.5 | 71 | 0.22 | 241 | 37.7 | 338 |
| | 15 | 230 | 46.0 | 519 | 12.1 | 114 | 13.9 | 136 | 1.19 | 116 | 32.1 | 383 |
| | 30 | 111 | 38.1 | 529 | 9.7 | 111 | 38.1 | 529 | 4.77 | | | |
| $NT_{0/15}CC_{30}$ | 0 | 567 | 50.2 | 408 | | 167 | 3.5 | 14 | 0.09 | 400 | 46.7 | 399 |
| | 15 | 373 | 56.4 | 598 | 13.3 | 73 | 4.1 | 30 | 0.40 | 300 | 45.8 | 474 |
| | 30 | 280 | 59.8 | 760 | 19.1 | 280 | 59.8 | 760 | 2.71 | | | |
| $SW1_{30}$ | 0 | 567 | 50.2 | 408 | | 358 | 15 | 91 | 0.25 | 209 | 35.2 | 317 |
| | 15 | 200 | 43.2 | 492 | 11.6 | 148 | 24.3 | 258 | 1.75 | 52 | 18.9 | 233 |
| | 30 | 50 | 23.0 | 333 | 6.7 | 50 | 23 | 333 | 6.66 | | | |
| $SW2_{30}$ | 0 | 567 | 50.2 | 408 | | 171 | 15.3 | 122 | 0.72 | 396 | 34.9 | 291 |
| | 15 | 371 | 44.5 | 458 | 11.1 | 111 | 13.3 | 137 | 1.24 | 260 | 31.2 | 320 |
| | 30 | 245 | 39.0 | 471 | 10.0 | 245 | 39.0 | 471 | 1.92 | | | |
| $UE_{30}$ | 0 | 567 | 50.2 | 408 | | 114 | 10.2 | 82 | 0.72 | 453 | 40 | 327 |
| | 15 | 423 | 50.1 | 513 | 12.4 | 96 | 15.7 | 173 | 1.81 | 327 | 34.4 | 340 |
| | 30 | 306 | 43.2 | 500 | 10.7 | 70 | 12.4 | 155 | 2.21 | 236 | 30.8 | 345 |

Tables 4 to 7. The tables show summary statistics for initial conditions, removals, and growth and residual stocking, if appropriate, for each cutting in each prescription. After each growth period, the number of trees per hectare was lower than after any cutting in the previous period as a result of mortality. Total yields over the 30-year period were highest for clear-cutting in year 30 in stands I, III, and IV and second highest for stand II where prescription $BA_{0/15}CC_{30}$ produced the most timber. Prescription $NT_{0/15}CC_{30}$ yielded the second highest volume for two stands, while the two prescriptions employing either B- or C-grade thinnings from below immediately followed by clear-cutting in year 30 ($TH1_0CC_{30}$ and $TH2_0CC_{30}$) generally produced the third or fourth greatest yield. The two shelterwood systems, one with the C-grade preparatory cut ($SW2_{30}$) and the other with the B-grade ($SW1_{30}$), consistently produced the fifth and seventh highest yields, respectively. Yields from both clear-cutting immediately ($CC_0$) and individual tree selection cutting ($UE_{30}$) cannot be compared directly with the other prescriptions, as both have standing inventory after year 30. Prescriptions $TH2_0CC_{30}$ and $SW2_{30}$, which employed C-grade thinnings from below initially, yielded considerably more timber overall 7 out of 8 times than the same prescriptions with B-grade initial thinnings.

Growth rates (periodic annual increment) varied considerably among the various prescriptions and stands. The lowest rate was 3.9 $m^3 \cdot ha^{-1} \cdot year^{-1}$ after the regeneration cut in the shelterwood prescription initiated with a B-grade thinning in stand III. The highest rate was 19.1 $m^3 \cdot ha^{-1} \cdot year^{-1}$ after the second cutting in prescription 9 applied to stand IV. Generally, growth rates were in the 8 to 12 $m^3 \cdot ha^{-1} \cdot year^{-1}$ range and were usually higher after initial thinnings of either grade compared with later entries. Growth rates for 30 years prior to clear-cutting without intermediate entries were among the highest, but in only one case (stand I) the highest. There are no published findings on growth rates after partial cutting in similar stands that can be used to validate the findings reported here with the exception of a study done by Omule (1988). This researcher reported periodic annual growth rates after thinnings calculated from tree measurements of around 20 $m^3 \cdot ha^{-1} \cdot year^{-1}$ for Douglas-fir stands with site index 36 to 46 m (mean of 40 m). Our findings compare favorably given the difference in site index (40 versus roughly 30 m for our stands), and the fact that we only accounted for growth in trees 12.5 cm DBH and larger, whereas all trees were included in the Omule study.

The B-grade thinnings from below consistently produced the lowest average volumes per tree, ranging from 0.087 to 0.308 $m^3$ (for stand II, the initial cutting for the $BA_{0/15}CC_{30}$ prescription produced a C-grade thinning from below). Average tree size for C-grade thinnings from below were roughly 2 to 3 times that shown for B-grade thinnings. The highest average volume per tree (3.403 to 6.664 $m^3$) consistently resulted from the overstory removal harvest in the shelterwood prescription beginning with the B-grade thinning from below ($SW1_{30}$). Clear-cutting following two thinnings to different prescribed residual basal areas ($BA_{0/15}CC_{30}$) produced the second highest average volume per tree. All multiple entry

**Table 8.** Gross values, harvesting costs, and net values by silvicultural prescription and treatment for stand I.

| | | | Harvesting system | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Line skidder | | Harvester–forwarder | | Swing yarder | |
| Prescription–cutting | Year | Gross value ($/m$^3$) | Cost ($/m$^3$) | Net value ($/m$^3$) | Cost ($/m$^3$) | Net value ($/m$^3$) | Cost ($/m$^3$) | Net value ($/m$^3$) |
| $CC_0$ | 0 | 35.36 | 29.07 | 6.29 | 26.24 | 9.12 | 52.32 | –16.96 |
| $CC_{30}$ | 30 | 54.63 | 15.94 | 38.69 | 16.13 | 38.50 | 28.73 | 25.90 |
| $TH1_0CC_{30}$ | 0 | 10.50 | 67.26 | –56.76 | 56.33 | –45.83 | 151.56 | –141.06 |
| | 30 | 61.90 | 13.76 | 48.14 | 14.41 | 47.49 | 22.77 | 39.13 |
| $TH2_0CC_{30}$ | 0 | 35.35 | 34.31 | 1.04 | 31.48 | 3.87 | 83.26 | –47.91 |
| | 30 | 56.56 | 15.61 | 40.95 | 15.91 | 40.65 | 27.55 | 29.01 |
| $BA_{0/15}CC_{30}$ | 0 | 10.33 | 70.57 | –60.24 | 58.99 | –48.66 | 158.47 | –148.14 |
| | 15 | 41.68 | 23.48 | 18.20 | 23.15 | 18.53 | 64.99 | –23.31 |
| | 30 | 66.52 | 13.26 | 53.26 | 14.17 | 52.35 | 20.26 | 46.26 |
| $NT_{0/15}CC_{30}$ | 0 | 10.50 | 69.21 | –58.71 | 57.87 | –47.37 | 155.93 | –145.43 |
| | 15 | 32.90 | 37.47 | –4.57 | 37.60 | –4.70 | 97.00 | –64.10 |
| | 30 | 62.82 | 13.66 | 49.16 | 14.34 | 48.48 | 22.19 | 40.63 |
| $SW1_{30}$ | 0 | 10.50 | 67.26 | –56.76 | 56.33 | –45.83 | 151.56 | –141.06 |
| | 15 | 47.37 | 19.24 | 28.13 | 19.01 | 28.36 | 50.47 | –3.10 |
| | 30 | 75.11 | 13.60 | 61.51 | 15.17 | 59.94 | 24.47 | 50.64 |
| $SW2_{30}$ | 0 | 35.35 | 34.31 | 1.04 | 31.48 | 3.87 | 83.26 | –47.91 |
| | 15 | 46.94 | 19.24 | 27.70 | 22.91 | 24.03 | 56.75 | –9.81 |
| | 30 | 57.31 | 15.79 | 41.52 | 16.07 | 41.24 | 38.35 | 18.96 |
| $UE_{30}$ | 0 | 35.40 | 38.03 | –2.63 | 35.20 | 0.20 | 86.92 | –51.52 |
| | 15 | 49.78 | 24.65 | 25.13 | 24.38 | 25.40 | 56.68 | –6.90 |
| | 30 | 54.08 | 21.53 | 32.55 | 21.78 | 32.30 | 47.31 | 6.77 |

prescriptions showed increasing average tree size with successive cuttings with the exception of individual tree selection applied to stand II.

### Harvesting costs, and gross and net values

The results from the simulation of harvesting costs and the calculation of gross and net values for each treatment in the nine prescriptions and four stands are shown in Tables 8–11. The pattern shown by harvesting costs generally mirrors that discussed above with respect to average tree size. Cuttings with the smallest average tree size (B-grade thinnings from below) had the highest harvesting costs, while the lowest costs were shown for cuttings with the biggest average tree size. The only exception to the trend was with overstory removals in the shelterwood prescriptions when a swing yarder was used that showed higher than expected costs. This is because care must be taken to avoid damage to residual trees (in this case the advance growth), and this requires lateral yarding with a drop-line carriage that is less productive and therefore more costly than conventional clear-cutting with the same machine. The effect of the sizes of trees taken was displayed most dramatically by those prescriptions that initiate with a B-grade thinning from below. For these prescriptions, harvesting costs for the first entry, independent of the system used, were about three to five times as high as for the final cutting, and in one case the difference was nearly 10-fold. Absolute differences were around \$40 to \$50/m$^3$ and in one case differed by an incredible \$165.38/m$^3$ (swing yarder, stand IV, $NT_{0/15}CC_{30}$). Harvesting costs for the two ground-based systems were very similar. The line skidder had a slight advantage in cuttings that produced larger timber, and the harvester–forwarder combination was favored slightly in smaller wood. Uncertainties with respect to actual equipment costs and machine productivities make it impossible to state conclusively which system was superior. Both ground-based systems were substantially cheaper than the swing yarder, with differences ranging from a low of roughly \$7 to a high of \$60/m$^3$. Generally, cable yarding costs were about double those of either ground-based system.

It is possible to obtain some feel for the difference in yarding costs associated with clear-cutting versus partial cutting by comparing the costs of final harvest between the $TH2_0CC_{30}$ (clearcut) and $SW2_{30}$ (partial cut) prescriptions. The final cuttings in these two prescriptions had very similar average tree size and volume harvested per hectare, which permits at least rough comparison. Differences in costs ranged from about \$7 to \$10/m$^3$, which represents a roughly 50% increase when partial cutting.

The pattern shown for gross value was the reverse of that described above for harvesting costs. Gross value was lowest for cuttings that produced the smallest average tree size and the lowest volume per hectare harvested (B-grade thinnings from below). These cuttings produced predominantly pulp-grade material, and gross value ranged from roughly \$10 to \$35/m$^3$. C-grade thinnings from below yielded timber with

**Table 9.** Gross values, harvesting costs, and net values by silvicultural prescription and treatment for stand II.

| Prescription–cutting | Year | Gross value ($/m$^3$) | Line skidder Cost ($/m$^3$) | Line skidder Net value ($/m$^3$) | Harvester–forwarder Cost ($/m$^3$) | Harvester–forwarder Net value ($/m$^3$) | Swing yarder Cost ($/m$^3$) | Swing yarder Net value ($/m$^3$) |
|---|---|---|---|---|---|---|---|---|
| $CC_0$ | 0 | 65.33 | 19.51 | 45.82 | 18.71 | 46.62 | 32.80 | 32.53 |
| $CC_{30}$ | 30 | 68.97 | 14.98 | 53.99 | 15.67 | 53.30 | 25.86 | 43.11 |
| $TH1_0CC_{30}$ | 0 | 23.28 | 44.57 | –21.29 | 37.98 | –14.70 | 113.25 | –89.97 |
| | 30 | 78.84 | 12.39 | 66.45 | 13.78 | 65.06 | 19.32 | 59.52 |
| $TH2_0CC_{30}$ | 0 | 65.41 | 21.55 | 43.86 | 20.75 | 44.66 | 49.41 | 16.00 |
| | 30 | 69.52 | 14.73 | 54.79 | 15.46 | 54.06 | 24.93 | 44.59 |
| $BA_{0/15}CC_{30}$ | 0 | 20.24 | 51.49 | –31.25 | 43.26 | –23.02 | 128.90 | –108.66 |
| | 15 | 53.59 | 18.14 | 35.45 | 18.01 | 35.58 | 45.12 | 8.47 |
| | 30 | 86.72 | 12.03 | 74.69 | 13.88 | 72.84 | 23.04 | 63.68 |
| $NT_{0/15}CC_{30}$ | 0 | 22.57 | 47.40 | –24.83 | 40.19 | –17.62 | 120.99 | –98.42 |
| | 15 | 51.06 | 24.66 | 26.40 | 24.42 | 26.64 | 54.54 | –3.48 |
| | 30 | 80.97 | 12.25 | 68.72 | 13.64 | 67.33 | 24.38 | 56.59 |
| $SW1_{30}$ | 0 | 23.28 | 44.57 | –21.29 | 37.98 | –14.70 | 113.25 | –89.97 |
| | 15 | 58.82 | 15.46 | 43.36 | 15.35 | 43.47 | 35.53 | 23.29 |
| | 30 | 97.61 | 12.21 | 85.40 | 14.99 | 82.62 | 20.65 | 76.96 |
| $SW2_{30}$ | 0 | 65.41 | 21.55 | 43.86 | 20.75 | 44.66 | 49.11 | 16.30 |
| | 15 | 67.06 | 18.97 | 48.09 | 18.96 | 48.10 | 42.18 | 24.88 |
| | 30 | 69.96 | 14.83 | 55.13 | 15.65 | 54.31 | 34.77 | 35.19 |
| $UE_{30}$ | 0 | 65.27 | 23.05 | 42.22 | 22.24 | 43.03 | 50.98 | 14.29 |
| | 15 | 83.32 | 17.24 | 67.64 | 18.54 | 66.16 | 35.34 | 50.05 |
| | 30 | 68.28 | 18.13 | 53.21 | 18.84 | 52.11 | 39.04 | 33.38 |

about 2 to 3 times the value of the B-grade cuttings, or between about \$35 and \$70/m$^3$. The highest gross value was consistently produced from the overstory removal in the $SW1_{30}$ prescription, which ranged from \$75.11 to \$115.64/m$^3$. The most uniform gross timber values were produced from the $TH2_{0/15}CC_{30}$ (C-grade thinning followed by clear-cutting), $SW2_{30}$ (shelterwood with C-grade initial thinning), and $UE_{30}$ (individual tree selection system). The difference in gross value between the lowest and highest value cuttings within these prescriptions did not exceed \$20/m$^3$, whereas with most of the other prescriptions (excluding clear-cutting only) the difference varied from roughly \$50 to \$80/m$^3$. Most importantly, the initial cuttings for these three prescriptions were about double the value of the first harvests in the other multiple entry prescriptions and were very close to the gross value shown for clear-cutting immediately.

The effect of tree size on both gross value and variable logging costs is depicted graphically in Fig. 1, which shows the results from clear-cutting stand IV after 30 years additional growth ($CC_{30}$). There are a number of interesting points demonstrated by the graph. First, it can be seen that the range in harvesting costs was equivalent to the range in gross value for this stand, or to put it another way, harvesting costs had as large an impact on net value as log prices. Second, beyond about 60 cm DBH, all harvesting systems were about equal in cost. Costs for the harvester–forwarder system rose at this point because trees became too big to be cut by the single-grip harvester so they had to be hand-felled. Third, as was noted above, the harvester–forwarder system enjoyed a slight advantage in smaller timber over the line skidder. Conversely, in larger wood the line skidder had lower costs. Finally, the marginal tree size for the three harvesting systems was between about 24 and 28 cm. This was the size of tree that made no

**Fig 1.** The effect of tree size on timber values and logging variable costs for clear-cutting with three different harvesting systems.

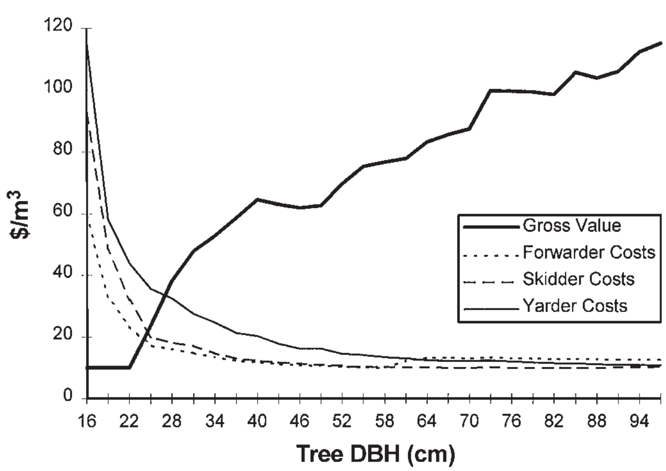

**Table 10.** Gross values, harvesting costs, and net values by silvicultural prescription and treatment for stand III.

| | | | Harvesting system | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Line Skidder | | Harvester–forwarder | | Swing yarder | |
| Prescription–cutting | Year | Gross value ($/m³) | Cost ($/m³) | Net value ($/m³) | Cost ($/m³) | Net value ($/m³) | Cost ($/m³) | Net value ($/m³) |
| $CC_0$ | 0 | 69.91 | 15.15 | 54.76 | 13.79 | 56.12 | 32.15 | 37.76 |
| $CC_{30}$ | 30 | 88.57 | 14.80 | 73.77 | 16.93 | 71.64 | 24.91 | 63.66 |
| $TH1_0CC_{30}$ | 0 | 27.49 | 46.88 | –19.39 | 42.36 | –14.87 | 115.25 | –87.76 |
| | 30 | 98.77 | 13.64 | 85.13 | 15.55 | 83.22 | 20.23 | 78.54 |
| $TH2_0CC_{30}$ | 0 | 69.95 | 30.15 | 39.80 | 25.83 | 44.12 | 65.32 | 4.63 |
| | 30 | 89.83 | 14.86 | 74.97 | 16.22 | 73.61 | 24.26 | 65.57 |
| $BA_{0/15}CC_{30}$ | 0 | 25.78 | 49.69 | –23.91 | 44.71 | –18.93 | 119.59 | –93.81 |
| | 15 | 72.26 | 22.00 | 50.26 | 21.66 | 50.60 | 50.57 | 21.69 |
| | 30 | 108.18 | 13.85 | 94.33 | 16.79 | 91.39 | 19.11 | 89.07 |
| $NT_{0/15}CC_{30}$ | 0 | | | | | | | |
| | 15 | 16.54 | 82.90 | –66.36 | 80.31 | –63.77 | 157.44 | –140.90 |
| | 30 | 89.93 | 14.62 | 75.31 | 15.94 | 73.99 | 24.28 | 65.65 |
| $SW1_{30}$ | 0 | 27.49 | 46.88 | –19.39 | 42.36 | –14.87 | 115.25 | –87.76 |
| | 15 | 81.18 | 18.36 | 62.82 | 18.04 | 63.14 | 40.71 | 40.47 |
| | 30 | 115.64 | 15.18 | 100.46 | 20.07 | 95.57 | 23.22 | 92.42 |
| $SW2_{30}$ | 0 | 69.95 | 30.15 | 39.80 | 25.83 | 44.12 | 65.32 | 4.63 |
| | 15 | 82.37 | 23.39 | 58.98 | 23.66 | 58.71 | 48.40 | 33.97 |
| | 30 | 90.15 | 15.41 | 74.74 | 16.80 | 73.35 | 33.40 | 56.75 |
| $UE_{30}$ | 0 | 69.93 | 34.79 | 35.14 | 33.59 | 36.34 | 69.97 | –0.04 |
| | 15 | 89.36 | 22.63 | 66.73 | 24.23 | 65.13 | 43.60 | 45.76 |
| | 30 | 97.34 | 18.60 | 78.74 | 21.29 | 76.05 | 26.31 | 71.03 |

contribution to covering fixed costs or profits, and for profits to be maximized no trees smaller than this size should be handled.

Net values (gross value minus harvesting costs) that represent the periodic cash flows varied considerably among the prescriptions, treatments, stands, and harvesting systems. With only a few exceptions the two clear-cutting prescriptions, C-grade commercial thinning followed by clear-cutting, shelterwood employing a C-grade thinning, and individual tree selection showed positive net values for all treatments. The exceptions were in the early treatments when the swing yarder was used, particularly in stand I where the first two entries showed negative net values. With only one exception, the B-grade thinnings from below showed negative net values regardless of the harvesting system used. At the prices used here these cuttings were simply not profitable. Conversely, C-grade thinnings were almost always profitable, even when conducted with the swing yarder. The only exception was, again, in stand I. Except for the B-grade thinnings from below, logging was shown to be profitable with both ground-based systems in all treatments. Harvesting with the swing yarder was not profitable in light partial cuts, where costs were as much as 10 times gross value and frequently double.

### Financial returns

The results from the analysis of the potential financial returns from the nine alternative prescriptions are shown in Tables 12–15 for stands I through IV, respectively. In stand I, the prescriptions with the three highest NPVs were clear-cutting immediately ($CC_{30}$), C-grade thinning followed by clear-cutting ($TH2_0CC_{30}$), and shelterwood beginning with a C-grade thinning ($SW2_{30}$) in that order for all harvesting systems. Ranking based on SEVs was identical, and these values were only slightly higher than the 30-year NPVs with the exception of uneven-age management ($UE_{30}$). This option nearly doubled in value, but still is not competitive with the majority of alterntives. For the ground-based systems, all prescriptions showed positive returns and the difference in NPVs between the highest and third highest values was roughly \$1500 to \$1700/ha, or 18 to 21%. For the cable system, the highest NPV ($CC_{30}$) was almost \$5000 higher than the second most profitable prescription ($TH2_0CC_{30}$), which was the only other option with positive returns. All other prescriptions that employed cable logging led to significant losses owing to the large number of small trees and the resulting low average volume per tree (see Table 4).

In stand II, the situation was dramatically different owing to the much higher initial stocking compared with stand I (see Tables 4 and 5). All prescriptions were profitable for both ground-based and cable systems, and the three highest ranking prescriptions were completely different compared with stand I. For ground-based logging, clear-cutting immediately ($CC_0$) followed by shelterwood management beginning with a C-grade thinning ($SW2_{30}$), and then clear-cutting in 30 years ($CC_{30}$) generated the three highest returns in that order. With cable

**Table 11.** Gross values, harvesting costs and net values by silvicultural prescription and treatment for stand IV.

| | | | Harvesting system | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Line skidder | | Harvester–forwarder | | Swing yarder | |
| Prescription–cutting | Year | Gross value ($/m$^3$) | Cost ($/m$^3$) | Net value ($/m$^3$) | Cost ($/m$^3$) | Net value ($/m$^3$) | Cost ($/m$^3$) | Net value ($/m$^3$) |
| $CC_0$ | 0 | 62.46 | 19.85 | 42.61 | 19.08 | 43.38 | 29.20 | 33.26 |
| $CC_{30}$ | 30 | 73.74 | 14.32 | 59.42 | 15.71 | 58.03 | 20.92 | 52.82 |
| $TH1_0CC_{30}$ | 0 | 35.26 | 37.03 | –1.77 | 31.98 | 3.28 | 79.46 | –44.20 |
| | 30 | 82.26 | 12.40 | 69.86 | 14.93 | 67.33 | 16.75 | 65.51 |
| $TH2_0CC_{30}$ | 0 | 62.49 | 23.68 | 38.81 | 22.91 | 39.58 | 44.76 | 17.73 |
| | 30 | 74.70 | 14.26 | 60.44 | 15.76 | 58.94 | 20.46 | 54.24 |
| $BA_{0/15}CC_{30}$ | 0 | 28.62 | 41.81 | –13.19 | 35.98 | –7.36 | 88.00 | –59.38 |
| | 15 | 60.39 | 19.23 | 41.16 | 18.50 | 41.89 | 39.13 | 21.26 |
| | 30 | 88.79 | 12.33 | 76.46 | 15.99 | 72.80 | 15.32 | 73.47 |
| $NT_{0/15}CC_{30}$ | 0 | 10.00 | 120.88 | –110.88 | 107.19 | –97.19 | 183.84 | –173.84 |
| | 15 | 28.29 | 48.40 | –20.11 | 44.28 | –15.99 | 85.79 | –57.50 |
| | 30 | 77.68 | 12.89 | 64.79 | 14.95 | 62.73 | 18.46 | 59.22 |
| $SW1_{30}$ | 0 | 35.26 | 37.03 | –1.77 | 31.98 | 3.28 | 79.46 | –44.20 |
| | 15 | 65.21 | 15.79 | 49.42 | 15.25 | 49.96 | 30.60 | 34.61 |
| | 30 | 96.92 | 13.05 | 83.87 | 18.02 | 78.90 | 18.47 | 78.45 |
| $SW2_{30}$ | 0 | 62.49 | 23.68 | 38.81 | 22.91 | 39.58 | 44.76 | 17.73 |
| | 15 | 69.07 | 20.32 | 48.75 | 20.84 | 48.23 | 37.05 | 32.02 |
| | 30 | 74.63 | 14.56 | 60.07 | 16.04 | 58.59 | 27.49 | 47.14 |
| $UE_{30}$ | 0 | 62.46 | 26.44 | 36.02 | 25.66 | 36.80 | 47.52 | 14.94 |
| | 15 | 80.93 | 17.97 | 65.51 | 20.38 | 62.64 | 30.60 | 53.61 |
| | 30 | 78.13 | 17.02 | 59.18 | 19.38 | 56.66 | 28.92 | 47.74 |

**Table 12.** Net present values ($/ha) for nine alternative silvicultural prescriptions applied to stand I.

| | 30-year planning horizon | | | Soil expectation value | | |
|---|---|---|---|---|---|---|
| | Line skidding | Harvester–forwarder | Swing yarder | Line skidding | Harvester–forwarder | Swing yarder |
| $CC_0$ | 1323 | 2116 | –5187 | 1496 | 2392 | –5865 |
| $CC_{30}$ | **8476** | 8434 | **5630** | **8573** | **8530** | **5694** |
| $TH1_0CC_{30}$ | 4468 | 5069 | –2645 | 4634 | 5257 | –2743 |
| $TH2_0CC_{30}$ | **7012** | ***7197*** | 788 | 7271 | **7463** | **817** |
| $BA_{0/15}CC_{30}$ | 4459 | 4973 | –3792 | 4624 | 5157 | –3932 |
| $NT_{0/15}CC_{30}$ | 4274 | 4795 | –3247 | 4432 | 4972 | –3367 |
| $SW1_{30}$ | 4076 | 4708 | –6261 | 4227 | 4882 | –6493 |
| $SW2_{30}$ | *6688* | 6925 | *–2458* | *6935* | *7181* | *–2549* |
| $UE_{30}$ | 1724 | 1889 | –3381 | 2835 | 2991 | –3206 |

**Note**: In Tables 12–15, figures in bold are the highest for the harvesting system, those shown in bold italics are second highest, and those shown in italics only are third highest.

logging, the C-grade thinning followed by clear-cutting in 30 years ($TH2_0CC_{30}$) replaced shelterwood as the second most profitable option. Again, the ranking was identical using SEVs, with $UE_{30}$ showing the largest increase over the 30-year NPV. Clear-cutting immediately yielded between roughly $7400 and $8200/ha more than the second best option depending on the harvesting system used, which represents between 23 and 36% higher returns. Profits from ground-based logging were about 1.5 times what was possible from cable harvesting for the top three prescriptions.

The results for stand III showed yet another pattern. With ground-based logging, clear-cutting immediately ($CC_{30}$) ranked highest, but shelterwood ($SW2_{30}$), clear-cutting in 30 years ($CC_{30}$), and the C-grade thinning followed by clear-cutting in 30 years ($TH2_0CC_{30}$) all generated returns that were very close to the top-ranked option (within 2–7%). With cable systems,

**Table 13.** Net present values ($/ha) for nine alternative silvicultural prescriptions applied to stand II.

| | 30-year planning horizon | | | Soil expectation value | | |
|---|---|---|---|---|---|---|
| | Line skidding | Harvester–forwarder | Swing yarder | Line skidding | Harvester–forwarder | Swing yarder |
| $CC_0$ | **32 003** | **32 569** | **22 593** | **36 188** | **36 828** | **25 548** |
| $CC_{30}$ | 17 222 | 17 000 | *13 724* | 17 418 | 17 194 | *13 881* |
| $TH1_0CC_{30}$ | 14 730 | 15 263 | 3 376 | 15 275 | 15 828 | 3 501 |
| $TH2_0CC_{30}$ | *22 904* | *22 888* | ***14 407*** | *23 751* | *23 734* | ***14 940*** |
| $BA_{0/15}CC_{30}$ | 15 656 | 16 167 | 3 283 | 16 235 | 16 765 | 3 405 |
| $NT_{0/15}CC_{30}$ | 14 737 | 15 283 | 1 526 | 15 282 | 15 849 | 1 583 |
| $SW1_{30}$ | 17 218 | 17 758 | 2 652 | 17 855 | 18 414 | 2 750 |
| $SW2_{30}$ | ***24 572*** | ***24 590*** | 12 466 | ***25 481*** | ***25 499*** | 12 927 |
| $UE_{30}$ | 16 084 | 16 005 | 8 945 | 18 860 | 18 741 | 10 534 |

**Table 14.** Net present value ($/ha) for nine alternative silvicultural prescriptions applied to stand III.

| | 30-year planning horizon | | | Soil expectation value | | |
|---|---|---|---|---|---|---|
| | Line skidding | Harvester–forwarder | Swing yarder | Line skidding | Harvester–forwarder | Swing yarder |
| $CC_0$ | **12 781** | **13 109** | 8 677 | **14 453** | **14 824** | *9 812* |
| $CC_{30}$ | ***12 613*** | 12 245 | **10 866** | 12 757 | 12 385 | **10 990** |
| $TH1_0CC_{30}$ | 9 869 | 9 882 | 4 958 | 10 234 | 10 247 | 5 142 |
| $TH2_0CC_{30}$ | 12 532 | *12 665* | *8 733* | *12 996* | *13 133* | 9 056 |
| $BA_{0/15}CC_{30}$ | 9 952 | 9 947 | 4 557 | 10 320 | 10 315 | 4 725 |
| $NT_{0/15}CC_{30}$ | 11 675 | 11 476 | ***9 594*** | 12 107 | 11 900 | ***9 948*** |
| $SW1_{30}$ | 10 282 | 10 297 | 3 673 | 10 662 | 10 678 | 3 809 |
| $SW2_{30}$ | *12 612* | ***12 779*** | 7 126 | ***13 078*** | ***13 251*** | 7 390 |
| $UE_{30}$ | 7 593 | 7 474 | 4 537 | 11 106 | 10 864 | 7 698 |

**Table 15.** Net present value ($/ha) for nine alternative silvicultural prescriptions applied to stand IV.

| | 30-year planning horizon | | | Soil expectation value | | |
|---|---|---|---|---|---|---|
| | Line skidding | Harvester–forwarder | Swing yarder | Line skidding | Harvester–forwarder | Swing yarder |
| $CC_0$ | **16 951** | **17 265** | ***13 135*** | **19 168** | **19 523** | **14 853** |
| $CC_{30}$ | 15 129 | 14 772 | **13 434** | 15 302 | 14 941 | ***13 587*** |
| $TH1_0CC_{30}$ | 14 206 | 14 146 | 9 329 | 14 732 | 14 669 | 9 674 |
| $TH2_0CC_{30}$ | *16 515* | *16 309* | *12 695* | *17 126* | *16 912* | *13 165* |
| $BA_{0/15}CC_{30}$ | 14 054 | 13 954 | 8 675 | 14 574 | 14 470 | 8 996 |
| $NT_{0/15}CC_{30}$ | 12 857 | 12 636 | 10 045 | 13 332 | 13 103 | 10 417 |
| $SW1_{30}$ | 15 258 | 15 284 | 8 720 | 15 823 | 15 849 | 9 042 |
| $SW2_{30}$ | ***16 898*** | ***16 738*** | 11 165 | ***17 523*** | ***17 357*** | 11 578 |
| $UE_{30}$ | 11 573 | 11 292 | 8 069 | 15 148 | 14 726 | 10 934 |

clear-cutting in 30 years ($CC_{30}$) ranked highest followed by thinning to a fixed number of trees per hectare ($NT_{0/15}CC_{30}$) and then $TH2_0CC_{30}$. In this case, the difference between the top-ranked and third best options was more than $2000/ha, or almost 20%. Ranking based on SEVs varied somewhat, but the best option was the same for the three harvesting systems as with 30-year NPV. The SEV for uneven-age management showed the greatest increase, but this option was still not competitive with the bulk of the other prescriptions. Initial stocking (volume per hectare) for this stand was substantially lower than for stand II and comparable to that of stand I, but with fewer trees per hectare meaning higher average volume per tree. This reduced harvesting costs for all systems and because of the balanced diameter distribution made even the prescriptions with light initial thinnings logged with cable systems profitable compared with stand I. Note that this did not mean that all cuttings were profitable for the various prescriptions, rather that losses were significantly lower in some cases (see Tables 8 and 10).

Stand IV also showed a unique pattern of results, although somewhat similar to those for stand III. All prescriptions were profitable for all harvesting systems, and either clear-cutting immediately or in 30 years ranked highest across the three logging methods. With ground-based logging, the two shelterwood systems ranked second and third with the option employing the C-grade thinning producing significantly higher returns in both cases. The difference between the first- and second-ranked prescriptions was negligible in one case and about \$500/ha (3%) in the other. With cable logging, clear-cutting immediately ($CC_0$) was ranked second followed by $TH2_0CC_{30}$. Again, the difference between the two top-ranked options was small (roughly \$300/ha, or 2.2%). The best ranked prescription employing only partial cutting ($SW2_{30}$) yielded \$2269/ha, or about 17% less than the number one ranked option. Ranking using SEVs was essentially identical with only the top two ranking options for cable logging trading places.

The sensitivity of the findings with respect to harvesting equipment costs was explored by assuming reduced capital costs (purchase price) for each system. The resulting reduction in total costs was about 17% for the harvester–forwarder combination and 10% for both the line skidder and swing yarder. Only stand I, which had the highest harvesting cost and lowest gross timber values, was used in the analysis. Harvesting costs dropped by between 3 and 6% for the line skidder, 6 and 11% for the harvester–forwarder, and 6 and 10% for the line skidder. In all cases cost reductions were greatest for cuttings where costs were originally the highest (B-grade thinnings). The effect on NPVs was more pronounced; however, in no case did prescriptions that were originally unprofitable become profitable, nor did the rankings change. Increases in the NPVs for the line skidder ranged from 2 to 11%, for the harvester–forwarder 2–30%, and for the swing yarder 9–12%. Predictably, the changes were greatest for prescriptions with B-grade thinnings, where the cost savings were also the highest.

The results for stand I were moderately sensitive to changes in the price of pulp and utility grade logs. Gross values more than doubled for the B-grade thinnings, but increased by only about 20% for C-grade thinnings. Increases in gross values ranged from roughly 1 to 20% for all other cuttings, with the smallest increments in the overstory removals fr the shelterwood options and clear-cutting after thinning to either a fixed basal area or number of trees per hectare. A total of four additional cuttings became profitable with the increases in gross timber values, three of which were regeneration cuts in shelterwood prescriptions and the other was a B-grade thinning. Increases in NPV for the three top-ranked prescriptions ranged from a low of \$655/ha for the most profitable option ($CC_{30}$) to a high of \$1216/ha for the third best ($SW2_{30}$). Prescriptions employing commercial thinnings showed greater gains in profitability than options based on clear-cutting only; however, there was no change in ranking among the prescriptions.

It is important to note that we are not recommending one silvicultural prescription or harvesting system over another. Generally, conditions at the site relating to sensitivity to soil disturbance and slope of the terrain will dictate whether ground-based systems can be used or cable systems are required. However, the findings here do show the opportunity costs associated with the decision to require a cable system and provide motivation for reflecting carefully on whether conventional restrictions are justifiable. They also suggest that attention should be focused on integrating the design of silvicultural treatments (grades of thinning for instance) with detailed predictions of harvesting costs and net values to ensure commercial operations are economically viable and alternative prescriptions employing partial cutting exclusively are not dismissed erroneously as financially inferior. In two out of the four stands examined here, a prescription based on partial cutting exclusively was highly competitive with clear-cutting provided ground-based logging was possible. In three out of four stands (all but stand IV) it appears that if the average size of trees cut were slightly higher in the initial thinnings (fewer smaller trees and (or) more larger ones) a prescription employing only partial cutting would yield the highest returns among all options.

## Conclusions

Tree size and the design of individual cuttings were shown to have a dramatic effect on harvesting costs and gross values, which together determine the financial returns possible from silvicultural treatments and prescriptions. Logging costs vary considerably among options for harvesting systems, and in some cases it may be possible to reduce costs and increase returns to the point of profitability by choosing an alternative system provided site conditions are not prohibitive. Accurate assessment of logging costs and gross values from the specific population of trees taken in individual cuttings is critical in the design of treatments to insure economic viability. The explicit incorporation of cutting-specific, individual-tree-based estimates of harvesting costs is also critical for the accurate calculation of potential financial returns from alternative silvicultural prescriptions.

Our findings indicate that under certain conditions financial returns from silvicultural prescriptions based on partial cutting in second-growth stands in coastal B.C. are competitive with those possible from even-age management based on clear-cutting. These results suggest that the financial burden associated with moving away from clear-cutting may not be as crippling as perhaps thought, and if commercial thinnings are designed carefully, the move may actually improve profits. With the increased demand for greater use of alternatives to clear-cutting to meet visual quality objectives and to promote conservation of biodiversity, foresters must explore options employing partial cutting more fully. These explorations must include analyses done at both the stand level, like the comparisons made here, and the forest level, where the results may be quite different as a result of provisions for adjacency constraints or changes in development costs. While the findings from this study are not intended to serve as “prescriptions” for how all or any second-growth stands are managed, they should provide additional motivation for further investigation and trials of alternatives to clear-cutting.

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