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nimal damage o coniferous plantations n Oregon and Washington

art II. an economic evaluation

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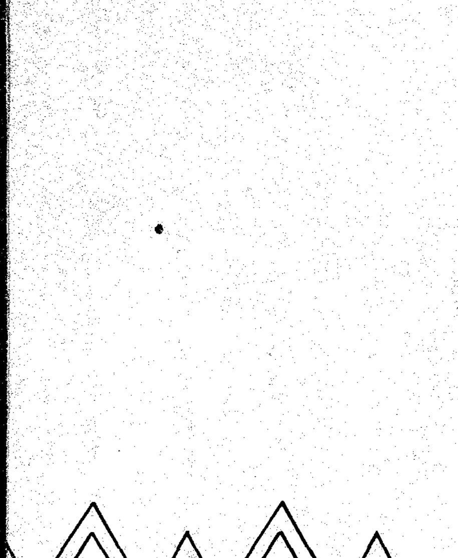

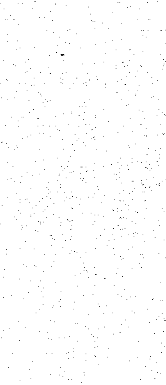

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contents

summary

Models of height growth and survival for Douglas-fir and ponderosa pine were fitted to data collected between 1963 and 1975 by the Cooperative Animal Damage Survey. Separate models were fitted to the trees protected and not protected from animal damage, and the models were statistically tested for differences. All of the difference between protected and unprotected models was attributed to animal damage, although some might reflect other slight benefits (for example, shading) from the cages used to protect the trees.

Damage and mortality varied greatly among the plantations; however, the significant difference between protected and unprotected portions was large. On the average, growth and yield were 13 percent less for unprotected trees, and present net worth returns (3%) were 18 percent less.

Assuming that planting rates continue in Oregon and Washington at the 1976 rate and that losses in Douglas-fir site 3 typify losses across all sites and species, animal damage decreases average present net worth $152 or $38 per acre planted, evaluated at 3- and 6-percent rates, respectively. Using representative allowable-cut-effect analysis, losses per acre average $539 and $359 at 3 and 6 percent, respectively. Animal damage in Oregon and Washington would reduce the total value of the forest resource by $1.83 billion and $230 million at the 3- and 6-percent rates, respectively.

Generally the analysis indicated that better sites, steep slopes, and large planting stock enhanced survival of unprotected trees, whereas low sites and south aspects increased mortality. In addition, 5 years proved a sufficiently long period for evaluating the impacts of early animal damage.

introduction

Recently the Pacific Northwest has experienced historic peaks in the demand for forest products and in stumpage prices. That demand is expected to continue increasing, yet old-growth forests on private lands are being depleted while allowable cut levels remain constant for public lands.

The development of this dilemma has been matched by increasing focus on intensive forest management. Such efforts, by both public and private agencies, emphasize rapid regeneration of current and "backlog" harvest areas with planting and early tending of plantations, rather than seeding and natural regeneration.

Because site preparation and planting are expensive, often $100 to $300 per acre, early tending tries to minimize animal damage. Failure of individual seedlings or whole plantations from animal damage requires replacement, interplanting, and protective measures that increase regeneration costs. Animal damage also causes early mortality and growth suppression, reflected in later stand development and yields. When incorporated into allowable cut determinations, such delays in regeneration and in expected yields result in both immediate and long-term reductions in harvest.

This study was undertaken to provide a method for systematically evaluating the physical and financial impacts of animal damage. By developing statistical models that we applied to field data collected in Oregon and Washington, we tested the hypothesis that survival and height differ between stands exposed to and protected from animal damage. Results of that analysis provide guidelines for protecting public and private forest plantations from animal damage.

The empirical portion of this study is based on 194 sample plots on Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) plantations in Oregon and Washington. These study plots were established during the 1963-64 and 1964-65 planting seasons by the Cooperative Animal Damage Survey (CADS) Committee in coordination with the Northwest Pest Action Council and the Western Forestry and Conservation Association. Types and agents of animal damage, recorded for periods of 5 and 10 years, are detailed in Dimock and Black (1968), Black et al. (1969), and Black et al. (1978).

The CADS data base we used included survey results for 183 plots (160 Douglas-fir and 23 ponderosa pine). Although Part I (Black et al. 1978) reported damage for all 194 plots, our analysis excluded 5 Douglas-fir and 6 ponderosa pine plots where protected trees experienced heavy mortality from causes other than animal damage. The 183 plots were established in Oregon and Washington during two growing seasons, but our comparisons do not differentiate state and year of planting. Nor are the results segregated by various public and private ownerships of the plots. However, the ponderosa pine data were analyzed separately from Douglas-fir data.

Each plot consisted of 100 uncaged trees and 10 trees caged to prevent animal damage. Types and agents of damage, height, and mortality for each tree were observed seven times—at planting and at the beginning of the first growing season, then each June for the next 5 years. A selected subset of 45 Douglas-fir plots was observed annually for 5 more years to document how the plots recovered from suppressed height growth.

Spacing and location were not measured for individual trees because instructions for plantation establishment had specifed 8- x 8-ft spacing or 680 trees per acre. Our analysis assumes this initial planting density.

Part I (Black et al. 1978) and previous reports (Dimock and Black 1968, Black et al. 1969) identify damage by deer, elk, three species of mice and voles, pocket gophers, hares and rabbits, mountain beavers, porcupines, bear, grouse, and domestic livestock. However, Part II does not analyze physical or economic damage by individual agents. Instead animal damage is treated as a homogeneous process of all agents, a process that accounts for differences—unaccounted for by other known variables or random variation—in height growth and mortality between the caged and uncaged trees.

height and survival models

model fitting

Linear regression models were step-wise fitted to the CADS observations, their transformations, and dummy variables derived from them. For model fitting, we used the arithmetic means of the annual observations rather than the individual tree values. We used 15 variables (Table 1) to develop 22 models (Table 2).

Table 1.

VARIABLES USED TO DEVELOP THE SURVIVAL AND HEIGHT MODELS.

Variable	Definition
HTU, HTC	Mean seedling height (in.)---caged (C) and uncaged (U)
SURU, SURC, SURP	Mean percent of seedlings surviving--caged (C), uncaged (U), and pooled (P)
t	Age since planting (years)
Stock 3[a]	Planting stock 3 years or older
ASPN, ASPE, ASPS, ASPW	Aspect--north (N), east (E), south (S), west (W)
Slope 2	Slope 6%-25%
Slope 3	Slope 26%-50%
Slope 4	Slope 50% +
Site H	Estimated site 1 or 2
Site L	Estimated site 4 or 5
Elev	Elevation (not significant in any model)
UCAG	Observations on uncaged trees

[a] One of each set of dummy variables can remain undefined and, in essence, be included in the intercept. The implicit variables are: stock < 3 years, estimated site III, no aspect, and slope 0-5%.

simple models

"Simple" describes a height or survival model with only time and the dependent variable, here height or survival, in the form:

$$HT = a_0 + a_1 t + a_2 t^2$$

or

$$SUR = 100\ (t+1)^{-b_0}$$

where HT is height (in.), SUR is survival (%), t is time since planting (years), and a and b are coefficients.

The height model is a simple polynomial like those often used for short-term fitting and projection. Without inflection points or a height asymptote, the height model cannot be used in long-term projections. This form is consistent with height observations of only 5 and 10 years as inflection points, and asymptotes occur at later ages.

The survival model is a negative exponential form previously used to explain plantation mortality[1]

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[1] David J. Depta. 1974. A probabilistic model of Douglas-fir reforestation for economic decision-making. Unpublished M.S. thesis, Univ. Calif., Berkeley. 167 p.

Table 2.

SURVIVAL AND HEIGHT EQUATIONS USING THE CADS DATA[a].

A. Simple Models

Species	Model[b]	r^2
Pine: 23 plots, 7 measurements	$HTC = 4.1522 + 0.69358t^2$ (17.269)	0.652
	$HTU = 3.9192 + 0.50971t^2$ (11.152)	0.439
	$SURC = 100\ (t+1)^{-0.16434}$ (-8.3743)	0.305
	$SURU = 100\ (t+1)^{-0.43103}$ (-13.422)	0.560
Douglas-fir: 160 plots, 7 measurements	$HTC = 8.8693 - 0.40332t + 1.5670t^2$ (0.57522) (11.731)	0.593
	$HTU = 9.2367 - 1.8208t + 1.3797t^2$ (-3.1311) (12.455)	0.512
	$SURC = 100\ (t+1)^{-0.23192}$ (-28.780)	0.425
	$SURU = 100\ (t+1)^{-0.39457}$ (-36.309)	0.541
Douglas-fir, 10 year subset: 45 plots, 12 measurements	$HTC = 8.1154 + 3.1587t + 1.2696t^2$ (2.1195) (8.7531)	0.740
	$HTU = 10.624 - 2.7626t + 1.3930t^2$ (-2.0334) (10.534)	0.644
	$SURC = 100\ (t+1)^{-0.093252}$ (-20.009)	0.428
	$SURU = 100\ (t+1)^{-0.25964}$ (-35.234)	0.697
Douglas-fir, 10 year subset: 45 plots, first 7 measurements	$SURC = 100\ (t+1)^{-0.10478}$ (-14.388)	0.397
	$SURU = 100\ (t+1)^{-0.28791}$ (-26.342)	0.688

[a] Unless otherwise stated, models are based on 5 years of observations.

[b] Numbers in parentheses are t values for coefficients.

and mortality in natural all-age stands (Hett and Louks 1971).

For the subset of 45 plots, additional models were fitted to the first 5 years of these data and to the full 10 years. Plotting and inspection showed the 5-year models for the subset to differ significantly from the 5-year model based on all 160 plots. Thus the 45 plots were not a random sample from the population at large. The subset models were used secondarily and subjectively to determine if projections based on 5 years of observation, when most of the mortality and height suppression occurred, would differ from projections based on 10 years of data. The projections differed little, suggesting that a 5-year observation period suffices for fitting plantation models of this sort.

multiple variable models

Multiple variable models also were fitted, but different variables proved significant in the models for caged and uncaged trees. Consequently, we used the simple models and followed Johnston's (1972) procedures to test our hypothesis that the regression models differ for caged and uncaged trees.

To improve the multiple variable models as predictors for specific plantation sites, we used additional observations on site, aspect, and size of planting stock. The relationships were of the form:

$$HT = a_o + a_1 t + a_2 t^2 + a_3 D_1 + a_4 D_2 \ldots$$

$$SUR = 100(t+1)^{[-b_0 + b_1 D_1 + b_2 D_2 \ldots]}$$

where the "D" represents dummy variables.

Dummy variables are function shifters with effects similar to a change in intercept. A dummy variable for a particular aspect had the value of "1" if the plot had the aspect, otherwise the value was zero. If the coefficient of the variable was significant, the variable was interpreted as having a significant positive or negative effect on the dependent variable. The criterion used for including a variable and coefficient was $\leqslant P = 0.05$ that the true coefficient value was zero.

results

simple models

Only a single quadratic age term was significant in the simple height models for pine, whereas both linear and quadratic terms were significant in the Douglas-fir models. In all cases, the r^2 (goodness of fit) statistic was higher for caged than uncaged trees with respect to height growth and lower with respect to survival.

These observations were probably due to two factors. First, height growth of caged trees varied less than that of uncaged trees due to

Table 2 (continued).

B. Multiple Variable Models

Species	Model[b]
Pine: 23 plots, 7 measurements	$\text{HTC} = 3.9143 + 0.85249 \text{ Slope } 2 + 0.63252t^2$ (7.5229) (3.3258) (14.690)
	$\text{HTU} = 3.9192 + 0.50971t^2$ (6.4807) (11.152)
	$\text{SURC} = 100(t + 1)^{[-0.34077 + 0.16564 \text{ Slope } 2 + 0.16579 \text{ Slope } 3 + 0.11587 \text{ Site L}]}$ (10.249) (3.9411) (3.3651) (2.9288)
	$\text{SURU} = 100(t + 1)^{[-0.71988 + 0.29629 \text{ Stock } 3 - 0.20859 \text{ ASPS} + 0.39919 \text{ Slope } 2 + 0.69600 \text{ Slope } 3]}$ (-16.616) (4.1879) (-2.6176) (4.8503) (8.1994)
Douglas-fir: 160 plots, 7 measurements	$\text{HTC} = 8.8693 + 1.3386 \text{ Stock } 3 + 0.86887 \text{ Slope } 4 + 3.3641 \text{ Site H} - 1.4059t - 0.61671 \text{ Slope } 3 - 1.9343 \text{ Site L}$ (14.4314) (5.6664) (2.8600) (13.471) (-2.1988) (-2.8600) (-6.6348)
	$\text{HTU} = 9.2367 + 1.0966 \text{ Stock } 3 + 0.78795 \text{ Slope } 4 + 2.3586 \text{ Site H} - 2.4458t - 0.81239 \text{ ASPS} - 0.78410 \text{ Site L}$ (17.2844) (5.4248) (3.1356) (10.885) (-4.3951) (-4.3797) (-3.1060)
	$\text{SURC} = 100(t + 1)^{[-0.26726 + 0.11721 \text{ ASPW} + 0.11196 \text{ Slope } 4 + 0.078508 \text{ Site H} + 0.095812 \text{ ASPE} - 0.036843 \text{ Slope}}$ (-20.681) (5.4972) (5.2361) (4.3974) (3.1102) (-2.0546)
	$\text{SURU} = 100(t + 1)^{[0.37066 - 0.10568 \text{ ASPS} - 0.064498 \text{ Slope } 3 - 0.13741 \text{ Site L} + 0.048000 \text{ Stock } 3 + 0.082359 \text{ ASPW}}$ (-15.896) (-4.5871) (-2.5553) (-4.8148) (2.0874) (2.6064)

the protection from animal damage. Second, because only 10 caged trees were observed on each plot, the survival variable could change only in discrete intervals of 10 percent, whereas the 100 uncaged observations could vary in 1-percent intervals. In both cases, the height variable was continuous.

These simple models were fitted so caged and uncaged models could be compared. On subjective grounds, the simple models of the 10-year subset clearly differed from the rest of the Douglas-fir data.

multiple variable models

The regression techniques and tests used in this study facilitated rapid descriptive analysis of the large array of data collected, and the aggregate differences derived between caged and uncaged relationships were large. The effects of individual variables, except those noted as possibly spurious with little theoretical biological support, generally agreed with established biological theories and hypotheses.

Pine. For height growth in uncaged pine, none of the dummy variables proved significant, and the best model was the simple one. In the caged model, gentle slope (Slope 2) showed a very small but significant positive impact on height.

The gentle to moderate slopes (Slope 2, Slope 3) increased survival of both caged and uncaged pines. The only other dummy variable significant for survival of caged pine was a possibly spurious positive impact by low site. The survival model for uncaged pine showed a significant positive effect for large planting stock (Stock 3) and a negative effect for south aspect (ASPS). The absence of these variables from the caged relationship may indicate that larger stock were better able to survive browsing and that the cage itself possibly shaded the trees.

	d.f.	r^2
	158	0.6750
	159	0.439
	156	0.448
	156	0.692
	1,113	0.688
1.5670t^2 13.366)	1,112	0.588
1.3797t^2 (13.534)	1,112	0.500
- 0.11508 Site L] (-5.4890)	1,112	0.594
0.073957 Slope 4 + 0.092354 Site H] (2.4902) (3.7787)		

Table 3.

TESTS OF DIFFERENCES BETWEEN CAGED AND UNCAGED MODELS.

A. Height

Species	d.f.	F	Significance
Pine	(1, 320)	49.9	≃0.80[a]
Douglas-fir	(3, 2394)	67.07	0.99

B. Pooled Regression Tests

Variable	Model[b]	d.f.
Pine height	$HT = 4.3426 - 0.86067\ UCAG + 0.68041t^3$ (10.6533) (-4.4359) (19.3459)	319
Pine survival	$SURP = 100\ (Age+1)^{[-0.16434 - 0.026669\ UCAG]}$ (-6.1753) (-7.0859)	320
Douglas-fir survival	$SURP = 100\ (Age+1)^{[0.23192 - 0.16265\ UCAG]}$ (-24.2438) (12.0224)	2,238

[a] Low significance is due to limited degrees of freedom (d.f.). An alternative test (section B) uses pooled regression with a dummy variable for uncaged trees.

[b] Numbers in parentheses are t values for the coefficients.

Douglas-fir. For height growth of both caged and uncaged Douglas-fir, low (L) site had an expected negative impact, and high (H) site had an expected positive impact (Table 2). In each instance, large planting stock enhanced growth as did slopes over 50 percent (Slope 4). Moderate slopes (Slope 3) negatively affected caged trees, but that may well have been spurious. South aspects (ASPS) slightly retarded height growth of uncaged trees.

For survival of both caged and uncaged Douglas-fir, Site H had a positive impact whereas Site L had a larger negative impact. Large planting stock (Stock 3) enhanced survival of the uncaged trees only. As in the height relationships, very steep slope (Slope 4) had a positive impact, whereas moderate steepness (Slope 3) was significant and negative in both the caged and uncaged model. Small positive impacts of east (ASPE) and west (ASPW) aspects in the caged and uncaged models, respectively, may have been spurious; however, the negative impact of south aspect in the uncaged model and its absence from the caged model possibly reflected greater animal use of those warmer aspects.

The coefficients of determination (r^2) reflected much unexplained variation in the data, possibly because of the small number of plots dispersed over species, region, and time of planting. Consequently, we did not analyze finer (regional or time of planting) breakdowns of those statistics reported by Black et al. (1978).

caged versus uncaged models

Regression models for height of Douglas-fir and pine were evaluated with an "F" test (Johnston 1972) for significant differences between caged and uncaged trees. Douglas-fir models differed significantly at P=0.01, but the level of significance was lower (P=0.20) for ponderosa pine due to limited degrees of freedom.

Consequently, we used a different technique to fit the regression model to the pooled caged and uncaged data for ponderosa pine with a dummy variable for uncaged. The coefficient of the dummy was highly significant at P=0.01 (Table 3).

Similarly, for survival of both pine and Douglas-fir, a pooled regression of the caged and uncaged data was fitted with a dummy variable for uncaged. The resulting coefficients for the dummy were highly significant (P=0.01), representing the increase in the mortality coefficient attributable to not caging. The dummy coefficient was exactly the difference between the caged and uncaged coefficients in the simple relationship.

optimizing management of damag

The key to evaluating early animal damage to coniferous plantations is a method for comparing yields and financial returns from a damaged stand and from the same stand undamaged. For a damaged stand at age 5, the procedure would project and compare the yields and financial returns throughout the rotation with those of an undamaged stand; the difference would be the projected impact of damage occurring up to age 5.

However, the situation is complicated by the fact that most forest management decisions, such as rotation and thinning regime, occur after age 5. Prescribing the same rotation and thinning regime to a stand 50 percent stocked and to a stand fully stocked at age 5 would vastly overstate the impact of animal damage.

Minor adjustments in thinning regime or rotation may reduce the loss impact. Alternately, the manager may minimize losses by establishing a new stand or concentrating regeneration efforts elsewhere. Consequently, the method of evaluation should optimize the management regime for a stand in any condition. The regime could be compared with alternatives for undamaged stands to determine the impact of animal damage and to derive rational expenditures for protecting or replacing trees.

dynamic programming

To optimize rotation and thinning for stands of various stocking levels, this study used dynamic programming which is explained in most introductory texts on operations research (such as Hillier and Lieberman 1974). The first application of this technique to North American forestry problems was by Hool (1966) and to thinning by Amidon and Akin (1968). The specific form of the dynamic programming algorithm we used is described by Brodie et al. (1978), and Table 4 lists the functional mensurational relationships.

To state the problem of thinning and rotation in dynamic programming form, we must first be able to describe stand condition in terms of two or more variables known as **state descriptors**—in this case, age in years and stocking level in cubic feet. The descriptors must be discrete rather than continuous, and so we chose **state intervals** of 10 years and 100 ft^3 levels of stocking. That is, at any given 10-year interval, a stand can be thinned to stocking levels at a large, but finite, number of discrete 100-ft^3 intervals. The development of a forest stand becomes a flow via stand growth from one age-stocking state to another. Managers can then decide to thin and reduce the stocking level before the growth flow continues to the next age-stocking state.

Next dynamic programming requires an optimal value function. This study used present net worth of thinnings and final harvest on either a single rotation or perpetual series (soil rent basis). This criterion implies that the manager wants to maximize the stand's net dollar return, including interest (capital opportunity cost). Noneconomic objectives such as volume maximization or nondiscounted cash flow maximization (forest rent) could be implemented by appropriately modifying computations.

There are an extremely large number of definable discrete stocking level paths for thinning a Douglas-fir stand to a rotation age of 70. Dynamic programming reduces the computational load of analyzing these alternatives by relying on the "principle of the discrete maximum," often referred to as the "principle of

Table 4.

GROWTH AND MORTALITY FUNCTIONS.

A. Normal Growth

Site	Function[a]
Ponderosa pine 80	$VOL = -1,208 + 127.57t - 0.8533t^2 + 0.0030298t^3 - 0.0000041275t^4$
Douglas-fir I (200)	$VOL = 4,461.4 + 318.44t - 0.029936t^2 - 0.012219t^3 + 0.000042937t^4$
Douglas-fir II (170)	$VOL = -4,114.8 + 290.69t - 0.028302t^2 - 0.0087032t^3 + 0.000032309t^4$
Douglas-fir III (140)	$VOL = -3,275.5 + 231.8t - 0.19922t^2 - 0.007382t^3 + 0.000027533t^4$
Douglas-fir IV (110)	$VOL = -2,160.7 + 156.14t - 0.16258t^2 - 0.0044977t^3 + 0.000016751t^4$

B. Approach to Normality[b]

$$N_{t+10} = 1.3157\ N_t - 0.46459\ N_t^2 + 0.16423\ N_t^3$$

C. Normal Mortality (10 year)[c]

Site	Function
I, II	$MORT = -76.761 + 21.709t - 0.12499t^2 + 0.0001869t^3$
III	$MORT = 123.36 + 9.7815t - 0.058656t^2 + 0.000093416t^3$
IV, V[d]	$MORT = -766.71 + 56.112t - 0.80448t^2 + 0.001709t^3$

D. Percent Normal Mortality[e]

$$PCTNMORT = 0.25159N_t + 1.4223N_t^2 - 0.64988N_t^4$$

[a] VOL = normal net yield (ft^3).

[b] Where t = age, N_t = percent normality at age t, and r^2 for the growth and normality relationships are all essentially unity.

[c] Derived from Staebler (1955) by Beuter et al. (1976).

[d] Constrained if $t > 40$, $t = 40$.

[e] Fitted for easier computation. The relationship for Sites IV and V was used for ponderosa pine.

optimality." In terms of the thinning problem, once the optimal thinning regime is determined for a given age and stocking level, the optimal regime for longer rotations depends only on the (older) age-stocking combinations not yet analyzed. Thus, the stocking levels for a given age need to be analyzed only once, vastly reducing the necessary calculations.

models of growth, yield, revenue, and cost

Optimal thinning regimes can be computed with models of growth, yield, revenue, and cost. Fourth-order linearly transformed polynomials were fitted for selected sites (Table 4) to the normal yield data for Douglas-fir (McArdle et al. 1961) and for ponderosa pine (Meyer 1938). The normal yield functions follow the form:

$$y = a + bt + ct^2 + dt^3 + et^4$$

where y is normal yield (ft^3), and t is age (years).

McArdle et al. (1961) also presented tabular information (their table 28) on the approach to normality. A linearly transformed cubic function forced through the origin fits the data well and correctly attributes zero growth to stands of zero stocking. The model follows the form:

$$N_{t+10} = fN_t + gN_t^2 + hN_t^3$$

where N is mortality (%).

Because no approach-to-normality information has been reported for ponderosa pine, we used the normality function developed for Douglas-fir. A diameter quality premium of the type developed by Darr (1973) was used to account for increasing values of larger diameter timber with maximum value at 20 inches (Table 5).

Table 5.

PRICE DATA CALCULATED FOR SPECIES AND SITES[a].
(dollars per cubic foot)

	Douglas-fir			Ponderosa pine
Age	Site II (170)	Site III (140)	Site IV (110)	Site 80
20	0.337	0.271	0.199	0.211
30	0.487	0.397	0.301	0.295
40	0.631	0.511	0.397	0.373
50	0.775	0.625	0.487	0.511
60	0.907	0.733	0.577	0.577
70	1.027	0.835	0.655	0.643
80	1.141	0.925	0.721	0.709
90	1.243	1.003	0.781	0.769
100	1.267	0.081	0.835	0.829
110	1.267	1.147	0.889	0.883
120		1.213	0.943	0.937
130		1.267	0.985	0.991
140			1.027	1.039

[a] $P = (3D-6)0.02 + 0.187$ where P = price per cubic foot and D = normal average stand diameter. Values assumed constant after D = 20 in.

Normal mortality data from Staebler (1955) was functionally fitted and combined with the intuitive assumption that mortality is a function of normality:

$$M_t = (a + bt + ct^2 + dt^3)\ \mathrm{PCNTMORT}$$

and

$$\mathrm{PCNTMORT} = aN_t + bN_t^2 + CN_t^4$$

where M_t is 10-year mortality at age t, and PCNTMORT is percent of normal mortality.

The growth model was continuous, whereas the stocking levels were discrete. This meant that a small "rounding" thinning of less than 100 ft^3 was always necessary to assure a discrete stocking level of 100 ft^3. Thinning was assumed to capture periodic mortality, but mortality capture required taking an additional 100 ft^3 of live growing stock. Thinning consisted of the "rounding" harvest, plus adjustment of growing stock levels, plus mortality capture. Thinnings of less than 100 ft^3 were nonoptimal, taken only to meet the constraint of the discrete stocking level.

Light thinnings cost more per unit than heavier thinnings. Tractor thinning costs from Aulerich et al. (1974) were used as an asymptote in a variable logging cost function which presumed a cost level 150 percent of their level for extremely small harvests:

$$LT = 0.10 + (0.05e^{-t/400})\ T + E_t$$

where LT is logging cost per acre, T is the level of thinning (ft^3), E is a fixed stand entry cost for a thinning ($2.50/acre here), and e is the base of the natural logarithms.

Two types of optimal regimes can be derived using an appropriate discount rate (i). The criterion of present net worth (PNW) maximizes the discounted value of all costs and revenues for a single rotation. However, this solution is economically incorrect because it fails to account for the opportunity cost of tying up the land with the current rotation rather than recycling it through subsequent rotations. Consequently, rotations in the PNW examples in our study are 10 to 30 years longer. The general and economically correct solution uses the soil expectation (Se) or soil-rent criterion which maximizes the discounted value of all costs and revenues for an infinite series of rotations. The procedures we used provide both solutions, and one criterion is a relatively simple transformation of the other:

$$PNW = \sum_{t=0}^{r} [(P_t T_t - LT_t)/(1+i)^t] + [(P_r H_r - L_r)/(1+i)^r] - R$$

$$Se = PNW\ [(1+i)^r/(1+i)^r - 1]$$

where P is selling price; L_r is final harvest cost; the t and r subscripts are age of thinning and final harvest, respectively; i is interest rate (as a decimal); and R is regeneration cost. Other variables are as previously introduced.

The procedure permits the simultaneous optimization of rotation length and thinning regime for stands of any initial stocking level and permits the impact of reduced stocking to be evaluated.

These statistical models provide aggregate descriptions of the average survival and average height growth experienced by protected and unprotected trees in the CADS survey. Within the data range, the models also serve as tools for predicting survival and height growth of protected and unprotected trees. However, the effective range of observed data is 5 years, so care must be taken with further projections.

With no inflection point, the height models are only appropriate for predicting the juvenile (increasing) phase of height growth. The 10-year subsample (Black et al. 1978) included plots whose protected and unprotected heights converged, diverged, or remained constant from the ages of 5 to 10. Furthermore, experimental results are inconclusive as to whether absolute height differences diminish or increase over projected rotation lengths. Consequently, we did not evaluate the economic impacts of height growth suppression.. If future studies of long-term stand development show significant impacts on height, they can be evaluated by simple adjustments in growth models.

The models show protection significantly increased survival at age 5. Projections beyond that show continued mortality at a decreasing rate (Table 6); however, evaluations in this study are based on survival at age 5.

Although the CADS plots were planted at 680 trees per acre, our study assumed that 600 trees surviving at age 5 would give the approximate normal stocking at age 20 (McArdle et al. 1961). For each discrete age-20 stocking level, management regimes were optimized from 100 ft^3 to "normal" stocking for the site. Impacts of reducing stocking level can be derived by comparing the regimes and values.

regime

Douglas-fir sites II (170), III (140), and IV (110) and for ponderosa pine, site 80 were analyzed separately. Each analysis assumed that the first thinning would be at age 30, then at 10-year intervals until the optimal rotation was reached. The persistence of reduced stocking (animal damage) in subsequent rotations is an implicit assumption when analyzing perpetual series. In general, reduced stocking (Tables 7–10): (1) reduced soil expectation value; (2) reduced levels of thinning at early ages with early thinning becoming nonoptimal for severe reduction; (3) lengthened optimal rotation; and (4) reduced physical yield as indicated by mean annual increment.

discount rate and value projections

The value of thinnings and final harvest (Table 5) was assumed to increase with age according to a

Table 6.

PROJECTED HEIGHT AND SURVIVAL USING THE SIMPLE MODELS FOR BOTH SPECIES.

	Height (in.)		Survival (%)	
Species and age	Caged	Uncaged	Caged	Uncaged
DOUGLAS-FIR				
5 years	46.0	34.6	66.0	49.3
10 years	161.5	129.0	57.3	38.8
20 years	627.6	524.7	49.4	30.1
PONDEROSA PINE				
5 years	21.5	16.7	74.5	46.2
10 years	73.5	54.9	67.4	35.5
20 years	281.6	207.8	60.6	26.9

Table 7.

THINNING YIELDS AND FINAL HARVEST OF SITE II (170) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.

(cubic feet)

Age 20 stocking	Age (years) 30	40	50	60	70	80	90	100	Total harvest	Mean annual increment
1,600[a]	517	649	1,097	4,182	2,802	8,945			18,192	227.40
1,600	517	649	1,097	4,182	2,802	8,945			18,192	227.40
1,500	469	657	828	4,069	2,802	8,945			17,770	222.13
1,400	416	561	779	3,841	2,802	8,945			17,344	216.80
1,300	457	600	646	3,263	2,802	8,945			16,721	209.01
1,200	392	501	688	2,913	2,802	8,945			16,241	203.01
1,100	423	531	635	2,200	2,802	8,945			15,536	194.20
1,000	348	513	536	1,839	2,802	8,945			14,983	187.29
900	367	425	495	1,328	2,685	8,945			14,245	178.06
800	33	360	558	1,181	3,267	2,515	7,385		15,299	169.98
700	67	357	464	528	3,149	2,515	7,385		14,465	160.72
600	92	342	351	459	2,313	2,515	7,385		13,457	149.52
500	7	290	314	436	1,705	2,515	7,385		12,652	140.58
400	12	251	269	399	786	2,275	7,385		11,377	126.41
300	5	29	256	273	391	1,668	7,385		10,007	111.19
200	85	94	32	195	291	273	6,164		7,134	79.27
100	50	12	25	55	243	167	1,037	3,676	5,265	52.65

[a] Protected from animal damage.

Table 8.

THINNING YIELDS AND FINAL HARVEST OF SITE III (140) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.

(cubic feet)

Age 20 stocking	Age (years) 30	40	50	60	70	80	90	100	110	120	130	Total harvest	Mean annual increment
1,300[a]	459	545	941	3,290	2,403	6,560						14,198	177.48
1,300	459	545	941	2,590	8,202							12,737	181.96
1,200	411	554	573	2,590	8,202							12,330	176.14
1,100	454	507	574	2,721	2,403	6,560						13,219	165.24
1,000	390	503	493	2,375	2,403	6,560						12,724	159.05
900	418	436	475	1,890	2,287	6,560						12,066	150.83
800	339	417	480	1,513	2,171	6,560						11,648	145.60
700	353	328	441	1,005	2,054	6,560						10,741	134.26
600	33	362	367	758	2,654	1,850	5,274					11,298	126.53
500	63	252	307	431	2,302	1,850	5,274					10,479	116.43
400	81	276	285	325	1,440	2,130	1,288	4,599				10,374	103.74
300	85	18	288	321	344	2,250	1,288	4,599				9,193	91.93
200	74	79	6	244	276	1,002	1,565	1,607	815	3,284		8,952	74.60
100	47	7	17	39	210	220	237	1,854	1,115	907	2,636	7,289	56.07

[a] Protected from animal damage.

relationship similar to that developed by Darr (1973). Such a quality premium substitutes age for diameter and fails to credit thinning with accelerated diameter growth. This resulted in light "mortality only" levels of thinning in the early periods. Recently we developed three descriptor dynamic programming procedures based on growth models with explicit treatment of diameter. Results indicate that heavier early thinning offers the advantage of accelerated diameter growth. These newer growth models are very sensitive to the initial number of trees, suggesting that animal-induced mortality would cause substantial losses.

No inflation rate or real stumpage value increases were used. The discount rate of 3 percent approximated the real rate of return (net of inflation) on long-term securities such as corporate bonds. On Douglas-fir sites, higher discount rates resulted in lower soil expectations with shorter rotations and heavier thinnings (Table 11). Small stock reductions from animal damage would cause these low soil expectations to become negative. Thus the relative impact of animal damage is great at high discount rates (even though its absolute value may be small). Minor animal

Table 9.

THINNING YIELDS AND FINAL HARVEST OF SITE IV (110) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.

(cubic feet)

Age 20 stocking (ft^3)	Age (years)										Total harvest	Mean annual increment
	30	40	50	60	70	80	90	100	110	120		
900[a]	88	423	466	2,462	1,958	1,423	857	2,892			10,569	105.69
900	88	423	466	1,862	5,440						8,279	118.27
800	57	333	419	2,137	1,674	4,196					8,816	110.20
700	26	335	442	1,780	1,558	4,196					8,337	104.21
600	90	273	424	1,296	1,442	4,196					7,721	96.51
500	47	255	375	1,037	1,726	1,123	3,420				7,933	88.14
400	94	260	235	297	1,726	1,123	3,420				7,155	79.50
300	25	43	250	314	1,353	1,303	857	2,892			7,037	70.37
200	39	40	208	185	267	1,423	1,157	1,023	194	2,349	6,885	57.38

[a] Protected from animal damage.

Table 10.

THINNING YIELDS AND FINAL HARVEST OF PONDEROSA PINE SITE 80, 3 PERCENT DISCOUNT RATE.

(cubic feet)

Age 20 stocking (ft^3)	Age (years)																		Total harvest	Mean annual increment
	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200		
1,000[a]	17	168	1,083	1,218	902	823	956	248	881	175	1,718								8,181	62.93
1,000	17	168	1,083	1,218	1,102	285	2,610												6,483	72.03
900	52	215	723	1,218	902	1,023	214	2,354											6,701	67.01
800	85	162	381	1,331	902	823	856	272	2,101										6,913	62.85
700	16	233	336	1,104	902	823	856	272	2,101										6,643	60.39
600	42	39	312	989	902	823	856	272	2,101										6,336	57.60
500	61	73	331	321	1,132	823	956	248	881	175	1,718								6,719	51.68
400	73	95	235	256	785	823	956	248	981	248	169	1,713							6,582	47.01
300	74	1	260	277	305	823	956	248	881	175	818	210	534	176	503	143	172	1,199	7,755	38.77
200	63	90	177	205	239	266	191	936	635	175	818	210	534	176	503	143	172	1,199	6,732	33.66
100[b]	39	57	75	92	148	206	222	239	157	501	169	913	178	204	630	143	172	1,199	5,344	26.72

[a] Protected from animal damage.

[b] Single rotation criterion for present net worth.

Table 11.

ECONOMIC IMPACT OF INTEREST RATES ON DOUGLAS-FIR THINNINGS AND FINAL HARVEST.

Interest rate	Se[a] ($)	Age (years)						Total harvest	Mean annual increment
		30	40	50	60	70	80		
		(ft^3/ac)							
SITE II (170)									
9%	-54.66	2,417	4,294					6,711	167.78
6%	+248.73	517	3,149	6,358				10,024	200.48
3%	+2,142.00	517	649	1,097	4,182	2,802	8,945	18,192	227.40
SITE III (140)									
9%	-108.65	1,859	3,693					5,552	138.80
6%	+77.73	459	2,545	5,077				8,081	161.62
3%	+1,245.90	459	545	941	2,590	8,202		12,737	181.96
SITE IV (110)									
9%	-158.97	737	3,029					3,766	94.15
6%	-73.18	237	1,279	3,793				5,309	106.18
3%	+485.47	88	423	466	1,862	5,440		8,279	105.69

[a] Negative values based on criterion for single rotation.

damage has modest relative impacts but more substantial absolute dollar impacts at the 3-percent discount rate. For purposes of comparison, the management regime and the damage analysis for Douglas-fir Site III were duplicated at a 6-percent discount rate (Tables 12—14).

costs of regeneration, site preparation, and protection

All analyses of Douglas-fir sites assumed that site preparation and planting cost $200 per acre. Massive animal damage control—mountain beaver trapping and herbicide treatments to reduce available pest forage before planting, then vexar tubing (Campbell and Evans 1975) of 150 trees per acre—was assumed to cost another $252.50 per acre. This high control cost was used to demonstrate how the best available animal-control technology can help problem areas. Higher regeneration costs due to animal control lengthened the optimal rotation, reducing the cumulative expense of high-cost protection and regeneration by applying them less frequently or to smaller areas.

For ponderosa pine, site preparation and planting cost $100 per acre. In addition, animal control costs were assumed to be $100 per acre for prebaiting of planting areas and for herbicide treatment to control gopher and other rodent forage.

derivation of impacts

For each site, we prepared a table of the optimal thinning intensity, total yield over the rotation, and mean annual increment for each age-20 stocking level (Tables 7—10). Volume production and value were not linearly related to damage level. Reductions in initial stocking produced less than proportional reductions in volume. For example, in

Table 12.
THINNING YIELDS AND FINAL HARVEST OF SITE III (140) DOUGLAS-FIR, 6 PERCENT DISCOUNT RATE. *(cubic feet)*

Age 20 stocking	Age (years) 30	40	50	60	Total harvest	Mean annual increment
1,300[a]	459	2,545	5,077		8,081	161.62
1,300	459	2,545	5,077		8,081	161.62
1,200	411	2,254	5,077		7,742	154.84
1,100	454	1,807	5,077		7,338	146.76
1,000	390	1,603	4,941		6,934	138.68
900	418	1,136	4,941		6,495	129.90
800	339	917	4,804		6,060	121.20
700	353	328	4,941		5,622	112.44
600	260	294	4,528		5,082	101.64
500	258	279	3,822		4,359	87.18
400	81	226	3,385		3,692	73.84
300	85	180	2,636		2,901	58.02
200	74	212	194	2,311	2,791	46.52
100	47	7	137	1,418	1,609	26.82

[a] Protected from animal damage.

Table 13.
ECONOMIC IMPACT OF REDUCED STOCKING ON SITE III (140) DOUGLAS-FIR, 6 PERCENT DISCOUNT RATE.

Age 20 stocking (ft^3)	Trees surviving age 5	Se	ΔRC	ΔSe	SERIES	Optimum rotation age (years)
		- - - - - - - -	($/ac)	- - - - - - - -		
1,300[a]	624	-190.78	252.50	267.00	5.72	50
1,300	624	76.21	--	--	350.24	50
1,200	576	61.42	13.99	14.79	331.52	50
1,100	528	44.74	29.76	31.47	310.41	50
1,000	480	28.49	45.13	47.72	289.85	50
900	432	10.02	62.60	66.19	266.47	50
800	384	-7.66	79.32	83.88	244.09	50
700	336	-27.84	98.41	104.06	218.54	50
600	288	-46.91	116.44	123.13	194.41	50
500	240	-69.72	138.02	145.94	165.54	50
400	192	-94.02	161.00	170.24	134.79	50
300	144	-119.14	184.75	195.36	103.00	50
200	96	-143.34	212.90	219.56	73.90	60
100	48	-172.25	240.93	248.47	36.38	60

[a] Protected from animal damage.

Table 14.
ALLOWABLE CUT EFFECT (ACE) IMPACT OF SITE III (140) DOUGLAS-FIR, 6 PERCENT DISCOUNT RATE.[a]

Age 20 stocking (ft^3)	ΔAc (ft^3/ac)	Present net worth Year 25	Year 26-∞	Total	Single rotation[a] (150 years)
		- - - - - - - - - -	($/ac)	- - - - - - - - - -	
1,300	0	--	--	--	--
1,300[b]	0	--	--	--	--
1,200	6.78	109.81	16.46	126.27	122.43
1,100	14.86	240.68	36.07	276.75	268.34
1,000	22.94	371.55	55.68	427.22	414.25
900	31.72	513.75	76.99	590.74	572.80
800	40.42	654.66	98.10	752.77	729.91
700	49.18	796.54	119.36	915.91	880.10
600	59.98	971.47	145.58	1,117.04	1,083.12
500	74.44	1,205.67	180.67	1,386.34	1,344.24
400	87.78	1,421.73	213.05	1,634.78	1,585.14
300	103.60	1,677.96	251.44	1,929.40	1,870.82
200	115.10	1,864.22	279.36	2,143.57	2,078.48
100	134.80	2,183.29	327.17	2,510.46	2,434.23

[a] Prices of old-growth and young-growth stands are $1.267 and $0.625 per cubic foot, respectively.

[b] Protected from animal damage.

Douglas-fir site III, reducing stocking from 104 precent of normal (1,300 ft^3) at age 20 to 48 percent of normal (600 ft^3) reduced the mean annual increment to 69 percent of normal. Biological adaptation is reflected in the approach-to-normality function, whereas managerial adaptation extended rotation from 70 to 90 years, eliminated the thinning at age 30, and reduced thinning intensities up to age 60. Table 8 also gives the optimal regime for a stand with 1,300 ft^3 protected at a cost of $252.50 per acre.

A second set of tables (15-18) to show economic impact for each site lists trees surviving (age 5) and soil expectation values. There ΔSe is the difference in soil expectation for the various stocking levels:

$$\Delta Se = Se_m - Se_s$$

where Se_m is the maximum full stocking level, and Se_s is the soil expectation for the particular reduced stocking level at age 20.

The ΔSe values can be interpreted as the reduction in site value if the specified stocking reductions occur in each of an infinite series of rotations. Although ΔSe values are familiar to forest economists, the ΔRC value is probably more readily interpreted by forest managers:

$$\Delta RC = \Delta Se[(1+i)^{r_s}-1]/(1+i)^{r_s}$$

where r_s is the rotation age for the initial stocking level s.

The multiplier, the inverse of the infinite series multiplier, is used to convert the infinite series ΔSe value to a single element in the series (ΔRC). The manager retrospectively interprets this value as the additional amount that could have been spent on regeneration to prevent stocking reduction to any particular level. If we assume that spending $252.50 per acre to prevent animal damage would have yielded full stocking (1,300 ft^3 at age 20) on Douglas-fir site III, we find that ΔRC is less than this amount for reduced levels of stocking between 1,300 ft^3 and 900 ft^3. This implies that the protection costs more than the damage caused for stocking reductions down to 900 ft^3; but at 800 ft^3 (62% of maximum stocking), the ΔRC ($302.89) exceeds the assumed prevention cost ($252.50). The ΔRC column gives some indication of the extra expenditures that can be rationally incurred to prevent damage of any particular level.

Some levels of stocking are so low that the manager would be better off eliminating the current stand; incurring the costs of site preparation, planting, and animal damage protection; and immediately starting a series of protected rotations. For this protected series, the soil expectation value (Se_{pt}) has been calculated using $252.50. If the expected value of managing the current stand through to its indicated rotation and then replacing it is less than the expected value of replacing it now, then the stand should be replaced. Using the term SERIES as a short form for "present series value at age 5 with protection in subsequent rotations," the appropriate transformation is:

Basically, the understocked soil expectation value is converted to a single series value and credited with the sunk regeneration cost which is not incurred if the stand is retained. This value is compounded 5 years to bring it to the "present," and the value of an infinite series of protected stands beginning after harvest of the understocked stand is added. The discounting period is the rotation minus 5 years to account for the fact that the stand is already 5 years old.

For Douglas-fir Sites II and III, this criterion indicates replacement at low stocking levels, but even the most severely damaged stands on Site IV should be retained due to the high costs of regeneration and protection, coupled with low productivity. Site II SERIES values (Table 15) indicate that stands of 700 ft^3 or less should be replaced, whereas Site III SERIES values (Table 16) indicate that stands of 400 ft^3 or less should be replaced.

This solution to the replacement problem approximates a more complicated solution involving retention and replacement at each of the candidate rotations that are less than the optimal understocked rotation length. Information for deriving this is available from the dynamic programming solutions and, in the several instances checked, coincided with the solution presented here.

$$\text{SERIES} = (1+i)^5\left\{Se_s \;\; [(1+i)^{r_s}-1/(1+i)^{r_s}] \; + \; RC\right\} + [Se_{pt}/(1+i)^{r_s-5}]$$

ACE impacts

A third set of tables for each site presents a different method of evaluating the impact of animal damage. Based on the allowable cut effect (ACE), this method—its use and misuse—has triggered considerable controversy. The ACE method has both valid and invalid interpretations that should be clearly distinguished. The ACE tables (Tables 14, 19-22) assume that the owner of a forest property has established an acre of plantation and immediately increased allowable cut by the anticipated mean annual increment of the plantation. Because the cut increase was based on anticipated growth, over-rotation-age surplus must exist to provide the current increase.

However, after animal damage occurs, the manager realizes that the plantation is not fully stocked and has a reduced mean annual increment (ΔAC). This reduction in mean annual increment is the amount that the forest manager must reduce current allowable cut, assuming that the manager links allowable cut to expected growth and increases and decreases it as events and expectations change. Initially this reduction in allowable cut would come from liquidation of old-growth trees and later from young-growth thinnings and final harvest.

The analysis assumed that the old-growth stands would last for 25 years, and then the harvest reductions will come from young-growth stands. The prices used are the maximum price (20-in. timber) for the first 25 years and thereafter the price of 50-year-old timber for the particular site. The calculation is:

$$\text{ACE} = p'\Delta AC[(1+i)^{25}-1]/i(1+i)^{25} + [(p\Delta AC/i)/(1+i)^{25}]$$

where p' is the price of old-growth timber, p is the price of young-growth timber, and ΔAC is the reduction in allowable cut.

Table 15.

ECONOMIC IMPACTS OF REDUCED STOCKING OF SITE II (170) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.

Age 20 stocking (ft^3)	Trees surviving age 5	Se	ΔRC	ΔSe	SERIES	Optimum rotation age (years)
		- - - - -	- - - - ($/ac)	- - -	- - - - - -	
1,600[a]	619	1,863.30	252.50	278.70	2,391.93	80
1,600	619	2,142.00	--	--	2,715.02	80
1,500	580	2,071.60	63.78	70.40	2,633.40	80
1,400	542	2,001.70	127.12	140.30	2,552.37	80
1,300	503	1,907.50	212.46	234.50	2,443.17	80
1,200	465	1,831.10	281.68	310.90	2,354.60	80
1,100	426	1,725.10	377.72	416.90	2,231.72	80
1,000	387	1,636.80	457.72	505.20	2,129.35	80
900	348	1,524.70	559.29	617.30	1,999.40	80
800	309	1,432.40	659.98	709.60	1,892.40	90
700	271	1,309.70	774.09	832.30	1,750.16	90
600	232	1,176.80	897.71	965.30	1,596.09	90
500	194	1,068.70	998.25	1,073.30	1,470.77	90
400	155	908.16	1,147.56	1,233.84	1,284.66	90
300	116	739.49	1,308.16	1,402.51	1,084.49	90
200	77	444.63	1,578.68	1,697.37	747.30	90
100	30	178.22	1,361.60	1,963.78	438.46	100

[a] Protected from animal damage.

Table 16.

ECONOMIC IMPACT OF REDUCED STOCKING OF SITE III (140) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.

Age 20 stocking (ft^3)	Trees surviving age 5	Se	ΔRC	ΔSe	SERIES	Optimum rotation age (years)
		- - - - -	- - - - ($/ac)	- - -	- - - - - -	
1,300[a]	624	963.39	252.50	282.51	1,348.69	80
1,300	624	1,245.90	--	--	1,676.19	70
1,200	576	1,189.40	49.36	56.50	1,610.70	70
1,100	528	1,119.70	114.34	126.20	1,529.89	80
1,000	480	1,058.50	169.78	137.40	1,458.95	80
900	432	981.03	239.98	264.87	1,369.13	80
800	384	911.59	302.89	334.31	1,288.64	80
700	336	823.33	382.86	422.57	1,186.32	80
600	288	748.38	462.72	497.52	1,099.43	90
500	240	656.17	548.49	587.73	992.54	90
400	192	545.17	664.26	700.73	863.86	100
300	144	421.47	781.53	824.45	720.45	100
200	96	269.20	948.56	976.70	543.93	120
100	48	94.88	1,126.38	1,151.02	341.84	130

[a] Protected from animal damage.

Table 17.

ECONOMIC IMPACT OF REDUCED STOCKING OF SITE IV (110) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.

Age 20 stocking (ft³)	Trees surviving age 5	Se	ΔRC	ΔSe	SERIES	Optimum rotation age (years)
		- - - - - - - - -	($/ac)	- - - - - - - -		
900[a]	621	209.70	252.50	275.77	474.95	100
900	621	485.47	--	--	794.65	70
800	552	448.75	33.27	36.72	752.08	80
700	483	407.94	70.24	77.53	704.77	80
600	414	352.37	120.59	133.10	640.35	80
500	345	306.09	166.84	179.38	586.89	90
400	276	236.60	231.48	248.87	506.14	90
300	207	179.77	289.79	305.70	440.26	100
200	138	93.99	380.20	39.48	340.81	120

[a] Protected from animal damage.

Table 18.

ECONOMIC IMPACT OF REDUCED STOCKING OF PONDEROSA PINE SITE 80, 3 PERCENT DISCOUNT RATE.

Age 20 stocking (ft³)	Trees surviving age 5	Se	ΔRC	SERIES	Optimum rotation age (years)
		- - - - -	- ($/ac) -	- - - - -	
1,000[a]	600	135.23	100.00	272.69	130
1,000	600	240.10	--	385.76	90
900	540	215.54	23.28	360.95	100
800	480	193.18	45.10	337.27	110
700	420	174.08	63.46	315.99	110
600	360	150.03	86.58	289.19	110
500	300	121.37	116.18	256.97	130
400	240	90.86	147.52	221.31	140
300	180	57.53	182.57	185.80	200
200	120	3.70	235.76	123.56	200
100[b]	60	-65.04	304.31	44.09	200

[a] Protected from animal damage.

[b] Single-rotation criterion for present net worth.

The values in the ACE tables, partitioned over various time spans, should be interpreted as the net reduction in discounted cash flow attributable to stocking reduction by animal damage. These values are about triple the ΔRC values which are investment indicators of the amount an economically rational manager would be willing to spend on protection. The ACE values represent discounted cash-flow losses attributable to animal damage, but they overstate by a factor of about three the justifiable investment in protection.

evaluating animal damage

The three sets of tables evaluate animal damage and provide guidelines for stand protection and replacement based on the assumption that undamaged or fully protected stands yield normal full stocking. The simple model for Douglas-fir indicated that survival at age 5 was only 66 percent for protected trees and 49.3 percent for unprotected trees. Assuming that 600 surviving trees give full stocking, an unprotected stand would have 296 surviving trees and a protected stand would have 396. Interpolating linearly in Table 16, we derive soil expectation values of $928.95 for the protected stand and $760.87 for the stand suffering average damage, a difference (ΔSe of $168.08 per acre. An average expenditure of $152.28 (ΔRC) would be justified for protection.

The SERIES value for the damaged stand cannot be calculated exactly because we do not know the extent of rotation lengthening (if any) that protection expenditures would induce; however, we can use the first part of the SERIES formula to calculate the PNW of a 5-year-old damaged stand. At $889.37, it exceeds the single rotation value for the undamaged stand ($811.63), indicating that the stand should be retained.

In Oregon and Washington, 360,837 acres were planted in fiscal year 1976 (U.S. Forest Service 1977). Assuming that the previously developed values for Douglas-fir Site III typify these plantings (no site or species breakdown of planting is given), then animal damage accounted for a loss of $60,649,483 in site values and would have justified an expenditure of up to $54,949,821 on protection. If this figure is capitalized (3%, infinite series) at this continuing level of planting, the net reduction in the timber resource value for the two states totals $1.83 billion.

Interpolating in the appropriate ACE table (Table 20, single rotational impact) and using the survival rates of 396 and 296 protected and unprotected trees gives ACE values of $1,076.17 and $1,615.24, respectively, a difference of $539.07 per acre. At a planting rate of 360,837 acres, the one year ACE loss is $194,516,402. At that rate, the present net worth of this annual loss (3%, infinite series) gives a $6.48 billion loss in the value of timber resources in Oregon and Washington.

Computing an infinite series of ACE losses is conceptually difficult because the value arises from an available surplus of harvestable timber that may not be available indefinitely. In this case, about half of the ACE impact is attributable to the first 25 years of the series.

an alternate interest rate

With a discount rate of 9 percent, as well as the cost and revenue assumptions previously used, all but the finest forest sites would be negative investments for forest regeneration and management (Table 11). At a real rate of 6 percent, investment opportunities are generally low but positive.

To demonstrate the impact of doubling the assumed interest rate from 3 to 6 percent, we constructed an alternate set of tables (12-14) using the same assumptions and derivations as in Tables 8, 16, and 20 for Site III.

A discount rate of 6 percent shortens rotation and intensifies thinning level (Table 20). A stand with full survival generates a soil

Table 19.

ALLOWABLE CUT EFFECT (ACE) IMPACT OF SITE II (170) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.[a]
(dollars)

Age 20 stocking (ft³)	ΔAC (ft³/ac)	Present net worth Year 25	 Year 26-∞	 Total	Single rotation[a] (80 years)
		- - - - - - - - - -	($/ac)	- - - - - - - -	- - - - - - - -
1,600	0	--	--	--	--
1,600[b]	0	--	--	--	--
1,500	5.27	116.27	65.02	181.29	168.50
1,400	10.60	233.86	130.78	364.64	338.91
1,300	18.39	405.73	226.90	632.63	587.98
1,200	24.39	538.10	300.92	839.02	779.81
1,100	33.20	732.47	409.63	1,142.10	1,061.50
1,000	40.11	884.93	494.88	1,379.81	1,282.44
900	49.34	1,088.56	608.76	1,697.32	1,577.54
800	57.42	1,266.83	708.46	1,975.29	1,835.89
700	66.68	1,471.12	822.70	2,293.82	2,132.05
600	77.88	1,718.22	960.89	2,679.11	2,490.04
500	86.82	1,915.46	1,071.91	2,987.37	2,775.88
400	100.99	2,228.09	1,246.03	3,474.12	3,228.94
300	116.21	2,563.66	1,433.82	3,997.48	3,715.35
200	148.13	3,268.11	1,827.65	5,095.76	4,736.14
100	174.75	3,885.41	2,156.09	6,011.50	5,587.25

[a] Prices of old-growth and young-growth stands are $1.267 and $0.775 per cubic foot, respectively.

[b] Protected from animal damage.

Table 20.

ALLOWABLE CUT EFFECT (ACE) IMPACT OF SITE III (140) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.[a]
(dollars)

Age 20 stocking (ft³)	ΔAC (ft³/ac)	Present net worth Year 25	 Year 26-∞	 Total	Single rotation[a] (70 years)
		- - - - - - - - - -	($/ac)	- - - - - - - -	- - - - - - - -
1,300	0	--	--	--	--
1,300[b]	4.48	98.84	44.58	143.42	131.64
1,200	5.82	128.40	57.91	186.31	171.00
1,100	16.72	368.88	166.37	535.25	491.15
1,000	22.91	505.45	227.96	733.41	673.13
900	31.13	686.80	309.75	996.55	914.64
800	38.46	848.52	382.68	1,231.20	1,130.01
700	47.70	1,052.38	474.62	1,527.00	1,401.49
600	56.43	1,244.98	561.49	1,806.46	1,657.99
500	65.53	1,445.75	652.03	2,097.78	1,925.36
400	78.22	1,725.73	778.30	2,504.03	2,298.22
300	90.03	1,986.28	895.81	2,882.09	2,645.20
200	107.36	2,368.63	1,069.24	3,436.87	3,154.39
100	125.12	2,760.45	1,244.96	4,005.41	3,676.19

[a] Prices of old-growth and young-growth stands are $1.267 and $0.625 per cubic foot, respectively.

[b] Protected from animal damage.

Table 21.

ALLOWABLE CUT EFFECT (ACE) IMPACTS OF SITE IV (110) DOUGLAS-FIR, 3 PERCENT DISCOUNT RATE.

(dollars)

Age 20 stocking (ft³)	ΔAC (ft³/ac)	Present net worth Year 25	Year 26-∞	Total	Single rotation[a] (70 years)
		($/ac)			
900[b]	0	--	--	--	--
900	12.58	277.54	97.53	375.07	349.28
800	8.07	178.04	62.56	240.60	224.06
700	14.06	310.20	109.00	419.20	390.38
600	21.76	480.08	168.71	648.79	604.17
500	30.13	664.74	233.60	898.34	836.57
400	38.77	855.36	300.59	1,155.95	1,076.46
300	47.90	1,056.79	371.37	1,428.16	1,329.95
200	60.89	1,343.38	472.09	1,815.47	1,650.92

[a] Prices of old-growth and young-growth stands are $1.267 and $0.487 per cubic foot, respectively.

[b] Protected from animal damage.

Table 22.

ALLOWABLE CUT EFFECT (ACE) IMPACTS ON PONDEROSA PINE SITE 80, 3 PERCENT DISCOUNT RATE.

(dollars)

Age 20 stocking (ft³)	ΔAC (ft³/ac)	Present net worth Year 25	Year 26-∞	Total	Single rotation[a] (90 years)
		($/ac)			
1,000[b]	0	--	--	--	--
1,000	9.1	200.77	3.59	284.36	272.12
900	5.02	110.75	46.11	156.86	150.11
800	9.18	202.53	84.33	286.86	274.51
700	11.64	256.81	106.92	363.73	348.08
600	14.43	318.36	132.55	450.91	431.51
500	20.35	448.97	186.93	635.90	608.53
400	25.02	552.00	229.83	781.83	748.18
300	33.26	733.80	305.52	1,039.32	994.59
200	38.37	846.54	352.46	1,199.00	1,147.39
100	45.31	999.64	416.22	1,415.85	1,354.92

[a] Prices of old-growth and young-growth stands are $1.267 and $0.577 per cubic foot, respectively.

[b] Protected from animal damage.

expectation of only $76.22, and animal damage eliminates all positive returns at stocking levels below 900 ft³ and 432 trees (Table 13). At all stocking levels, the amount that a manager would retrospectively have been willing to spend on animal damage protection (ΔRC) is less than the assumed cost. At levels that yield negative soil expectations, even planting and soil preparation costs are not recovered. The SERIES values are relatively high, indicating the desirability of retaining all existing damaged stands. In this instance, the second part of the SERIES equation is negative due to the negative soil expectation of a protected stand.

Table 14 has a smaller relative difference in the ACE values than the higher values associated with the lower discount rate in Table 20. The ACE tables assume that the revenue reductions begin immediately and, therefore, the increased discount rate has a lesser impact on ACE values than on soil expectation.

Using Table 13 and interpolating as previously, a stand with 396 surviving trees has a soil expectation value of -$3.24, whereas the average undamaged stand with 296 surviving trees has a soil expectation of -$43.73—a net difference of $40.49 (ΔSe) or $38.30 (ΔRC) for a single rotation.

discussion

Using the planting rate of 360,837 acres, animal damage reduced site value an average of $14,611,493 in 1976 and would have justified spending up to $13,818,259 on protection. If this figure is capitalized (6%, infinite series) at this continuing level of planting, the net reduction in timber resource value in Oregon and Washington would be $230 million.

Interpolation in Table 14 (single rotation impact) yields ACE values of $690.63 and $1,049.28 per acre for 396 and 296 surviving trees, respectively. That per acre difference of $358.65 would total $129,415,393 for the year. The present net worth of this annual rate of loss (6%, infinite series) gives a $2.16 billion loss in the value of the timber resources of Oregon and Washington. Once again we have the conceptual problem of continuing available surplus; however, at this higher interest rate, nearly 80 percent of the loss occurs in the first 25 years of the series.

Table 23 is useful for comparing these 3 and 6 percent values.

Our statistical analysis clearly shows that impacts of animal damage vary widely. Average aggregate evaluations such as the one for Oregon and Washington, therefore, are subject to wide variation; however, even with allowance for wide fluctuation, the losses from animal damage are substantial.

We have linked biological observations during the early phases of regeneration with later stand management and harvest returns. Note that the survival and height predicted from the regression models we used to analyze the CADS data differ from the empirical levels previously reported (Black et al. 1978). This is reasonable because regression models need pass only through the mean of all yearly observations and not through the mean of each annual mean. Although our procedures have been used only for average aggregate assessments, individual plots also can be assessed with the tables we provide.

This financial analysis assumed high regeneration and protection costs because that is their recent general trend. The discounting analysis was based on a real rate of 3 percent rather than on market rates which include inflationary and risk expectations. We did not assume increasing real stumpage price; analysis including that and these other factors at currently anticipated levels can result in extremely high soil expectations. Although these homogenized real and inflated expected dollars have some meaning to forest economists, the present net worths presented here are more readily interpreted in current real dollars.

Dynamic programming can be useful to optimize thinning regimes when analyzing diverse silvicultural alternatives. More sophisticated dynamic programming techniques are forthcoming to also incorporate diameter growth accelerated by thinning.

Table 23.

ANIMAL DAMAGE IMPACTS WITH ALTERNATE DISCOUNT RATES.

Discount rate	Average loss per acre planted			Annual loss[a]		Total loss[a]	
	PNW	Se	ACE	PNW	ACE	PNW	ACE
(%)	- - - - - - ($) - - - - - -			(million $)		(billion $)	
3	152.28	168.08	539.07	60.6	194.5	1.83	6.48
6	38.30	40.49	358.65	13.8	129.4	0.23	2.16

[a] Total and annual values are based on an annual planting rate of 360,837 acres.

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Regression models of height growth and survival were fitted to aggregate data for trees, protected and not protected from animal damage, that had been surveyed on Douglas-fir and ponderosa pine plantations in Oregon and Washington. Animal damage significantly affected both height and survival. Dynamic programming analysis—using both soil expectation (Se) and allowable cut effect (ACE) indicators—was used to derive (1) optimal economic regimes for managing stands with full and depressed stocking levels, (2) management guidelines for protection expenditure and stand replacement, and (3) physical impacts on volume yield. At current rates of planting in Oregon and Washington and at a 3 percent discount rate, animals cause an estimated $60 million annually in damage, reducing the net capitalized value of the timber resource by $1.8 billion. Likewise, present net worth decreases by 18 percent, and growth and yield by 13 percent. Several other discount rates showed different proportional impacts from animal damage.

Key words: dynamic programming, Douglas-fir, ponderosa pine, survival, height growth, protection.

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