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An economic analysis of fertilization and thinning effects on Douglas-fir stands at Shawnigan Lake

K.M.Duke, G.M. Townsend and W.A. White

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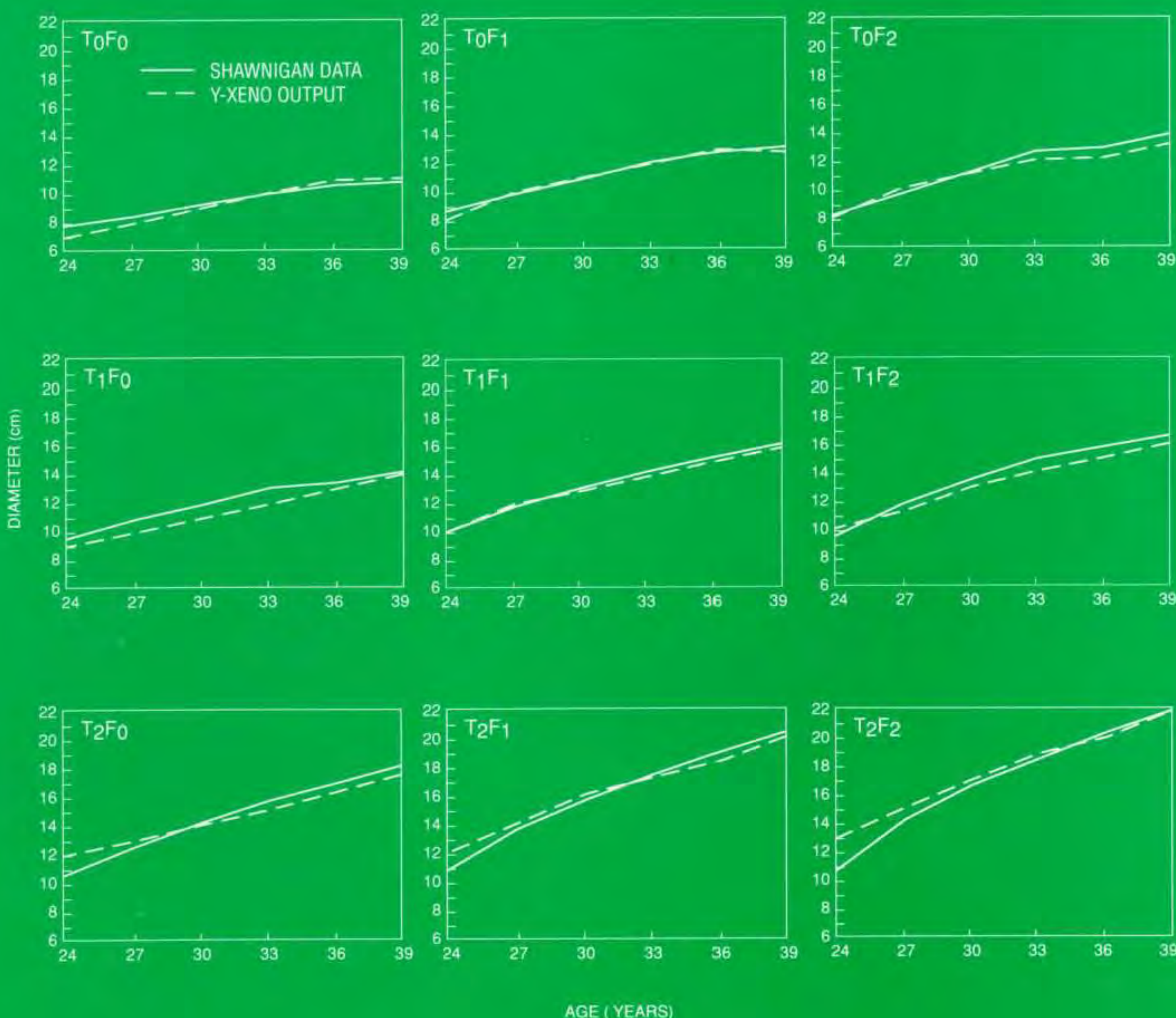

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Abstract

An economic analysis of the Forestry Canada silviculture experiment near Shawnigan Lake, British Columbia is conducted. Y-XENO, a single-tree density-dependent growth model is used to project, from age 24 to 120 years, nine combinations of thinning and fertilization for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on a poor site. Costs and benefits as a function of stand diameter are estimated, and forestry investment criteria are used to evaluate each treatment on both an incremental and a regime basis. The effect of assumptions of rising real prices and treatment of silviculture costs as an initial investment and alternatively as a harvest cost are examined. The best treatment was found to be a combination of heavy thinning and fertilization.

Résumé

On a fait une analyse économique d'une expérience de sylviculture menée par Forêts Canada près du lac Shawnigan, en Colombie-Britannique. On a utilisé Y-XENO, modèle de croissance dépendant de la densité pour essence unique, de l'âge de 24 ans à 120 ans, pour neuf combinaisons de systèmes d'éclaircie et de fertilisation de peuplements de Douglas taxifoliés (*Pseudotsuga menziesii* (Mirb.) Franco) sur sol pauvre. On a estimé les coûts et les avantages en fonction du diamètre du peuplement et utilisé les critères d'investissement dans le domaine de la foresterie pour évaluer chaque traitement sur la base d'un traitement à la fois et d'une séquence de traitements. On a examiné les répercussions de l'accroissement supposé des coûts réels et considéré le traitement des coûts de sylviculture en tant qu'investissement initial et aussi en tant que frais de récolte. On a établi que le meilleur traitement était celui qui allait une éclaircie et une fertilisation importantes.

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Introduction

The economics of intensive forest management is a controversial issue in British Columbia. Originally envisioned as the answer to the problem of rapidly declining stocks of mature timber, silvicultural investment has been questioned by some economists who argue that the discounted net benefits of such practices are at best marginal (Anderson 1985). Foresters, on the other hand, argue that such conclusions ignore the significant benefits of future employment in the province's most vital industry, as well as the non-timber benefits produced by forests, such as recreation and wildlife. Rather than contribute to the controversy, the purpose of this report is to present economic comparisons of various intensive silviculture treatments based on standard investment decision criteria.

The focus of this report is the Forestry Canada silviculture project at Shawnigan Lake, British Columbia. The initial section outlines the history and experimental design of the project. The second section discusses the methodology of the economic analysis, considering each treatment regime as a separate stand of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). There is a brief discussion regarding appropriate forestry investment criteria and the various costs and values used. Analysis results are presented in the third section. A discussion of the tree growth simulator, Y-XENO, and the methodology employed to produce the growth estimates used throughout the paper can be found in Appendix A.

History of the Shawnigan Lake experiment

The multi-disciplinary Shawnigan experiment was initiated in 1970 by the Pacific Forestry Centre. The objective of the project is to obtain a better understanding of the response of the forest ecosystem to various levels of fertilization and thinning. Results of the experiment are to be used to produce a growth model based on biological growth processes.

The project site is located northwest of Shawnigan Lake, British Columbia. It was burned by wildfire in 1925 and salvage-logged in 1927. The area naturally regenerated to Douglas-fir and was again burned by wildfire in 1942. The site was planted with just over 2000 trees per ha of Douglas-fir in 1948 despite a stocking level of natural seedlings (2000/ha) that would be considered sufficient by current standards. Soil quality is poor and the area is classified as site index 25 m at 50 years breast height age.

In 1971, an initial 3 x 3 experimental design was implemented with three urea fertilization levels (0, 224 and 448 kg N/ha) and three thinning intensities (zero, one-third, and two-thirds basal area removed). Each of the nine treatments was applied on two 0.08-ha plots. In 1972 the experiment design was duplicated on 18 additional plots. Further experiments included the use of ammonium nitrate in place of urea, increased fertilization levels and, in 1981, refertilization of the 1972 plots at initial fertilization levels. Growth estimates for the original nine treatments are the basis for the economic analysis presented here. Each particular treatment has been given a representative symbol (Table 1). For further information on the experimental design and growth data, refer to the establishment report (Crown and Brett 1975) or any of the subsequent progress reports (e.g. Barclay and Brix 1985).

The economics of silviculture

The economic objective of thinning and fertilization

The primary objective of thinning and fertilization is to increase the size of each tree which reduces harvesting and trucking costs while increasing log value (Fight and Briggs 1986). Thinned stands tend to be of a more uniform tree size, further reducing the costs of harvest. An additional benefit attributable to thinning and fertilization is reduced rotation ages, which in turn provide earlier returns to investment and higher allowable annual cuts. If, for example, thinning and fertilizing reduces the rotation period from 80 to 60 years, the land is freed for regeneration 20 years earlier. The capital that accrues during these 20 years in the form of new stands of trees is a benefit attributable to the applied treatment.

Table 1. Treatments applied at the Shawnigan Lake site and their symbols

Thinning		Fertilization	
Symbol	Treatment	Symbol	Treatment
T_0	no basal area removed	F_0	0 kg N/ha
T_1	1/3 basal area removed	F_1	224 kg N/ha
T_2	2/3 basal area removed	F_2	448 kg N/ha

Example: T_2F_1 refers to heavy thinning (two thirds of basal area removed) combined with light fertilization (224 kg N/ha).

Methodology of the economic analysis

The economic analysis was carried out in three stages. The first stage involved the estimation of the biological response to treatments. In the second stage, costs and revenues were estimated. Finally, investment decision criteria were selected and used to compare and rank the treatments. Comparative economic analyses are made between the actual Shawnigan treatments and two hypothetical treatments. It was not the objective of this report to find an optimal silviculture regime for a bare land situation but rather to analyze the actual Shawnigan sites. Thus, when comparisons are made between regimes it must be remembered that initial stand conditions across treatments were not identical.

Both a regime and incremental analysis were conducted on each treatment. The regime analysis investigates the costs and benefits of the entire sequence of forest management activities over the life of the stand. The incremental analysis investigates only those benefits attributable to the investment in thinning or fertilization (or both), and not those benefits that would have been realized without these treatments. All incremental analyses are based on comparisons to the control plot, T_0F_0.

The analysis is performed under the assumption that real prices are increasing at 1% per annum, a level of price increase which is supported by historical trends (USDA Forest Service 1982).[1,2] Basic silviculture costs, which include the costs of broadcast burning and planting, are approached from two perspectives. The first views these costs as a capital investment incurred in year 0. The alternative view is that, since the forestry companies are responsible under current provincial legislation for reforestation, basic silviculture costs are in fact a cost that must be taken into account at the time of harvest. The investment decision at year 0 is not based on bare land, but rather between plots that have already been burned and planted following the previous harvest, as required by statute. Only when it comes time to harvest the forest does it become necessary to consider these costs in the harvest decision. The difference in the cost of planting and site preparation in present value terms between these two views is substantial. For example, assuming a rotation age of 80 years and a discount rate of 4%, the cost of basic silviculture at the Shawnigan Lake site is $1010/ha in present value terms when treated as a year 0 investment; in contrast, the cost of the same basic siliviculture is only $43.82/ha when the investment is discounted from the time of harvest.

Growth projections

Growth projections for each silvicultural treatment are estimated using the Y-XENO growth model (Northway 1988). Y-XENO is a single-tree, density-dependent growth model. Y-XENO was calibrated to model the 15 years of growth data available from the Shawnigan project as closely as possible. Subsequently, each treated stand was projected to 120 years of age (see Appendix A for further details).

Costs and values

Among the crucial elements of any economic analysis are the values and costs pertinent to the problem. Site or stand specific costs and values are more favorable than average costs. As discussed earlier, fertilization and thinning shortens the rotation age and increases the average size of the treated trees. Since harvesting costs and tree value are a function of tree size, the use of average costs and values per hectare or per cubic metre may obscure the economic benefits of increased value and decreased harvest costs due to larger stem size. For example, since thinning may reduce total merchantable volume relative to an unthinned stand for typical second-growth rotation periods, the use of average values and costs, which do not recognize the benefits of larger tree diameters, would indicate no economic gain from thinning (Mitchell and Cameron 1985).

The process of collecting and analyzing data to predict costs and values as a function of tree and average stand diameter is relatively new in British Columbia. The necessary data are often difficult to locate. The

[1] At an earlier stage of the analysis treatments were analyzed assuming constant prices into the future. Economic rotations ranged from 102 years to in excess of 200 years and NPVs were negative regardless of how basic silvicultural costs were considered. For example, the NPV of T_2F_2 was -$1272/ha with basic silviculture as a year 0 investment while NPV was -$281/ha with basic silviculture as a cost at the time of harvest. The analysis is reported for increasing real prices because many experts believe that prices for second-growth timber will increase in real terms.

[2] While it would have been desirable to incorporate some degree of cost reduction sensitivity analysis into the report it was not possible because the required break even real price increases are greater than the costs of harvest in all instances. For example, T_2F_2 requires a minimum 1.19% per annum real price increase for 78 years to break even (refer to Table B1 in Appendix B). This is equivalent to a $27 618/ha increase in gross revenues at year 78, or $1 295.96/ha in present value terms. Harvest costs, however, are only $17 529/ha in constant terms, or $822.59/ha in present value terms. Therefore, costs would have to become negative before the treatment would break even. Decreases in silviculture costs, particularly basic silviculture, would have an impact on the viability of each treatment. However, even in the best of regimes, these costs would have to be reduced to near zero to achieve positive results. It can be assumed that, for analytical purposes, any decrease in costs will be equivalent to an increase in real prices.

problem is compounded by the long time periods being considered which increase the degree of uncertainty and risk. For instance, what will be the level of demand for second growth logs in 50 to 60 years and what harvesting system will be dominant? Can we expect the emergence of substitutes for forestry products? Plainly, these are difficult yet relevant questions.

Estimates of the value of the Shawnigan Lake timber are based on the prices of Douglas-fir on the Vancouver log market (Sterling Wood Group Inc. 1988). The XENO model calculates timber value based on the top end diameter of 5-m logs. Each tree on the plot grown by the model is cut into 5-m logs and a value for each log is determined by the top end diameter and the volume in the log. The model also calculates the number of stems per hectare and the diameter distribution in the stand. Using this data it then determines the revenue per hectare and average revenue per cubic metre. Through this procedure, changes in tree diameter and height resulting from silvicultural inputs are reflected in changes in value. All prices and costs used in this analysis are expressed in real 1986 dollars and are therefore net of any inflationary effects.

Harvesting and transport costs are more difficult to estimate due to the lack of available information and the uncertainty surrounding future harvesting systems. The gentle terrain and relatively small diameters expected at harvest age mean that the Shawnigan site will likely be mechanically felled, and yarded with some type of ground system such as grapple skidders. Transportation costs will be low due to the relatively short distance to mill (45 km) and the excellent road conditions. Costs of felling and bucking, yarding, contracting overhead, and transportation are from Nawitka Resource Consultants (1987). Logging costs vary as a function of average stand diameter. Development costs were estimated at approximately 25% of average old-growth development costs for the British Columbia coast, or $845/ha (British Columbia 1988a). This figure is comparable to industry projections and is based on the assumption that development of second-growth stands will often only require the reactivation of roads built for harvesting the initial old-growth stands. An administrative overhead cost of $8/m^3 was obtained from the British Columbia Forest Service (British Columbia 1987).

Table 2. Silviculture costs

Treatment		Cost ($/ha)
Broadcast burn[a]		298
Planting:	base[b]	326
	seedlings[a]	386
Spacing[c]:	1/3 basal area removed	450
	2/3 basal area removed	575
Fertilization[d]:	224 kg N/ha	195
	448 kg N/ha	245

[a] B.C. Forest Service Silviculture Branch
[b] British Columbia 1988b
[c] White 1988
[d] The cost of heavier fertilization is extrapolated from the cost of the lighter application using British Columbia 1988b and McCloskey 1981.

The benefits and costs used in this paper do not consider the intangible benefits and costs attributable to the forest such as recreation and wildlife habitat. Nor does the report consider the employment benefits associated with ensuring the continuation of a strong forestry sector, particularly in small communities that depend on the forest sector.

Silviculture costs

Silviculture costs used in this report are not identical to those incurred at Shawnigan Lake in 1971. Since the objectives of the Shawnigan Lake project are of a biological nature, cost data were not collected for each particular thinning and fertilization regime. Such cost data, even if available, would not be directly comparable with operational forestry as the site was fertilized by hand and very selectively thinned. The high number of trees planted in 1948 increases the planting costs relative to a present day operational regime. The silvicultural costs used in this analysis are presented in Table 2 and are in 1986 dollars.

Fertilization costs include both the costs of the fertilizer and the cost of helicopter application. Thinning costs are a function of the number of stems and average stand diameter. For example, a stand that is extremely dense with a small average diameter may be more costly to thin than a moderately dense stand with a larger average diameter that requires fewer trees to be felled (White 1988).

The estimated costs for each of the nine treatments are presented in Table 3. All thinning and fertilization treatments are considered to have occurred at stand age 24 and are discounted to year 0 for the analysis.

Investment decision criteria

The net present value (NPV), soil expectation value (SEV), benefit cost (B/C) ratio, and internal rate of return (IRR) investment decision criteria have been chosen to rank the silvicultural treatments.[3] These four

[3] For further discussion of forestry investment decision criteria refer to Gunter and Hanley 1984, Leuschner 1984, and Davis and Johnson 1987.

Table 3. Treatment costs for each regime (exclusive of basic silviculture)

Treatment	Costs ($/ha)	Discounted[a] Costs ($/ha)
T_0F_0	0.00	0.00
T_0F_1	195.00	76.07
T_0F_2	245.00	95.58
T_1F_0	450.00	175.55
T_1F_1	645.00	251.63
T_1F_2	695.00	271.13
T_2F_0	575.00	224.32
T_2F_1	770.00	300.39
T_2F_2	820.00	319.90

[a] Discount rate is 4%

methods of investment evaluation are generally considered superior to other criteria, such as the pay-back period, because they account for the time value of money and the opportunity cost of capital (Mishan 1985).

1. Regime investment criteria

Ranking the treatments by order of maximum economic benefit is a two-stage process. First, the optimum rotation period is selected for each treatment based on maximum SEV. These rotation periods seldom coincide with the optimal biological rotation, i.e., the age of maximum mean annual increment (see Appendix C for a comparison of economic and biological rotations). The biological rotation assumes a discount rate equal to zero, which implies that there is no capital cost to holding trees and land. Bentley and Teeguarden (1965) argue that this can only be true if the firm has no alternative investment or consumption choices.[4]

The regime SEV is derived by first calculating NPV where:

$$NPV = \sum_{t=0}^{R} \frac{B_t}{(1+i)^t} - \sum_{t=0}^{R} \frac{C_t}{(1+i)^t}$$

where: B_t = total benefits
C_t = total costs
i = discount rate
t = number of years
R = rotation period

NPV is then multiplied by the factor $(1+i)^R/((1+i)^R-1)$ to obtain the regime SEV. This process is often referred to as normalization.

Unlike the single-period NPV criterion, SEV includes all returns at harvest and the costs of holding timber for an additional period over an infinite time horizon. In other words, the SEV assumes that the land presently being used to grow trees will always be used to grow trees and its productive capability will remain constant. Additionally, because the SEV measures net benefits over an infinite time horizon, it is more accurate than the NPV when comparing treated stands that have differing rotations (Leuschner 1984). The SEV optimum rotation occurs where SEV is maximized, and the SEV rotation may or may not coincide with the NPV rotation age.

After determining the optimum rotation period the second step of the ranking process is to rank according to maximum economic benefit. Using the NPV or SEV criteria, treatments are ranked according to which has the greatest NPV or SEV. If a decision maker faces a budget constraint then ranking by maximum NPV or SEV may not be the superior methods and the B/C ratio may be used instead (Mishan 1985).

The regime B/C ratio is calculated by dividing the gross benefits of a treatment by the total gross costs, where gross benefits are the gross revenues and gross costs are the silviculture and harvesting costs. If the B/C ratio is greater than one, which implies that benefits are greater than costs, then the silviculture investment is worthwhile at the discount rate selected for the analysis. The optimal rotation period occurs where the ratio is maximized.

Like the B/C ratio, the IRR is a ranking criterion that is used when the decision maker is under a budget constraint. It is the rate of return on an investment such that the discounted benefits of the treatment investment equal the discounted costs. The projects may then be ranked according to which has the highest IRR. The principal advantage of the IRR criterion is that it does not require the explicit use of a discount rate, although it is implicitly assumed that the decision maker is using some minimum rate of return as a guideline as to whether the project is desirable. The major disadvantage of the IRR is that there may be more than one IRR at which NPV equals zero (Schofield 1987).

[4] The argument may be made for a zero interest rate in the case of government investment in forestry, as a matter of policy. That is to say, law and regulation may require a minimum level of forestry, hence a zero interest rate. For this analysis we assume the interest rate is greater than zero.

2. Incremental investment criteria

The incremental SEV measures only the net benefits attributable to the extra silviculture investment. Incremental SEV is calculated by subtracting the regime SEV of the control plot from the regime SEV of the treatment in question.

The incremental B/C ratio is somewhat more complicated. It is calculated by dividing the incremental gross benefits by the incremental gross costs of the treatment. The incremental gross benefits are the gross revenues of the treated plot less the gross revenues of the control. The incremental costs are the additional treatment costs plus the change in harvest costs compared to the control. All gross benefits and costs must be normalized.[5] If the B/C ratio is greater than one, then the incremental benefits are greater than the incremental costs and the treatment is superior to the control plot. The treatments are ranked according to highest B/C ratios.

The incremental IRR is the rate of return such that the discounted incremental gross benefits of the treatment equal the discounted incremental gross costs.[6] As in the regime analysis, the projects are then ranked by highest IRR.

3. The discount rate

The selection of a discount rate, *i*, has a tremendous impact on the present value of each treatment because of the long rotation periods in question. The use of a positive discount rate in all of these criteria implies that society prefers consumption today over future consumption unless it is induced to forego present consumption by the promise of receiving a minimum compensation of *i* percent of foregone consumption. The appropriate discount rate is a matter of great controversy amongst economists and much literature has been devoted to the subject (Mishan 1985; Heaps and Pratt 1989). In this analysis a real discount rate of 4% is used.[7]

Economic analysis

Regime results

1. Shawnigan treatments

When basic silviculture is considered as a year 0 investment no treatment produces a positive NPV or SEV. The treatments are ranked in the same order by both maximum NPV and SEV in Table 4.

Heavy thinning combined with heavy fertilization

Table 4. Regime analysis results when basic silviculture is considered as year 0 investment

Treatment	NPV[a] ($/ha)	SEV[a] ($/ha)	Rotation[b] (yrs)	B/C	IRR (%)
T_2F_2	-291	-305	78	0.86	3.64
T_2F_1	-432	-449	84	0.78	3.47
T_2F_0	-500	-515	90	0.71	3.37
T_1F_1	-573	-587	96	0.68	3.31
T_1F_2	-628	-643	96	0.65	3.23
T_1F_0	-682	-699	102	0.56	3.09
T_0F_1	-711	-722	108	0.50	2.96
T_0F_2	-746	-757	108	0.48	2.90
T_0F_0	-748	-757	114	0.40	2.77

[a] Based on 4% discount rate.

[b] Under the conditions examined here the NPV rotation and the SEV rotation were equal in each case. Under some conditions the NPV rotation and the SEV rotation can differ.

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[5] Calculation of the normalized incremental benefit-cost ratio:
The normalized incremental benefit-cost ratio measures the average incremental change in benefits for each dollar invested in the silviculture treatment. This ratio is normalized in the sense that it refers to the sum of the discounted benefits, or costs, of a particular treatment regime over an infinite number of rotation periods. The procedure used to normalize this ratio and the advantages to normalization are discussed in the section on investment decision criteria.
The change in benefits (ΔB) is the normalized gross revenues from the treated plot, minus the normalized gross revenues from the control. The incremental costs (ΔC) are the difference between the treated and control plot treatment costs plus the difference in harvesting costs, i.e.,

$$\frac{\Delta B}{\Delta C} = \frac{\Delta GR_n}{\Delta HC_n + \Delta TC_n}$$

where: ΔGR_n = discounted normalized change in gross revenues
ΔHC_n = discounted normalized change in harvest costs
ΔTC_n = discounted normalized change in treatment costs
n = normalized

[6] Calculation of the normalized incremental IRR:
We want the discount rate, *i*, such that the difference between the normalized incremental benefits of the treatment and the normalized incremental costs of the investment equal zero. Therefore, the equation given in footnote 5 becomes:

$$\Delta B - \Delta C = \Delta GR_n - (\Delta HC_n + \Delta TC_n)$$

This procedure is equivalent to finding the *i* that allows
SEV(treatment) - SEV(control) = 0.

[7] The British Columbia Ministry of Forests currently uses a real rate of 4% for financial and economic forestry analysis (Source: Industry Development and Marketing Branch, Ministry of Forests, Victoria.).

Table 5. Regime analysis results when basic silviculture is considered as a harvest cost

Treatment	NPV[a] (\$/ha)	SEV[a] (\$/ha)	Rotation[b] (yrs)	B/C	IRR[c] (%)
T_2F_2	671	705	78	1.56	6.20
T_2F_1	540	561	84	1.55	5.80
T_2F_0	480	495	90	1.65	5.80
T_1F_1	413	423	96	1.52	5.41
T_1F_2	358	367	96	1.44	5.22
T_1F_0	305	310	102	1.54	5.35
T_0F_1	283	288	108	1.67	5.94
T_0F_2	250	253	114	1.58	5.60
T_0F_0	249	253	108	1.99	—

[a] Based on 4% discount rate.

[b] Under the conditions examined here the NPV rotation and the SEV rotation were equal in each case. Under some conditions the NPV rotation and the SEV rotation can differ.

[c] IRR for T_0F_0 cannot be calculated because all costs are applied against revenues at year of harvest. The IRR is that rate which will discount net revenue at harvest to zero, which is *i*=infinity

(T_2F_2) produces the best results while the untreated control (T_0F_0) realizes the poorest results. The excellent growth response to heavy fertilization combined with the positive effects of thinning allows the T_2F_2 stand to attain the largest average diameter (see tables in Appendix A for projected stand characteristics). However, the treatment does not produce sufficient gains to pay for the initial investment and capital carrying costs of basic silviculture. Conversely, the untreated stand (T_0F_0) carries a high number of stems and the average diameter is therefore small. As a result, harvesting costs are higher and log values are lower even though there is more gross volume. The T_2F_2 stand has the shortest economic rotation length because it reaches its most economically efficient tree size before any other treatment. The T_0F_0 stand, due to a high number of trees and the resulting small average diameter, has the longest rotation age. Heavy fertilization with no thinning (T_0F_2) realizes the same SEV as T_0F_0 because the increase in net revenues as a result of fertilization is offset by the additional cost of the treatment.

Treatments are ranked from the heaviest thinning intensity to no thinning. In stands subjected to light (T_1) or no (T_0) thinning, light fertilization (F_1) ranks higher than either heavy fertilization (F_2) or no fertilization (F_0). This indicates that the response to heavier fertilization, given light or no thinning, is insufficient to cover the extra cost of the heavier fertilization. In stands subjected to heavy thinning (T_2), however, heavy fertilization (F_2) produces much better results than either light fertilization (F_1) or no fertilization (F_0), indicating that only when the stand density is greatly reduced are the trees able to fully utilize the additional fertilizer.

Ranking by B/C ratio or IRR does not change the ordering according to the maximum SEV. The B/C ratios are less than one because the benefits of all nine treatments are less than the costs. The IRRs are all less than the minimum required rate of return of 4%.

When basic silviculture costs are considered to be incurred at the time of harvest, positive NPVs and SEVs are obtained for all treatments (Table 5). This is because basic silviculture costs are now discounted from the time of harvest and therefore have much less impact on total costs. The SEV ranking, however, does not change from the previous analysis; heavy thinning combined with heavy fertilization (T_2F_2) still ranks as the superior treatment.

Ranking treatments by B/C does change the overall order compared to SEV ranking. T_0F_0, T_0F_1 and T_0F_2 move to first, second and fourth positions, respectively. This is a result of the small investment required for each treatment and the fact that harvest and basic silviculture costs are discounted heavily due to the long rotation lengths in question. Therefore, the denominator of the B/C ratio becomes much smaller.

The IRR also changes the ranking compared to the SEV ranking. T_2F_2 still ranks the highest but T_0F_1 and T_0F_2 move up to second and fifth position. Again, this is a reflection of the small investment required for these treatments. The IRR for T_0F_0 is undefined because all costs are applied against gross revenue at the date of harvest. The IRR becomes that rate which will discount net revenue to 0, which is infinity.

2. *Hypothetical treatments*

Over the years the views and attitudes of forest managers with respect to silviculture have changed. What was once viewed as excessive or abnormal is today seen as operational. For example, when the Shawnigan Lake site was thinned, removing two-thirds of the basal area, or approximately 2500 of 3500 stems, was considered very heavy thinning. Today, thinning to 600 stems per ha in Douglas-fir stands is common practice in British Columbia. Similarly, very high initial stand densities were once desirable. The Shawnigan Lake stands, which carried over 2000 naturally regenerated seedlings per ha, were planted with an additional 2200 stems per ha in 1948. Today, a stand with 2000 stems per ha, natural or plantation, would be considered more than sufficiently stocked.

Given these considerations, two additional runs were conducted on Y-XENO using the parameters of the Shawnigan Lake site. The first, TEST1, involved thinning to 600 stems per ha and fertilization at 224 kg N/ha. Thinning costs were raised to \$625/ha to reflect

Table 6. Regime analysis results of two hypothetical treatments: TEST1 (thinning to 600 stems/ha) and TEST2 (natural stocking with no thinning or fertilization). Cost of basic silviculture is considered as a year 0 investment.

Treatment	NPV[a] ($/ha)	SEV[a] ($/ha)	Rotation	B/C	IRR (%)
TEST1	-467	-485	84	0.75	3.42
TEST2	440	451	96	1.59	4.99

[a] Based on a 4% discount rate
[b] Under the conditions examined here the NPV rotation and the SEV rotation were equal in each case. Under some conditions the NPV rotation and the SEV rotation can differ.

Table 7. Regime analysis results of two hypothetical treatments: TEST1 (thinning to 600 stems/ha) and TEST2 (natural stocking with no thinning or fertilization). Cost of basic silviculture is considered as a harvest cost.

Treatment	NPV[a] ($/ha)	SEV[a] ($/ha)	Rotation[b]	B/C	IRR[c] (%)
TEST1	506	525	84	1.56	5.66
TEST2	731	749	96	2.62	—

[a] Based on a 4% discount rate
[b] Under the conditions examined here the NPV rotation and the SEV rotation were equal in each case. Under some conditions the NPV rotation and the SEV rotation can differ.
[c] The IRR cannot be calculated for TEST2 because all costs are applied against gross revenues at the time of harvest. The IRR is that rate which will discount net revenues to zero, which is infinity.

the higher number of stems removed. The second run, TEST2, was projected from year 0 assuming that the level of natural stock was sufficient. No management other than broadcast burning is applied. The results are presented in Tables 6 and 7.

When basic silviculture is considered as a year 0 investment, extra heavy thinning (TEST1) ranks third relative to the original nine treatments in terms of SEV, the B/C ratio and the IRR (Tables 4 and 6).[8] It is apparent that the extra thinning does not pay relative to the T_2 level of thinning. Natural stocking and no thinning or fertilization (TEST2) ranks higher than any of the nine Shawnigan Lake treatments and TEST1 according to all four investment criteria. This is a direct result of the much lower basic silviculture cost of $298/ha for TEST2 relative to $1010/ha for the other treatments (Table 2).

When basic silviculture costs are considered as harvest costs (Table 7), extra heavy thinning (TEST1) ranks exactly as in the previous analysis according to the NPV and SEV criteria; however, it falls to fifth amongst the original nine treatments according to the B/C and IRR criteria. Natural stocking and no thinning or fertilization (TEST2) enjoys a higher NPV, SEV and B/C than T_2F_2. The IRR cannot be calculated for TEST2.

Incremental results

1. Shawnigan treatments

The incremental net benefits (SEV), the incremental B/C ratio and the incremental IRR results for the individual treatments do not change whether basic silviculture costs are considered as a year 0 investment or a harvest cost (Table 8). Since this is an incremental comparison, basic silviculture costs, which represent an equivalent fixed sunk cost for each treatment, are eliminated from the analysis. Therefore, the way these costs are considered will have no bearing on the incremental comparisons.

The incremental net benefits rank the treatments exactly as the regime analysis SEV did in the previous analysis. Heavy thinning combined with heavy fertilization (T_2F_2) is much superior to the control plot (T_0F_0), while heavy fertilization and no thinning (T_0F_2) offers no incremental net benefits for the additional investment. Heavier thinning (T_2) produces better results than light or no thinning.

Table 8. Incremental analysis results[a]

Treatment	Incremental Net Benefits[b] ($/ha)	$\Delta B^c / \Delta C$	IRR[c] (%)
T_2F_2	452	1.45	5.93
T_2F_1	308	1.41	5.41
T_2F_0	242	1.47	5.34
T_1F_1	170	1.31	4.84
T_1F_2	114	1.20	4.58
T_1F_0	58	1.18	4.44
T_0F_1	35	1.20	4.54
T_0F_2	0	1.00	4.00
T_0F_0	0	—	—

[a] Based on 4% discount rate.
[b] Difference in SEV between the treated stand and the control.
[c] IRR and B/C for T_0F_0 cannot be calculated because it would be a comparison to itself and would be undefined

[8] As with the nine Shawnigan treatments, economic analyses using constant prices were conducted. Again, large negative NPVs and SEVs were obtained. Rotation ages ranged between 108 and 120 years. TEST2 did realize a positive NPV and SEV of $30.55/ha and $30.83/ha when basic silvicultural costs were applied at the time of harvest.

Since all treatments have an incremental SEV greater than or equal to the control, the incremental B/C ratios are greater than or equal to one. The incremental B/C ratio only changes the ranking slightly in comparison to the incremental SEV ordering. T_2F_0 surpasses T_2F_2 and T_2F_1 as the better investment according to this criteria, indicating that the additional fertilizer investment lowers the average incremental return per dollar. The difference, however, is small. The ranking according to incremental IRR also changes slightly with T_0F_1 surpassing T_1F_0.

2. Hypothetical Treatments

When basic silviculture is considered a year 0 investment, extra heavy thinning (TEST1) falls to fourth in terms of incremental B/C ratio and IRR, behind T_2F_2, T_2F_1 and T_2F_0 (Tables 8 and 9). It ranks third according to the incremental net benefits criterion behind T_2F_2 and T_2F_1. Natural stocking with no thinning or fertilization (TEST2) is much superior to the nine treatments analyzed earlier and TEST1 when basic silviculture is treated as a year 0 investment. Incremental net benefits are more than \$700 better than the next best treatment, T_2F_2 (Tables 8 and 9). This difference can largely be explained by the \$712 difference in basic silviculture costs between the two treatments. Neither the B/C ratio nor the IRR could be calculated for TEST2.[9]

Ranking of the hypothetical treaments relative to the original nine treatments does not change whether basic silviculture is considered a harvest cost or a year 0 investment (Tables 8, 9 and 10). However, the incremental SEV of natural stocking with no thinning or fertilization (TEST2) is reduced substantially when basic silviculture is considered a harvest cost instead of a year 0 investment. This is attributable to the much lower present value of basic silviculture costs in the control plot, T_0F_0, when basic silviculture is considered a harvest cost, thereby reducing the SEV difference between TEST2 and the original nine treatments.

[9] Neither the incremental IRR nor the incremental B/C ratio for TEST2 can be calculated because the incremental change in costs is negative due to the much lower basic silviculture costs associated with TEST2 (\$298 versus \$1010). This implies a negative B/C ratio (see note 4). The IRR cannot be determined because the change in treatment costs is negative and is greater than the change in harvest costs. Therefore, the equation in footnote 6 becomes:

$$\Delta B - \Delta C = \Delta GR_n - (\Delta HC_n + (-\Delta TC_n))$$

$$\text{where } |\Delta TC_n| > |\Delta HC_n|$$

There is no IRR at which this equation will equal 0.

Table 9. Incremental analysis results[a] of two hypothetical treatments: TEST1 (thinning to 600 stems/ha) and TEST2 (natural stocking with no thinning or fertilization). Cost of basic silviculture is considered as a year 0 investment.

Treatment	Incremental[b] Net Benefits (\$/ha)	$\frac{\Delta B}{\Delta C}$[c]	IRR[c] (%)
TEST1	272	1.40	5.24
TEST2	1208	—	—

[a] Based on a 4% discount rate
[b] Difference in SEV between the treated stand and the control.
[c] The B/C ratios and IRRs are calculated in comparison to T_0F_0

Table 10. Incremental analysis results[a] of two hypothetical treatments: TEST1 (thinning to 600 stems/ha) and TEST2 (natural stocking with no thinning or fertilization). Cost of basic silviculture is considered as a harvest cost.

Treatment	Incremental[b] Net Benefits (\$/ha)	$\frac{\Delta B}{\Delta C}$[c]	IRR[c] (%)
TEST1	272	1.40	5.24
TEST2	496	—	—

[a] Based on a 4% discount rate
[b] Difference in SEV between the treated stand and the control.
[c] The B/C ratios and IRRs are calculated in comparison to T_0F_0 and are based on SEV rotations.

Conclusion

From an economic point of view, investing in any type of silviculture on a poor site such as the Shawnigan Lake site only makes sense if price increases are expected and basic silvicultural costs are treated as a harvest cost. Otherwise, the costs of silviculture investments are simply too high and the benefits too low to justify such treatments. It is doubtful that any firm or government would invest already scarce silvicultural funds in any type of management regime on such sites except for planting and site preparation, as required by legislation. A real price increase of 1% per annum does little to improve economic feasibility unless basic silvicultural costs are considered harvest costs.

On the Shawnigan Lake site, heavier thinnings produce better economic results than light or no thinning, according to all ranking criteria when basic silviculture is considered as a year 0 investment. Combinations of fertilization and thinning produce better economic results than only thinning. Heavy fertilization (F_2) is only justified relative to light or no fertilization when combined with heavy thinning (T_2). T_2F_2 ranks highest amongst the nine Shawnigan treatments according to the SEV and IRR ranking criteria on both a regime and an incremental basis, while T_2F_0 ranks highest according to the B/C ratio on an incremental basis.

Although it is a hypothetical treatment that was never applied at the Shawnigan Lake site, natural stocking with no thinning or fertilization (TEST2) was by far the superior treatment, according to all regime and incremental ranking criteria. The low silvicultural costs of this treatment obviously play a key role in explaining why it performs better than other treatments.

On a poor site such as the Shawnigan Project, the greatest economic return is realized from a regime of natural regeneration without any form of incremental silviculture investment. If the decision is made to invest in incremental forest management and the objective is to maximize economic (SEV) returns, then a combination of heavy fertilization and thinning to high stand densities relative to current operational densities is the appropriate treatment.

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Appendix A

XENO

XENO is a proprietary product of MacMillan Bloedel Ltd. XENO is the generic name for a family of forest management decision support systems developed by MacMillan Bloedel. The two models used in this analysis are Y-XENO, a stand growth model, and E-XENO, a financial analysis model designed to analyze output from the Y-XENO growth model.

Y-XENO is a distance-dependent mixed-species model (Northway 1987). The model has been developed and calibrated with data from permanent sample plots established as part of MacMillan Bloedel's extensive growth and yield program.

A useful feature of Y-XENO is that stand projections can be started from any age by inputting stand age, average diameter, the coefficient of variation for the diameter distribution and site index. For this analysis, the starting age of the projections was set at twenty-four, the age of the Shawnigan stand at the time of initial treatment. Treatment data was input to the model (e.g., thin to 1000 stems per ha) and each treated stand was then projected to 120 years of age. Since the model contains random growth components necessary to mimic stand development, ten projections were made for each treatment and then averaged to reduce the possibility that treatment projections were skewed by any individual random seed. The average projections were then compared to the 15 years of height (Figure A1) and diameter (Figure A2) data that have been collected from the project. The model projections agree very well with the actual data. Tables A1-A9 show the projected growth data to age 120.

Y-XENO models fertilization by aging each tree. The effect is to increase the stand growth to that of a stand that is 12 years older, resulting in higher volumes at an earlier age relative to unfertilized stands. As the effectiveness of the fertilization diminishes over time, the stand continues to grow at the rate of the aged stand. If fertilization occurs early in the life of the stand, the volumes of the fertilized and unfertilized stands will eventually converge.

Y-XENO models thinning effects through individual tree crown response to additional growing space. The absence of a shading effect leads to a response in crown length and the absence of disputed growing space leads to a response in crown width.

There were some differences in initial conditions between treatment plots, particularly with respect to the number of stems. For instance, T_0F_1 had 3642 stems at age 24 versus 3493 on the T_0F_2 plot. The control plot had a higher number of stems initially then any other treatment. These differences alone will account for some of the post-treatment differences between the control plot and the treated plots results, as well as between the treated plots themselves. In most cases, however, the differences were relatively minor.

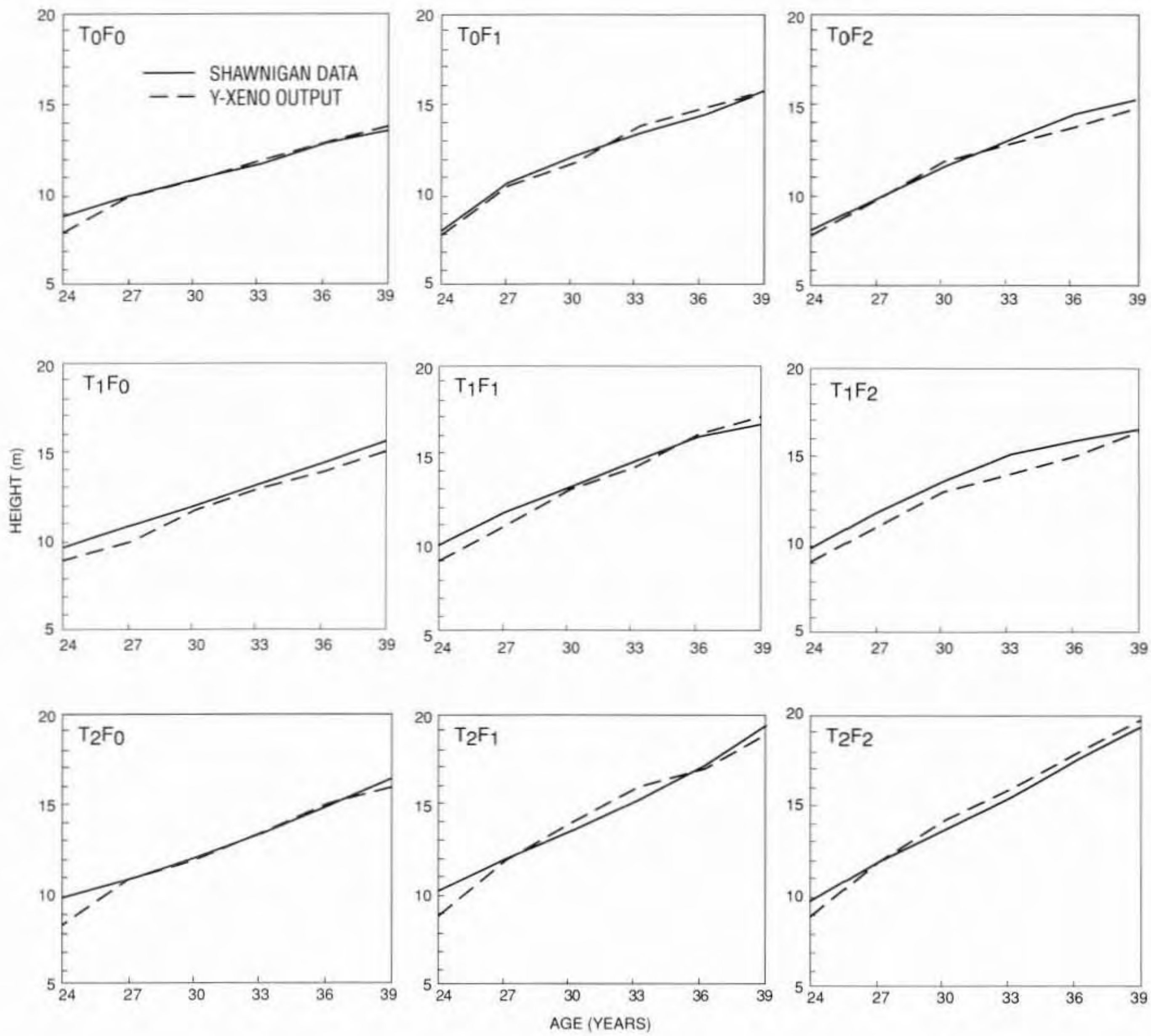

Figure A1. Comparison of Y-XENO projections with actual heights for various treatments at the Shawnigan Lake site from age 24 to age 39.

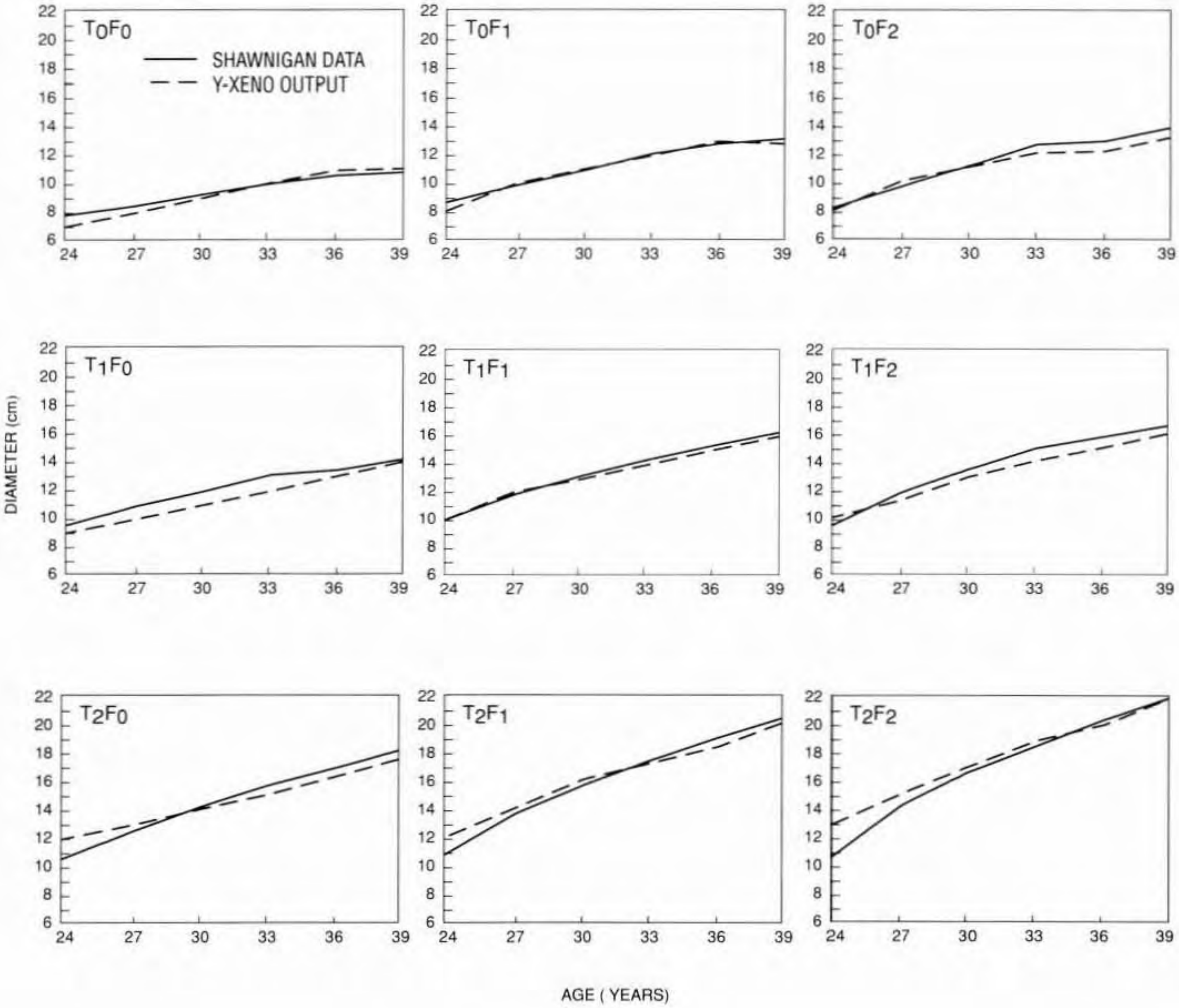

Figure A2. Comparison of Y-XENO projections with actual diameters for various treatments at the Shawnigan Lake site from age 24 to age 39.

Table A1. Y-XENO projection of stand growth to age 120. Treatment = T_0F_0 (no thinning and no fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] ($m^3\ ha^{-1}\ a^{-1}$)	Stems (/ha)	Volume (m^3/ha) Gross[2]	Volume (m^3/ha) Merchantable[3]
24	7.0	0.0	4567	78.5	0.0
30	9.0	0.0	4268	145.2	0.0
36	11.0	0.0	3957	223.4	0.0
42	12.0	0.0	3609	306.5	0.0
48	13.0	0.0	3257	391.3	1.0
54	14.1	0.1	2940	474.6	5.0
60	15.2	0.6	2661	554.1	35.0
66	16.0	1.6	2428	627.2	108.0
72	17.0	2.8	2266	695.3	204.0
78	18.0	4.1	2120	759.6	317.0
84	19.0	4.9	1980	818.2	409.0
90	19.2	5.3	1858	873.1	477.0
96	20.0	5.5	1758	925.2	526.0
102	20.5	5.5	1662	973.5	558.0
108	21.0	5.4	1574	1016.8	582.0
114	21.7	5.3	1505	1059.3	604.0
120	22.0	5.2	1443	1098.9	625.0

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A2. Y-XENO projection of stand growth to age 120. Treatment = T_0F_1 (no thinning and light fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] ($m^3\ ha^{-1}\ a^{-1}$)	Stems (/ha)	Volume (m^3/ha) Gross[2]	Volume (m^3/ha) Merchantable[3]
24	8.0	0.0	3642	79.8	0.0
30	11.0	0.0	3439	187.2	0.0
36	13.0	0.0	3183	278.0	0.0
42	14.0	0.1	2938	364.3	3.5
48	15.0	0.6	2678	450.0	30.0
54	16.0	2.0	2454	532.0	108.3
60	17.0	3.8	2265	609.0	227.3
66	18.1	5.3	2114	682.0	345.5
72	19.0	6.0	1991	750.3	435.5
78	20.0	6.5	1895	813.9	503.6
84	20.3	6.6	1805	873.9	555.7
90	21.2	6.6	1712	930.6	593.3
96	21.9	6.5	1633	983.0	626.7
102	22.2	6.4	1559	1032.9	653.4
108	23.0	6.3	1491	1081.5	678.1
114	23.2	6.2	1435	1126.9	701.8
120	24.1	6.0	1379	1169.5	722.0

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A3. Y-XENO projection of stand growth to age 120. Treatment = T_0F_2 (no thinning and heavy fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] (m^3 ha^{-1} a^{-1})	Stems (/ha)	Volume (m^3/ha) Gross[2]	Merchantable[3]
24	8.0	0.0	3493	76.2	0.0
30	11.0	0.0	3346	163.7	0.0
36	12.1	0.0	3142	248.3	0.0
42	14.0	0.1	2919	331.7	2.0
48	15.0	0.5	2672	415.4	24.0
54	16.0	1.6	2450	497.3	88.0
60	17.0	3.3	2267	574.1	195.0
66	18.0	4.7	2121	646.9	312.0
72	19.0	5.7	2003	715.8	411.0
78	19.8	6.2	1898	779.7	485.0
84	20.1	6.4	1801	839.9	540.0
90	21.0	6.4	1706	895.9	579.0
96	21.9	6.4	1628	944.5	613.0
102	22.1	6.3	1552	999.2	641.0
108	22.9	6.2	1493	1045.8	668.0
114	23.2	6.1	1442	1091.3	695.0
120	23.9	6.0	1399	1134.2	722.0

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A4. Y-XENO projection of stand growth to age 120. Treatment = T_1F_0 (light thinning and no fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] (m^3 ha^{-1} a^{-1})	Stems (/ha)	Volume (m^3/ha) Gross[2]	Merchantable[3]
24	9.0	0.0	1961	51.0	0.0
30	11.0	0.0	1955	91.6	0.0
36	13.0	0.0	1932	147.0	0.0
42	14.2	0.2	1874	212.2	7.0
48	16.0	1.2	1775	283.3	60.0
54	17.1	2.7	1683	357.5	145.0
60	19.0	4.1	1575	430.4	246.0
66	20.0	5.2	1483	501.4	341.0
72	21.0	5.8	1402	568.9	415.0
78	22.0	6.1	1335	634.1	474.0
84	23.0	6.2	1274	694.9	522.0
90	23.7	6.3	1215	753.3	564.0
96	24.3	6.3	1172	809.6	605.0
102	25.2	6.3	1127	861.7	641.0
108	25.9	6.2	1079	912.3	670.0
114	26.7	6.1	1040	953.5	698.0
120	27.3	6.1	1008	1002.9	726.0

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A5. Y-XENO projection of stand growth to age 120. Treatment = T_1F_1 (light thinning and light fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] ($m^3\ ha^{-1}\ a^{-1}$)	Stems (/ha)	Volume (m^3/ha)	
				Gross[2]	Merchantable[3]
24	10.0	0.0	1798	57.2	0.0
30	13.0	0.0	1785	131.6	0.2
36	15.0	0.6	1745	206.7	21.4
42	17.0	2.5	1674	280.8	105.0
48	18.0	4.3	1583	359.2	206.0
54	19.9	5.7	1497	437.9	307.0
60	21.0	6.5	1420	514.3	389.0
66	22.0	6.9	1356	588.2	456.0
72	23.0	7.1	1296	658.1	513.0
78	24.0	7.2	1240	726.6	564.0
84	25.0	7.3	1189	791.5	612.0
90	25.7	7.3	1136	852.8	653.0
96	26.6	7.2	1094	910.2	692.0
102	27.4	7.2	1057	966.5	731.0
108	28.1	7.1	1026	1016.7	766.0
114	28.7	7.0	992	1067.2	797.0
120	29.4	6.9	955	1115.7	823.0

[1] Based on merchantable volume.
[2] Include mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A6. Y-XENO projection of stand growth to age 120. Treatment = T_1F_2 (light thinning and heavy fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] ($m^3\ ha^{-1}\ a^{-1}$)	Stems (/ha)	Volume (m^3/ha)	
				Gross[2]	Merchantable[3]
24	10.0	0.0	2042	64.5	0.0
30	13.0	0.0	2017	141.4	0.0
36	15.0	0.4	1960	221.7	14.0
42	16.3	2.0	1874	300.9	85.0
48	18.0	4.2	1773	384.2	200.0
54	19.0	5.8	1662	466.4	312.0
60	20.5	6.7	1566	546.8	401.0
66	21.6	7.1	1472	624.7	469.0
72	22.5	7.3	1399	695.5	526.0
78	23.5	7.3	1311	762.1	568.0
84	24.5	7.3	1251	825.7	611.0
90	25.3	7.2	1195	889.0	652.0
96	26.1	7.2	1146	947.3	688.0
102	26.9	7.0	1091	1002.7	717.0
108	27.5	6.9	1051	1052.8	747.0
114	28.2	6.8	1019	1101.6	777.4
120	28.8	6.7	984	1146.2	802.7

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A7. Y-XENO projection of stand growth to age 120. Treatment = T_2F_0 (heavy thinning and no fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] (m^3 ha^{-1} a^{-1})	Stems (/ha)	Volume (m^3/ha) Gross[2]	Merchantable[3]
24	12.0	0.0	901	40.4	0.0
30	14.0	0.0	899	70.4	0.0
36	16.4	0.8	894	111.6	28.6
42	18.6	2.5	880	160.7	103.4
48	20.5	3.6	852	217.1	155.4
54	22.1	4.3	818	277.5	232.6
60	24.1	4.8	786	339.2	288.9
66	25.4	5.2	752	401.6	341.8
72	27.0	5.5	727	461.1	392.5
78	28.2	5.7	707	519.2	442.5
84	29.3	5.8	682	575.6	487.7
90	30.4	5.9	660	629.9	530.6
96	31.6	6.0	640	682.8	571.7
102	32.6	6.0	624	733.4	613.3
108	33.5	6.1	614	781.8	654.3
114	34.4	6.1	601	829.3	691.1
120	35.0	6.0	588	872.5	724.8

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A8. Y-XENO projection of stand growth to age 120. Treatment = T_2F_1 (heavy thinning and light fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] (m^3 ha^{-1} a^{-1})	Stems (/ha)	Volume (m^3/ha) Gross[2]	Merchantable[3]
24	12.0	0.0	935	41.1	0.0
30	16.0	0.4	927	100.7	13.0
36	18.0	2.6	913	160.2	94.0
42	21.0	4.7	876	244.7	197.0
48	23.0	5.5	836	315.6	266.0
54	24.5	5.9	798	379.1	321.0
60	26.0	6.2	766	439.6	371.0
66	27.1	6.4	732	500.1	419.0
72	28.6	6.5	705	556.1	465.0
78	29.6	6.5	685	610.9	510.0
84	30.6	6.6	666	664.7	553.0
90	31.6	6.6	650	714.7	594.0
96	32.6	6.6	635	764.8	633.0
102	33.5	6.6	621	810.6	670.0
108	34.2	6.5	609	855.5	705.0
114	35.0	6.5	603	898.7	736.0
120	35.7	6.4	581	937.4	765.0

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Table A9. Y-XENO projection of stand growth to age 120. Treatment = T_2F_2 (heavy thinning and heavy fertilization).

Age (yrs)	Diameter (cm)	M.A.I.[1] ($m^3 ha^{-1} a^{-1}$)	Stems (/ha)	Volume (m^3/ha) Gross[2]	Merchantable[3]
24	13.0	0.0	935	49.6	0.0
30	17.0	1.5	929	120.9	46.0
36	20.0	4.6	906	206.9	165.0
42	23.0	5.9	856	290.1	247.0
48	24.6	6.4	812	362.3	309.0
54	26.1	6.7	777	428.4	364.0
60	27.7	6.9	741	491.7	414.0
66	29.0	7.1	720	555.7	468.0
72	30.0	7.2	702	613.9	517.0
78	31.0	7.2	684	670.0	564.0
84	32.0	7.2	664	724.5	606.0
90	33.0	7.2	653	778.0	650.0
96	33.9	7.2	641	830.2	694.0
102	34.6	7.2	628	877.3	730.0
108	35.5	7.1	610	924.2	762.0
114	36.5	7.0	599	968.3	796.0
120	37.1	6.9	584	1009.8	823.0

[1] Based on merchantable volume.
[2] Includes mortality and thinning volumes.
[3] Based on a minimum DBH of 17.5 cm and a 10-cm top.

Appendix B

Calculation of the per annum percentage increase in real prices required to break even

For each regime the minimum per annum increase in real prices, holding costs constant and considering basic silviculture as a year 0 investment, that would allow each treatment to obtain a NPV equal to zero was calculated (Table B1).

To determine the annual percentage increase it is necessary to determine the growth factor x such that the NPV of the treatment equals zero:

$$\frac{(1+x)^t\,(PQ)-HC}{(1+i)^t} - \frac{SC_{24}}{(1+i)^{24}} - BSC = 0$$

where: P = average price per m^3 in constant terms
Q = merchantable volume (m^3)
HC = harvest costs
SC_{24} = year 24 silvicultural costs
BSC = basic silvicultural costs at year 0

This equation can be rewritten as

$$\frac{(1+x)^t\,(PQ) - HC}{(1+i)^t} = TC_d$$

where TC_d is the total discounted treatment costs.

This can be rewritten as:

$$(1+x)^t = \frac{TC_d\,(1+i)^t + HC}{PQ}$$

To obtain the per annum required percentage increase in real prices take the t root of $1+x$ and subtract 1.

$$x = \sqrt[t]{\frac{TC_d\,(1+i)^t + HC}{PQ}} - 1$$

This growth percentage, x, must be calculated for each period and the minimum selected. Table B1 presents the minimum price increase and the rotation period associated with that price increase. A larger per annum real price increase will shorten the rotation period.

T_2F_2 requires the lowest minimum increase of the nine treatments as well as the shortest rotation period. All treatments require a per annum increase greater than 1% but less than 2%. There is a distinct pattern in that the heavier the thinning the less the required real price increase.

Table B1. Minimum per annum percentage growth rates required for NPV= 0

Treatment	Rotation (yrs)	Percentage increase required
T_2F_2	78	1.19
T_2F_1	84	1.30
T_2F_0	90	1.39
T_1F_1	90	1.41
T_1F_2	90	1.45
T_1F_0	102	1.58
T_0F_1	102	1.65
T_0F_2	108	1.69
T_0F_0	108	1.81

Appendix C

Biological versus economic rotations

This paper has discussed optimal rotation periods in terms of economic criteria. Foresters are usually more concerned with the biological rotation, which is the age at which maximum mean annual increment (MAI) occurs. This is equivalent to saying that the discount rate is equal to zero and implies that there is no cost to holding capital for an additional period.

The ranking of treatments by biological rotation age depends on fertilization but not thinning as it does in the economic NPV analysis. This is due to the fact that Y-XENO responds to fertilization by aging the stand of trees, thereby pushing the culmination of MAI forward (Appendix A). Thinning, on the other hand, pushes maximum MAI further out.

The economic rotation is longer than the biological rotation for six of the nine treatment regimes. Only the heavy thinning (T_2) treatments, which produce economies of size, have shorter economic than biological rotation ages. These rotation ages support Heaps' (1985) observation that financial rotations are highly dependent on factors such as soil fertility and real prices. Only good sites with favorable harvesting conditions have economic rotation ages that are less than the biological rotation, unless real prices rise sufficiently.

Table C1. Biological and economic rotations (1% per annum real price increase with basic silviculture as harvest cost)

Treatment[a]	Biological rotation (yrs)	NPV ($/ha)	Economic rotation (yrs)	NPV ($/ha)
T_0F_0	96	161	114	253
T_0F_1	84	103	108	283
T_0F_2	84	69	108	249
T_1F_0	96	290	102	305
T_1F_1	84	359	96	413
T_1F_2	72	195	96	358
T_2F_0	108	413	90	480
T_2F_1	90	525	84	540
T_2F_2	84	693	78	719

[a] See Table 1 for explanations of treatments.