# Potential Yield, Return, and Tree Diversity of Managed, Uneven-aged Douglas-Fir Stands

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The effects of different management regimes on uneven-aged Douglas-fir stands in the Pacific Northwest of the United States were predicted with a simulation model. Management alternatives were defined by residual stand structure and cutting cycle. The residual stand structure was set by basal area–diameter-q-ratio (BD*q*) distributions, diameter-limit cuts (assuming concurrent stand improvement), or the current diameter distribution. Cutting cycles of 10 or 20 years were applied for 200 years. The current diameter distribution was defined as the average of the uneven-aged Douglas-fir stands sampled in the most recent Forest Inventory and Analysis conducted in Oregon and Washington. Simulation results were compared in terms of financial returns, timber productivity, species group diversity (hardwoods *vs* softwoods), size class diversity, and stand structure. Other things being equal, there was little difference between 10- and 20-year cutting cycles. The highest financial returns were obtained with either a 58.4 cm diameter-limit cut, or a BD*q* distribution with 8.4 $m^2$ of residual basal area, a 71.1 cm maximum diameter, and a *q*-ratio of 1.2. Using the current stand state as the residual distribution was the best way to obtain high tree size diversity, and high species group diversity. Several uneven-aged regimes gave net present values comparable to that obtained by converting the initial, uneven-aged stand to an even-aged, commercially thinned, plantation.

**Keywords** uneven-aged management, Douglas-fir, WestPro, simulation, economics, diversity.

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# 1 Introduction

The Pacific Northwest region of the United States contains the largest standing net volume of softwood timber and is second in total softwood production when compared to all other regions of the United States (USDA Forest Service 2001). The principal species is Douglas-fir (*Pseudotsuga mensziesii*), which accounted for 60 percent of the lumber production in 1999 (Warren 2001).

Even-aged management with clear-cutting and artificial regeneration has a long history in this region. It has produced large amounts of high-quality timber at low cost (Curtis 1998). Recently, however, there has been a growing interest in other methods (O'Hara 1998, Emmingham 1998). This is due to the concern about the visual impacts of clear-cutting, and a heightening of the social value of forests that look undisturbed by man, though they may be actively managed (Curtis and Carey 1996, Curtis and Marshall 1993). With public interest continuing to grow, ballot initiatives by grassroots campaigns may soon make it legally impossible to continue clear-cutting (Miller and Emmingham 2001).

Uneven-aged management is one alternative that could generate sustainable harvests while maintaining continuous forest cover and protecting stand diversity (Guldin 1996). Research on uneven-aged Douglas-fir forests is somewhat scarce (Emmingham 1998, Curtis 1998). But, studies of other forest types in the United States and abroad suggest that uneven-aged management can be economically viable while preserving forest stand diversity (Buongiorno et al. 1994, 1995, Schulte and Buongiorno 1998, Volin and Buongiorno 1996).

This paper reports the results of simulations of various uneven-aged management regimes for Douglas-fir forests in Oregon and Washington, west of the Cascades Mountains. It compares regimes in terms of productivity, financial returns and ecological (diversity) criteria. It also compares these uneven-aged regimes with the yields and financial returns from converting an uneven-aged stand to an even-aged plantation with or without thinnings, or with shelterwood management.

# 2 Methods and Data

## 2.1 WestPro Program

The simulations were performed with the WestPro software (Ralston et al. 2003a). WestPro is a spreadsheet add-in program for projecting the growth, yield, and structure of uneven-aged Douglas-fir stands in the Pacific Northwest. WestPro employs a density-dependent matrix model that simulates tree growth, mortality, and recruitment. The model was calibrated with field data from the Pacific Northwest Forest Inventory and Analysis program collected on 66 uneven-aged Douglas-fir sample plots in western Oregon and Washington. Plots classified as uneven-aged had fewer than 70 percent of the trees within 30 years of one another in age (PNW FIA 2000). The plots had been measured at two successive inventories, and showed no evidence of planting activity. The model was tested by predicting on each plot the number of trees per hectare, by species group (softwoods or hardwoods), and size class at the second inventory, given the number at the first inventory. There was generally no significant difference between the mean predicted and observed number of trees by size class and species group. Furthermore, the results of 200-year projections without harvest were consistent with prior knowledge of old-growth Douglas-fir forests (Ralston et al. 2003b).

In management applications, WestPro users define the diameter distribution of the initial stand, by hardwoods and softwoods, the target (desired) diameter distribution after harvest, and the cutting cycle. Optional data for financial applications are prices, costs and interest rate. The program then calculates stand state for each future year, the annual yield, indices of diversity of tree size and species group, and net present value (NPV). WestPro also suggests a marking guide to achieve those results (Ralston et al. 2003a).

## 2.2 Initial Stand State

The initial stand state used in all the simulations (Table 1) was defined by the average number of hardwood and softwood trees per hectare,

**Table 1.** Initial stand state and tree values used in simulations.

| Diameter class midpoint (cm) | (Trees/ha) |  | Stumpage value ($/tree) [1] |  |
|---|---|---|---|---|
|  | Softwoods | Hardwoods | Softwoods | Hardwoods |
| 10.2 | 176.7 | 65.7 | 0.00 | 0.00 |
| 15.2 | 103.5 | 35.8 | 0.00 | 2.04 |
| 20.3 | 73.4 | 18.3 | 3.33 | 4.60 |
| 25.4 | 53.1 | 14.8 | 1.81 | 8.24 |
| 30.5 | 34.3 | 8.6 | 16.04 | 25.98 |
| 35.6 | 26.4 | 3.2 | 33.82 | 27.66 |
| 40.6 | 15.6 | 2.2 | 55.14 | 33.25 |
| 45.7 | 12.4 | 1.5 | 80.00 | 42.75 |
| 50.8 | 8.9 | 0.7 | 108.40 | 56.16 |
| 55.9 | 5.9 | 0.7 | 140.34 | 73.47 |
| 61.0 | 5.7 | 0.2 | 175.83 | 94.69 |
| 66.0 | 3.7 | 0 | 214.86 | 119.82 |
| 71.1 | 2.5 | 0 | 257.43 | 148.86 |
| 76.2 | 2.0 | 0 | 303.54 | 181.81 |
| 81.3 | 1.7 | 0 | 353.19 | 218.66 |
| 86.4 | 1.0 | 0 | 406.39 | 259.42 |
| 91.4 | 0.7 | 0 | 463.13 | 304.09 |
| 96.5 | 0.5 | 0 | 523.41 | 352.67 |
| 101.6+ | 2.2 | 0 | 587.23 | 405.15 |
| Basal Area ($m^2$/ha) | 29.8 | 4.6 |  |  |

[1] For a stand basal area of 34.4 $m^2$/ha and site index of 29.3 m. Volume and thus value per tree varies with stand basal area and site index.

over all 66 plots used to construct the growth model. Therefore, the results are indicative of the expected effects of different management regimes if they were applied to the entire area represented by these plots, keeping in mind that the differences between prediction and realization on individual plots could be substantial (Ralston et al. 2003b).

The total basal area of this representative initial stand was 34.4 $m^2$/ha, 87% in softwood trees, and 13% in hardwoods. The dominant softwood species were Douglas-fir and western hemlock (*Pseudotsuga menziesii, Tsuga heterophylla*) and the dominant hardwoods were bigleaf maple and red alder (*Acer macrophyllum, Alnus rubra*) (Ralston 2002). Softwood trees were present in all the nineteen 5.1 cm size classes, ranging from 7.6 to 12.7 cm trees to trees 99.1 cm and larger; the largest hardwood trees were 61.0 cm in diameter. The standing net volumes amounted to 258 $m^3$/ha of sawtimber and 21 $m^3$/ha of pulpwood worth together about $11 700/ha at current stumpage prices.

Although the initial stand was defined as the average of 66 plots in Oregon and Washington, 43 of these plots were in Oregon, and WestPro was run as if the initial stand was in Oregon. There is a slight difference between Oregon and Washington because hardwoods were found to grow somewhat faster in Washington (Ralston et al. 2003b). The average site index across both states was 29.3 meters, estimated using King's method (1966).

## 2.3 Management Regimes

Three broad types of management were simulated with WestPro. One used the initial distribution of trees per hectare as the target stand state. The second used a basal-area–diameter-$q$-ratio (BD$q$) distribution to define the target state. A BD$q$ distribution is defined by the stand basal area, the largest and smallest tree diameter, and the ratio of the number of trees in adjacent diameter classes, $q$. The third management was a diameter-limit that took all the trees above a specific size. In all cases, the cutting cycle was 10 or 20 years and simulations were run for 200 years.

### *2.3.1 Maintaining the Current Stand State*

In this approach, the number of trees cut, by species and size class, was the difference between the number of trees at harvest time and the initial number. No tree was cut if the number of trees at harvest time was less than the initial. The objective of this management was to maintain the original stand composition by tree size and species group, while providing a sustainable flow of timber and income.

### *2.3.2 Managing for a BDq Distribution*

BD*q* (basal area, maximum diameter, *q* ratio) distributions can be defined in various ways. WestPro has a BD*q* calculator that uses the stand basal area, the diameter of the smallest and largest trees, and a *q*-ratio defining the ratio of the number of trees in adjacent size classes. Managements based on BD*q* distributions are well established (Smith 1997, Oliver and Larson 1996). Recent examples of applications include Buongiorno et al. (2000) and Schulte and Buongiorno (1998) for northern hardwood and southern loblolly pine stands. A stand with a BD*q* distribution is considered "balanced" in that continuous propagation, combined with constant growth and mortality rates, are believed to sustain the number of trees in each size class.

The larger the *q* is, the steeper the diameter distribution. Here, the *q*-ratio was set at 1.2, for a somewhat flatter distribution than in the initial stand state in Table 1 where $q = 1.4$. Table 2 shows the number of trees per hectare by species and diameter class for the three BD*q* targets. The light, medium, and heavy regimes maintained 32.1, 26.4, and 20.7 $m^2$/ha of basal area after harvest, compared to the current 34.4 $m^2$/ha. Miller and Emmingham (2001) suggest 18.4 $m^2$ to 27.5 $m^2$/ha to encourage Douglas-fir regeneration. The ratio of hardwoods basal area to softwoods was nearly the same as in the initial stand for the three alternatives. These basal areas, and $q = 1.2$ led to maximum diameters of 81.3, 76.2, and 71.1 cm for softwoods, and 55.9, 50.8, and 45.7 cm for hardwoods. WestPro allows for different *q* ratios for hardwoods and softwoods, however this is rarely done in practice, and was not investigated here.

### *2.3.3 Diameter-Limit Cut*

With this method, trees larger than a prescribed diameter were harvested. Though controversial, this type of management is worth investigating because of its simplicity. For this management to be silviculturally sound, it must be also assumed that most cull trees and trees of low vigor or having serious defects would be removed at the time of harvest, regardless of size. This is necessary to avoid "high grading" and the dysgenic effect of harvesting only the best trees. Lu and Buongiorno (1993) found that a diameter-limit cut with explicit removal of cull trees was financially optimal in northern hardwoods. The WestPro model does not distinguish trees by quality, and thus the stand improvement could not be modeled. The same applies to the BD*q* regimes and the "current distribution" approaches, for which it must also be assumed that the cull trees would be removed. Nevertheless, in some circumstances, it may be desirable to maintain some cull trees and non-commercial species to enhance biological diversity.

Here, diameter limits were set at 88.9, 68.6, or 58.4 cm for softwoods, and concurrently at 63.5, 43.2, or 33.0 cm for hardwoods, denoted as high, medium, and low diameter limits. The high diameter limit would leave a residual stand with larger trees than the light BD*q* regime, while the medium and low diameter limit would leave large trees of about the same size as the medium and heavy BD*q* regime (Table 2). The main difference of the diameter limit approach relative to the BD*q* is that it would let the stand acquire its own natural distribution, without trying to force it to a particular *q* ratio – an objective that is hard to achieve in practice.

## 2.4 Performance Criteria

WestPro calculates the stand state for each year and production statistics for each harvest. The stand state is characterized by:

- The number of live trees by size and species group,
- The basal area of hardwoods and softwoods,
- The stand diversity in terms of species groups and size classes.

**Table 2.** Target BD$q$ distributions [1].

| | Softwoods (trees/ha) | | | Hardwoods (trees/ha) | | | Total (trees/ha) | | |
|---|---|---|---|---|---|---|---|---|---|
| Diameter (cm) | Light[2] | Medium | Heavy | Light | Medium | Heavy | Light | Medium | Heavy |
| 10.2 | 49.7 | 44.7 | 38.8 | 13.8 | 12.1 | 9.6 | 63.3 | 56.6 | 48.4 |
| 15.2 | 41.3 | 37.1 | 32.4 | 11.4 | 10.1 | 7.9 | 52.9 | 47.2 | 40.5 |
| 20.3 | 34.3 | 30.9 | 26.9 | 9.6 | 8.4 | 6.7 | 44.0 | 39.3 | 33.6 |
| 25.4 | 28.7 | 25.7 | 22.5 | 7.9 | 6.9 | 5.4 | 36.6 | 32.9 | 28.2 |
| 30.5 | 24.0 | 21.5 | 18.8 | 6.7 | 5.7 | 4.7 | 30.6 | 27.4 | 23.5 |
| 35.6 | 20.0 | 18.0 | 15.6 | 5.4 | 4.9 | 4.0 | 25.5 | 22.7 | 19.5 |
| 40.6 | 16.6 | 14.8 | 13.1 | 4.7 | 4.0 | 3.2 | 21.3 | 19.0 | 16.3 |
| 45.7 | 13.8 | 12.4 | 10.9 | 4.0 | 3.5 | 2.7 | 17.8 | 15.8 | 13.6 |
| 50.8 | 11.6 | 10.4 | 9.1 | 3.2 | 2.7 | – | 14.8 | 13.1 | 9.1 |
| 55.9 | 9.6 | 8.6 | 7.7 | 2.7 | – | – | 12.4 | 8.6 | 7.7 |
| 61.0 | 7.9 | 7.2 | 6.2 | – | – | – | 7.9 | 7.2 | 6.2 |
| 66.0 | 6.7 | 5.9 | 5.2 | – | – | – | 6.7 | 5.9 | 5.2 |
| 71.1 | 5.7 | 4.9 | 4.4 | – | – | – | 5.7 | 4.9 | 4.4 |
| 76.2 | 4.7 | 4.2 | – | – | – | – | 4.7 | 4.2 | – |
| 81.3 | 4.0 | – | – | – | – | – | 4.0 | – | – |
| Basal Area ($m^2$/ha) | 27.5 | 23.0 | 18.4 | 4.6 | 3.4 | 2.3 | 32.1 | 26.4 | 20.7 |

[1] $q$ = 1.2 is the ratio of number of trees in adjacent size classes.
[2] Post-harvest basal area was 32.1, 26.4 and 20.7 $m^2$/ha for light, medium and heavy, respectively.

Diversity is measured with Shannon's Index (Shannon and Weaver 1963, Pielou 1977) based on the proportion of basal area by species group or size class. The proportion of basal area rather than the number of trees was used to give more weight to the largest trees. With two species groups and nineteen size classes, diversity can range from 0 to 0.69 for species, and from 0 to 2.94 for size. Diversity is highest when the basal area is equally distributed across all size classes or species groups (Magurran 1988).

The productivity criteria computed by WestPro are:

- Basal area cut at each harvest, per unit of land area, by softwoods and hardwoods and the average annual production over the entire simulation.
- Sawtimber and pulpwood cut at each harvest, per unit of land area, by softwoods and hardwoods and average annual production.

The financial criteria are:

- Harvest income per unit of land, that is the stumpage value, gross or net of the fixed re-entry cost per unit area (for sale preparation and administration).
- Net present value of harvests of the net income from each harvest, and the cumulative net present value per unit of land area. This cumulative net present value excludes the value of the growing stock left at the end of the simulation. Including it would assume that the stand is clear-cut at that time, which is not true in uneven-aged management. Regardless, with an interest of 3% per year, the present value of the residual stock after 200 years is negligible.

Here, the stumpage prices were adapted from regional timber sale reports (Log Lines 2001). In WestPro, softwood trees less than 22.9 cm DBH and hardwoods less than 27.9 cm DBH are valued as pulpwood and larger trees as sawtimber. Prices were set at $29 per green metric ton for pulpwood and $779 per $m^3$ for softwoods, and $19 per green metric ton and $585 per $m^3$ for hardwoods. Table 1 shows the stumpage price per tree by diameter and species group for the initial stand. In future stand states, volume per tree depends not only on diameter and site index, but also on stand basal area (Ralston et al. 2003b).

The fixed cost of re-entry was set at $628/ha per harvest, the estimated cost of preparing and administering timber sales in the state of Washington (Lu 2002). Because the data behind this average cost were mostly for even-aged sales, the re-entry cost for uneven-aged stands might be higher. The real interest rate was set at a conservative 3% per year (the yield of A bonds, net of inflation, was 3.7% per year from 1970 to 1999).

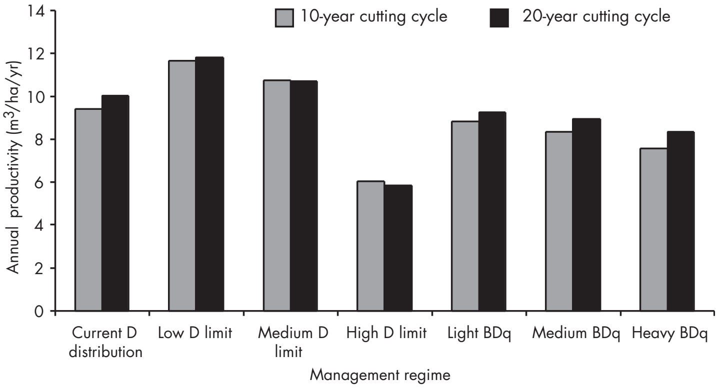

**Fig. 1.** Average annual productivity by management regime, over 200 years of simulation.

# 3 Results

## 3.1 Productivity of Management Alternatives

Figure 1 shows the average annual production for all managements. In all cases, most of the harvest was in sawtimber, pulpwood representing less than 2% of the total annual production. In terms of species, about 5% of the harvest was in hardwoods.

The low and medium diameter-limit managements gave the highest annual production, up to 11.9 $m^3$/ha/y. The current diameter distribution and the light BD*q* came next. The high diameter-limit cut produced the least, about 5.6 $m^3$/ha/y. The current diameter distribution produced at least as much as the BD*q* selections.

The length of cutting cycle had little effect on productivity, although the 20-year cycle was somewhat better for the current diameter distribution and the BD*q* managements.

## 3.2 Financial Effects of Management Alternatives

Over a 200-year simulation, the low diameter-limit cut gave the highest net present value, over $15 440/ha, followed by the heavy BD*q* and the current distribution management (Fig. 2). The least profitable was the high diameter-limit cut, returning less than $4940/ha. The NPV varied little between cutting cycles.

Financial performance was positively correlated with productivity, except for the BD*q* regimes. The reason is that the heavy BD*q* led to a larger initial harvest than the medium and the light BD*q*. As a result, its NPV was higher because earlier returns are discounted less. However, the heavy BD*q* gave a lower average annual production over 200 years than the light BD*q* (Fig. 3).

The fixed costs of re-entry and interest rates may vary by owner and thus affect the results. For example, Fig. 4 shows that a 10-year cutting cycle gave a higher NPV than a 20-year cutting cycle for re-entry costs below $370/ha, while a 20-year cutting cycle was better for a higher re-entry cost. Conversely, a 10-year cycle gave a lower NPV for interest rates below 3.5%, but a higher NPV for higher interest rates (Fig. 5). Still, for a given cutting cycle and interest rate, the ranking of alternatives according to NPV is independent of the re-entry cost, because the effect of the re-entry cost is to decrease the NPV of all alternatives by the same amount.

## 3.3 Effects of Managements on Stand Condition

Regardless of management regime, the stand eventually reaches a steady state, where the growth over the length of a cutting cycle just replaces the amount harvested, be it measured in trees, basal area, or diversity measures.

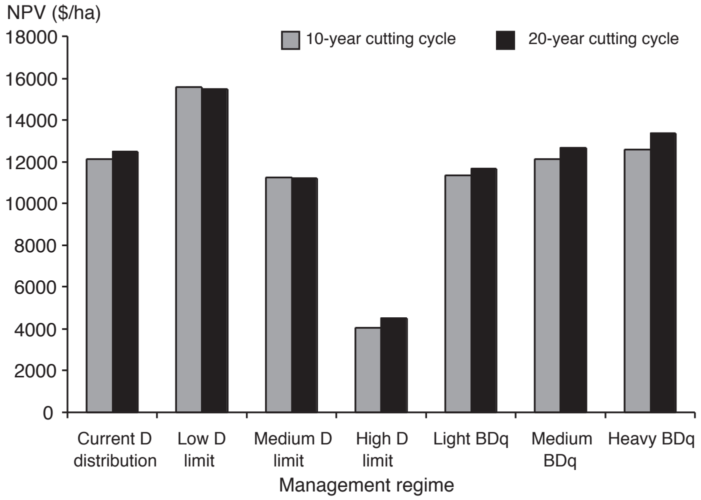

**Fig. 2.** Cumulative net present value by management regime over 200 years of simulation.

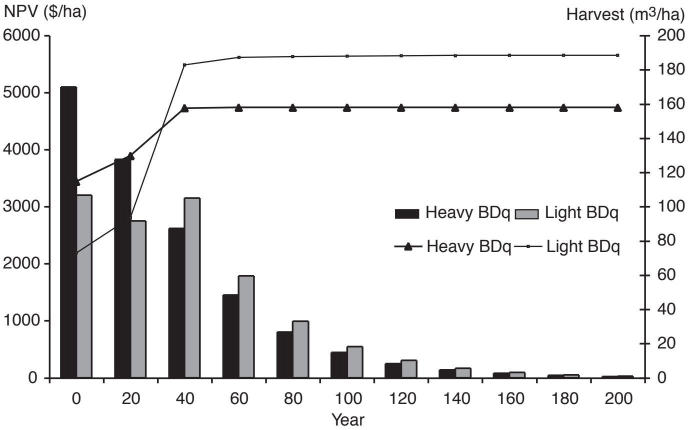

**Fig. 3.** Contribution to NPV (columns) and harvest (lines) of two BDq management regimes with a 20-year cutting cycle. Harvest volume is measured at the time of harvest.

### *3.3.1 Effects on Basal Area*

Figure 6 shows time series of total stand basal area (softwoods and hardwoods) for the low diameter-limit, heavy BD*q*, and current diameter distribution management with a 20-year cutting cycle. The current diameter distribution and the heavy BD*q* led to a steady state almost immediately. Instead, the low diameter limit caused a gradual increase in stand basal area for 80 years, then a decrease to the sustainable level. The medium and light BDq distributions gave results that were similar to those of the current diameter distribution.

Overall, the high diameter-limit management maintained the highest stand basal area, the heavy BD*q* the lowest, and the current diameter distribution was in between. Table 3 shows that after 180 years, when all regimes had reached a steady state, the heavy BD*q* management left a post-harvest basal area of 20.9 $m^2$/ha. This is still above the critical level of 18.4 $m^2$/ha where

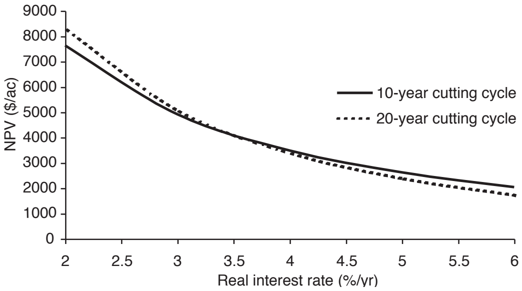

**Fig. 4.** Sensitivity of net present value to real interest rate, with current diameter distribution management.

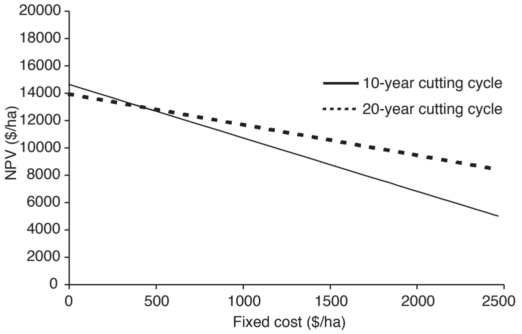

**Fig. 5.** Sensitivity of net present value to fixed re-entry cost for sale preparation and administration, with current diameter distribution management.

shrubs and undergrowth may over take the stand (Miller and Emmingham 2001). In the long run, the current diameter distribution management maintained about the same post-harvest basal area as the light BD*q*. The diameter-limit managements maintained more basal area than any of the others.

### 3.3.2 Effects on Stand Diversity

The species and size class diversity are plotted over time in Figs. 7 and 8 for the current diameter distribution, low diameter-limit, and heavy BD*q* management, with a 20-year cutting cycle. Managing for the current diameter distribution obtains the highest diversity of tree-species and tree-size, and for both measures it reaches a steady state almost immediately.

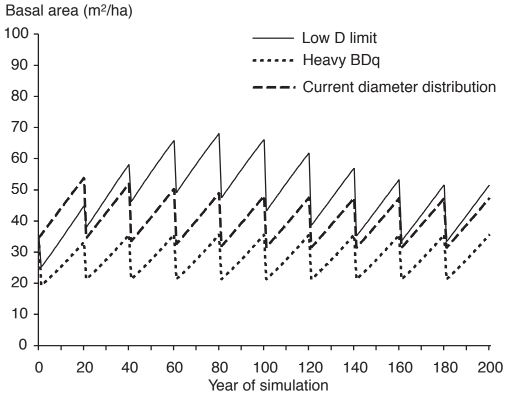

**Fig. 6.** Stand basal area for three management regimes.

**Table 3.** Basal area after 180 years.

| Management | Cutting cycle (years) | Basal area ($m^2$/ha) Cut | Left |
|---|---|---|---|
| Current diameter distribution | | | |
| | 10 | 8.3 | 31.2 |
| | 20 | 16.8 | 31.2 |
| Diameter limit | | | |
| High | 10 | 8.3 | 80.3 |
| | 20 | 14.7 | 79.0 |
| Medium | 10 | 10.6 | 44.8 |
| | 20 | 21.8 | 42.7 |
| Low | 10 | 9.6 | 34.7 |
| | 20 | 19.3 | 33.1 |
| BD*q* selection | | | |
| Light | 10 | 8.3 | 31.9 |
| | 20 | 16.5 | 32.1 |
| Medium | 10 | 7.8 | 26.6 |
| | 20 | 16.1 | 26.6 |
| Heavy | 10 | 7.1 | 20.9 |
| | 20 | 14.9 | 21.1 |

The species diversity for the low diameter-limit cut decreases steadily in the first 80 years, to a minimum, then climbs back to a steady state higher than for the heavy BD*q* target (Fig. 7). However, the size class diversity for the low diameter-limit cut is consistently below that of the heavy BD*q* (Fig. 8).

Most management regimes improved upon the unmanaged (no harvest) stand's species diversity at the steady state (Table 4). The highest post-harvest species diversity was reached by the medium diameter limit, and the lowest by the heavy BD*q*.

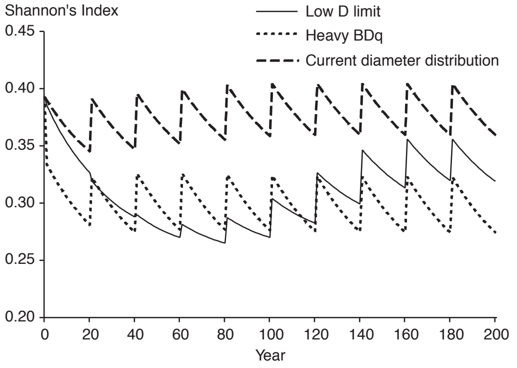

**Fig. 7.** Species group diversity for three management regimes.

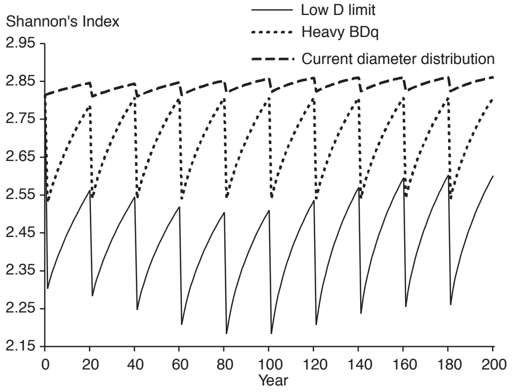

**Fig. 8.** Tree size diversity for three management regimes.

**Table 4.** Species group diversity after 180 years, 20-year cutting cycle.

| Management | Species group diversity (Shannon's index) Pre-cut | Post-cut |
|---|---|---|
| Current diameter distribution | 0.36 | 0.40 |
| Diameter Limit | | |
| High | 0.34 | 0.36 |
| Medium | 0.35 | 0.41 |
| Low | 0.32 | 0.36 |
| BD*q* selection | | |
| Light | 0.32 | 0.37 |
| Medium | 0.30 | 0.35 |
| Heavy | 0.27 | 0.32 |
| No Harvest | 0.32 | |

**Table 5.** Tree size diversity after 180 years, 20-year cutting cycle.

| Management | Tree size diversity (Shannon's index) Pre-cut | Post-cut |
|---|---|---|
| Current diameter distribution | 2.86 | 2.82 |
| Diameter Limit | | |
| High | 2.68 | 2.53 |
| Medium | 2.68 | 2.41 |
| Low | 2.60 | 2.26 |
| BD*q* selection | | |
| Light | 2.86 | 2.68 |
| Medium | 2.83 | 2.61 |
| Heavy | 2.80 | 2.54 |
| No Harvest | 2.59 | |

Managed stands also gave higher size diversity before harvest (Table 5), but only the current diameter distribution management and the light and medium BD*q* gave larger post-harvest size diversity than the stand with no harvest. Managing for the current diameter distribution led to the highest size diversity after harvest, and the low diameter-limit cut led to the lowest.

### *3.3.3 Effects on Stand Structure*

Table 6 shows the pre-harvest diameter distribution of the stand and the cut after 180 years, when a steady state was reached, for different management regimes, including no harvest.

The low diameter-limit management maintained no tree in the three largest size classes, resulting in low size class diversity (Table 5), and the trees cut were primarily between 58 and 79 cm in diameter. Managing according to the heavy BD*q* and current diameter distribution allowed a few trees to grow into the 101.6+ cm diameter class. The heavy BD*q* cut all trees 76.2 cm and above while the current diameter distribution left some of them. Heavy BD*q* and current diameter distribution management differed most in the smallest size classes where the heavy BD*q* removed many trees while working towards the current diameter distribution removed none. Comparing the state after 180 years under “current diameter distribution” (Table 6) with the

**Table 6.** Tree distribution after 180 years, 20-year cutting cycle.

| DBH Class (cm) | Trees/ha [1]<br>Low D Limit<br>Pre-cut | <br>Low D Limit<br>Cut | <br>Heavy BD$q$<br>Pre-cut | <br>Heavy BD$q$<br>Cut | <br>Current diameter distribution<br>Pre-cut | <br>Current diameter distribution<br>Cut | <br>No harvest |
|---|---|---|---|---|---|---|---|
| 10.2 | 108.5 | 0.0 | 85.5 | 36.8 | 106.3 | 0.0 | 130.0 |
| 15.2 | 81.8 | 0.0 | 54.6 | 14.3 | 80.8 | 0.0 | 42.7 |
| 20.3 | 66.0 | 0.0 | 39.8 | 6.2 | 63.8 | 3.2 | 31.1 |
| 25.4 | 55.1 | 0.0 | 31.9 | 4.0 | 52.9 | 0.5 | 25.0 |
| 30.5 | 47.2 | 0.0 | 26.7 | 3.7 | 44.7 | 2.0 | 21.3 |
| 35.6 | 37.3 | 7.7 | 22.7 | 4.0 | 37.3 | 7.4 | 20.3 |
| 40.6 | 30.1 | 2.7 | 19.5 | 4.0 | 30.4 | 12.4 | 20.3 |
| 45.7 | 26.2 | 0.7 | 16.8 | 3.7 | 23.7 | 9.9 | 20.5 |
| 50.8 | 24.5 | 0.2 | 14.1 | 4.9 | 18.0 | 8.2 | 20.8 |
| 55.9 | 23.7 | 0.0 | 11.4 | 4.0 | 13.3 | 6.9 | 20.8 |
| 61.0 | 21.3 | 21.3 | 9.4 | 3.2 | 9.9 | 4.2 | 20.3 |
| 66.0 | 15.6 | 15.6 | 7.9 | 2.7 | 7.4 | 3.7 | 19.8 |
| 71.1 | 8.9 | 8.9 | 6.9 | 2.5 | 5.7 | 3.0 | 18.8 |
| 76.2 | 4.0 | 4.0 | 5.4 | 5.4 | 4.2 | 2.2 | 17.5 |
| 81.3 | 1.5 | 1.5 | 4.0 | 4.0 | 3.2 | 1.5 | 16.1 |
| 86.4 | 0.5 | 0.5 | 2.5 | 2.5 | 2.5 | 1.2 | 14.3 |
| 91.4 | 0.0 | 0.0 | 1.2 | 1.2 | 1.7 | 1.0 | 12.6 |
| 96.5 | 0.0 | 0.0 | 0.5 | 0.5 | 1.5 | 0.7 | 10.6 |
| 101.6+ | 0.0 | 0.0 | 0.2 | 0.2 | 4.0 | 2.0 | 32.1 |

[1] Softwoods and hardwoods.

initial state (Table 1) shows that cutting back the stand towards the distribution that we start with may still produce a very different stand after a long time period.

### *3.3.4 Convergence to Old Growth*

When the stand grew without harvest (last column of Table 6), it acquired after 180 years an old-growth like structure. For example, the Old-Growth Definition Task Group (1986) sets a minimum of 20 large (greater than 81.3 cm DBH) Douglas-firs per hectare in old-growth forests, but concedes that stands will typically contain 37 to 111 trees. The simulated distribution contained about 86 such trees, mostly softwoods (Ralston 2002). The total basal area of the un-harvested stand after 180 years was over 109.0 m$^2$/ha. This is consistent with Franklin et al. (1981) who reported basal areas on old-growth Douglas-fir stands in the Cascade Range reaching 103.3 m$^2$/ha. Although this kind of experiment is a big extrapolation outside of the data range, it is useful to ensure that the model structure is not flawed, as it would be if it predicted exponential growth, or the disappearance of all trees.

## 4 Comparison with Even-Aged Management

### 4.1 Productivity

The yields of uneven-aged management obtained in this study were compared with those from yield tables and other models of even-aged Douglas-fir stands (Table 7). The maximum mean annual increment suggested by the yield tables for even-aged Douglas-fir on an intermediate site is 10.1 m$^3$/ha/y (McArdle et al. 1961). This is similar to the yield predicted by WestPro with the current diameter distribution management regime and a 20-year cutting cycle. But, the SPS program (Arney 1988) suggests a lower yield for unthinned even-aged stands.

Thinning increases the productivity of even-aged stands (Curtis and Carey 1996). Table 8 shows the yield of commercially thinned stands, where only trees above 14.2 cm DBH are removed, on a site with an index of 32 meters at 50 years. With the same initial stand and thinning regime, the DFSIM model (Curtis et al. 1981) predicts a somewhat higher yield than SPS. Both predictions are very similar to the yields obtained in this study for uneven-aged management with the current diameter distribution as target, or low-diameter limit. However, adding pre-commercial thinning may result in higher yields for even-aged management (Curtis 1994).

Shelterwood is another even-aged management that retains some high canopy cover, albeit temporarily. The ZELIG.PNW (Urban 1993) simulation left 15% of the larger trees on a moderately high quality site, with no thinning between planting and harvesting. The resulting yield was substantially less than that of the uneven-aged management regimes evaluated here.

**Table 7.** Annual productivity of even and uneven-aged stands, intermediate site.

| Management | Model | Productivity ($m^3$/ha/y) |
|---|---|---|
| Even-aged | | |
| Unthinned | Yield Tables [1] | 10.3 |
| | SPS [2] | 8.9 |
| Thinned | DFSIM [3] | 10.9 |
| | SPS [2] | 10.4 |
| Shelterwood | ZELIG.PNW [4] | 6.2 |
| Uneven-aged | | |
| Low Diameter-limit [5] | WestPro | 11.8 |
| Current diameter distribution [5] | WestPro | 10.0 |
| Heavy BDq selection [5] | WestPro | 8.3 |

[1] McArdle et al. (1961)
[2] Curtis (1994)
[3] Curtis et al. (1982)
[4] Busing and Garman (2002)
[5] with a 20-year cutting cycle

### 4.1.1 Financial Returns

To compare even-aged and uneven-aged management, we assumed the initial stand state used in this study. In the even-aged case, the initial stand was clear-cut and a new plantation established immediately. For lack of better information, it was assumed that the same stumpage price would apply for both types of management, and the same re-entry cost to administer a timber sale. In reality, stumpage prices may be somewhat lower for uneven-aged stands, and re-entry costs could be higher. The simulation does take into account that the re-entry costs recur more frequently under uneven-aged management.

Costs to replant Douglas-fir range between $245 to $620 per hectare, including the cost of seedlings and labor. We assumed $618/ha, but total costs of reforestation can reach almost $1230/ha, when the need for hardwood and grass control, chemical site preparation, and mountain beaver control are considered (Atkinson and Fitzgerald 2002, Rose and Morgan 2000). We assumed no reforestation cost in uneven-aged management, consistent with natural regeneration.

The initial stand had a value of $11 713/ha (net of re-entry costs of $628/ha). It was assumed that the land would then be planted with 988 trees per hectare, and that the stand would be thinned at age 37, 50, 67, and 85 years, with a final clear-cut at age 100. The corresponding yields and the size of trees predicted with DFSIM version 1.0 are in Table 8 (Curtis et al. 1982).

**Table 8.** Net present value of conversion to even-aged management [1].

| Action | | | | | Year | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 37 | 50 | 67 | 85 | 100 | 137 | 150 | 167 | 185 | 200 |
| | clearcut | thin | thin | thin | thin | clearcut | thin | thin | thin | thin | clearcut |
| Trees/ha before cut | 682 | 897 | 605 | 398 | 279 | 213 | 897 | 605 | 398 | 279 | 213 |
| Trees/ha after cut | 988 | 650 | 430 | 294 | 222 | 988 | 650 | 430 | 294 | 222 | 988 |
| Volume cut ($m^3$/ha) | 279 | 74 | 92 | 103 | 100 | 782 | 74 | 92 | 103 | 100 | 782 |
| Average DBH cut (cm) | 44 | 22 | 25 | 31 | 39 | 57 | 22 | 25 | 31 | 39 | 57 |
| Gross harvest income ($/ha) | 12331 | 1317 | 1557 | 2278 | 3754 | 34493 | 1317 | 1557 | 2278 | 3754 | 34493 |
| Replanting costs ($/ha) | 618 | – | – | – | – | 618 | – | – | – | – | 618 |
| Re-entry cost ($/ha) | 628 | 628 | 628 | 628 | 628 | 628 | 628 | 628 | 628 | 628 | 628 |
| NPV ($/ha) | 11085 | 230 | 213 | 227 | 255 | 1730 | 12 | 10 | 12 | 12 | 89 |
| Total NPV ($/ha) | 13875 | | | | | | | | | | |

[1] Initial stand as in Table 1, even-age yields from Curtis et al. (1982), site index 32.0 m.

Table 8 also shows the present value of each harvest. The cumulative net present value over 200 years was \$13 875/ha. This is about \$800 less than the NPV obtained by uneven-aged management with the low diameter-limit cut, and nearly the same as with the heavy BD*q* (Fig. 1). The largest tree diameter obtained in the even-aged stand would be 56.9 cm (Table 8). This would also be the size of the largest trees left after harvest by the low diameter limit cut in uneven-aged management, while before harvest there would be some trees as large as 86.4 cm in diameter (Table 6). The heavy BD*q* regime would leave trees 71.1 cm in diameter after harvest, and produce some trees larger than 99.1 cm before harvest.

# 5 Summary and Conclusion

The results of the simulation experiments suggest that a wide range of managements is feasible for uneven-aged Douglas-fir in the Pacific Northwest. Harvesting to a target distribution, (with a particular BD*q*, or the current distribution), or applying diameter limits, produced sustainable harvests and residual stocks, in the long run.

The choice of a particular management depends on the objectives. Choosing the current distribution as the target could be an attractive compromise between financial returns and diversity of stand and species. Similar objectives might be achieved with simple diameter limit rules, but they must be complemented by stand improvement measures to avoid long-term dysgenic effects. Within the examples examined here and the related assumptions, uneven-aged management was financially competitive with uneven-aged management.

Overall, the length of the cutting cycle had little effect on the financial returns and productivity of the managements considered here. A 20-year cycle has the advantage of lowering the frequency of disturbances and the costs of re-entry, but for a given target it increases the shock to the stand, due to the larger difference between the actual stand state and the target state at the time of harvest.

Light, medium, and heavy BD*q* targets gave similar productivity, financial, and diversity results, despite the differences in the residual basal area. Instead, the three diameter-limit cuts examined gave divergent results. The high diameter limit removed few large trees at each harvest, resulting in low profit and productivity but very high stand basal areas. Conversely, the low diameter limit generated the highest financial returns but gave diversity levels similar to managing for the current diameter distribution. An advantage of the diameter-limit approach over a target distribution, be it a BD*q* distribution, the current distribution, or another choice distribution, is the ease of implementation. Marking guides based on BD*q* distributions are often difficult and impractical with current methods (O'Hara 1998), and control would be as difficult with distributions defined in any other way. Thus, diameter-limit management with attendant stand improvement seems to be worth exploring. It could easily be further modified to protect against dysgenic effects by maintaining a specific number of trees larger than the diameter limit.

An important issue that is missing in the current version of WestPro is that of wood quality. In the results presented here, the only determinant of tree value is tree volume (determined in part by stand density). Different management regimes may however significantly alter wood quality, and thereby its unit price. Research is needed to link stand state, such as stand density, and tree growth rate to measures of wood quality.

The results presented here are based on simulations with a model. The model predictions are expected values; that is, averages valid only over many stands. There may be much difference between the predicted and the actual result on any particular stand, especially over long time periods. Yet, long time periods are needed to trace the long-term effect of a management, and to eliminate the effect of different terminal states in the economic assessment of alternatives. Risk could be taken explicitly into account in a simulation framework, by sampling from the variance-covariance matrix of the error term in the model (Kaya and Buongiorno 1987), but at a cost of some complication in interpreting the results.

Furthermore, only a few of the many possible management regimes have been examined here. As interest in uneven-aged Douglas-fir forests continues to grow, other approaches will be proposed, adapted to different owners' objectives, and models like WestPro should be useful in comparing them. Ultimately, however, the modeling results should be checked with field experiments applying some of the alternatives suggested here to a wide range of forest stand conditions.

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## Appendix

This model used in Westpro has the following form (Ralston et al. 2003b):

$$\mathbf{y}_{t+1} = \mathbf{G}_t (\mathbf{y}_t - \mathbf{h}_t) + \mathbf{I}_t$$

where $\mathbf{y}_t$ refers to the number of live trees per unit area, $\mathbf{y}_t = [y_{ijt}]$, with $i = 1$ for Douglas-fir and other softwoods, and $i = 2$ for hardwoods, $j$ = diameter class, and $t$ = year.
$\mathbf{h}_t = [h_{ijt}]$ is the number of trees harvested in year $t$. The growth matrix $\mathbf{G}_t$ is:

$$\mathbf{G}_t = \begin{bmatrix} \mathbf{G}_{1t} & \\ & \mathbf{G}_{2t} \end{bmatrix}$$

with:

$$\mathbf{G}_{it} = \begin{bmatrix} a_{i1t} & & & & \\ b_{i1t} & a_{i2t} & & & \\ & \ddots & \ddots & & \\ & & b_{i,n-2,t} & a_{i,n-1,t} & \\ & & & b_{i,n-1,t} & a_{i,n,t} \end{bmatrix}$$

where $n$ is the number of diameter classes, $b_{ijt}$ is the probability that a tree of species $i$ and in diameter class $j$ at $t$ is alive and in diameter class $j + 1$ at $t + 1$, and $a_{ijt}$ is the probability that the same tree is alive and still in diameter class $j$ at $t + 1$, calculated as:

$$a_{ijt} = 1 - b_{ijt} - m_{ijt}$$

where $m_{ijt}$ is the probability that a tree of species $i$ and diameter class $j$ dies between $t$ and $t + 1$.

The recruitment vector, $\mathbf{I}_t$, is:

$$\mathrm{I}_t = \begin{bmatrix} I_{1t} \\ I_{2t} \end{bmatrix}$$

where $I_{it}$ is the number of trees of species $i$, that enters diameter class 1 between $t$ and $t + 1$.

The yearly upgrowth rate is, for softwoods:

$$b_{ijt} = \frac{1}{5.1}(0.089 + 0.009\, D_j - 0.000059\, D_j^2 + 0.0133\, S - 0.0061\, B_t)$$

and for hardwoods:

$$b_{ijt} = \frac{1}{5.1}(0.05 + 0.004\, D_j - 0.00004\, D_j^2 + 0.007 S - 0.001\, B_t)$$

where $D_j$ is the average tree diameter in diameter class $j$ (in cm, measured at breast height), $S$ is the site index (in meters, measured by the height of the dominant trees in the stand at age 50 years), and $B_t$ is the stand basal area, in m$^2$/ha, a function of $\mathbf{y}_t$ an $\mathbf{h}_t$.

The annual mortality rate, $m_{ijt}$, is:

$$m_{ijt} = \frac{1}{10.6} \frac{e^{z_{itT}}}{1 + e^{z_{ijT}}}$$

where, for softwoods:

$$z_{ijt} = -2.42 - 0.09 D_j + 0.0005 D_j^2 + 0.03 S + 0.013 B_t$$

and for hardwoods $z_{ijt} = 0.10$.

The recruitment softwoods is:

$I_t = 6.56 - 0.048 B_t$

while for hardwoods it is:

$I_t = 1.83$ (trees/ha/y).

The tree volume ($m^3$) is for softwoods:

$$v_{ijt} = -1.835 - 0.0020 D_j + 0.00097 D_j^2 + 0.0427 S + 0.00993 B_t$$

and for hardwoods:

$$v_{ijt} = -1.835 - 0.0020 D_j + 0.00097 D_j^2 + 0.0427 S + 0.00993 B_t$$