# Estimation and application of a growth and yield model for uneven-aged mixed conifer stands in California

JINGJING LIANG[1], J. BUONGIORNO[1] and R.A. MONSERUD[2]

[1] *Department of Forest Ecology and Management, University of Wisconsin-Madison, Madison WI 53706, USA*
[2] *USDA Forest Service, Pacific Northwest Forest Experiment Station, Portland, Oregon, USA*

Email: jbuongio@wisc.edu

## SUMMARY

A growth model for uneven-aged mixed-conifer stands in California was developed with data from 205 permanent plots. The model predicts the number of softwood and hardwood trees in nineteen diameter classes, based on equations for diameter growth rates, mortality and recruitment. The model gave unbiased predictions of the expected number of trees by diameter class and species group over eight to twelve years, on 28 validation plots that were not used in model estimation. The results of predictions of undisturbed growth over more than a century were consistent with previous knowledge about succession and productivity in this forest type. The growth model, embedded in the CalPro simulator, was applied to project the effects of managing stands to maintain the current average stand state over the observed plots, with cutting cycles of ten or twenty years. The results suggested that uneven-aged management could match the productivity of even-aged systems. The ten-year cutting cycle led to higher productivity, higher present value of harvests, higher tree species diversity but lower tree size diversity than the twenty-year cycle.

Keywords: mixed species, growth, mortality, recruitment, uneven-aged

## INTRODUCTION

Mixed-conifer forests are one of the most extensive vegetation types in California, covering 13 percent of the state's area (Barbour and Major 1977). The mixed-conifer forest contains ponderosa pine (*Pinus ponderosa*, Dougl. ex Laws.), Jeffrey pine (*Pinus Jeffreyii*, Grev. & Balf.), sugar pine (*Pinus lambertiana*, Dougl.), Douglas-fir (*Psuedotsuga menzesii*, (Mirb.) Franco), white fir (*Abies concolor*, (Gord. & Glend.) Lindl. ex Hildebr.) and incense cedar (*Libocedrus decurrens*, Torr.). The extent of the mixed-conifer type and the amount of timber harvested from the west slopes of the Sierras suggest the need for accurate growth and yield prediction methods to help in their management.

California's forest products industry is an important component of the state's economy. The primary and secondary industry employs over 110,000 workers, 4.1 percent of the state's total manufacturing workforce, with an annual payroll of 0.5 billion. (U.S. Dept. of Commerce 2001). Mixed conifer forests, while providing society with products vital to everyday life, also shelter wildlife, and improve air and water quality.

In managing those forests for multiple purposes, uneven-aged systems in multi-species stands is an attractive alternative to even-aged, monospecific regimes. Uneven-aged stands host more biological diversity, maintain a continuous cover at all times, tend to be more aesthetically pleasing (Guldin 1996), provide better bird habitat (Ambuel and Temple 1983) and greater general biodiversity (Hansen *et al.* 1991). Financially, the system may be advantageous, particularly if it can rely on free natural regeneration (Buongiorno 2001). As a result, uneven-aged stands have long accounted for a substantial portion of the harvested area on private and public forests in California (Ewing et al 1988).

The model presented here is intended to help predict some of the economic and ecological consequences of uneven-aged management in this forest type. This diameter-class, species-specific, non-spatial model is an extension of earlier matrix models of uneven-aged forest stands (e.g. Buongiorno and Michie 1980, Ralston *et al.* 2003, Schulte and Buongiorno 2004). It has three elements: tree growth, mortality, and recruitment. A related diameter-class model (SHAF; Adams and Ek 1974) was used to develop optimal uneven-aged management strategies in northern hardwood stands in Wisconsin (Adams and Ek 1974).

Other growth models are available for mixed conifer stands in California. CACTOS (Wensel and Biging 1987) is an individual tree non spatial stand growth model calibrated using industry data from mixed conifer stands in northern California. It does not include regeneration, but it does include a separate stand generator (STAG; Biging *et* *al.* 1991). CACTOS also accepts tree lists generated by the regeneration/young stand programs SYSTUM-1 (Ritchie and Powers 1993) and CONIFERS (Ritchie 1999 2003). The Forest Vegetation Simulator (FVS; Wykoff *et al.* 1982, Teck *et al.* 1997) is also an individual tree stand simulator with a long history as a stand management tool. Three variants are available for California (Ritchie 1999): *SORNEC* and *Klamath* for mixed stands in northern California and southwestern Oregon, and *WESSIN* for the western Sierra Nevada. Although considerable stand optimization has been done for uneven-aged mixed conifer stands with the North Idaho variant of FVS (Haight and Monserud 1990), these three California variants lack regeneration modules, which preclude a long-term uneven-aged analysis.

The present growth model uses data from stands at all stages of development, from juvenile to over mature, and from the entire state of California. Furthermore, by modeling recruitment, it enables long-term predictions of stand dynamics and of the associated patterns of succession with or without human intervention.

## MODEL STRUCTURE

The growth model has the following form:

$$\mathbf{y}_{t+1} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{R} + \boldsymbol{\varepsilon}_t \qquad (1)$$

where $\mathbf{y}_t = [y_{ijt}]$ is a column vector representing the number of live trees per unit area (hectare) of species group $i$ ($i$=1,2,...,$m$), diameter class $j$ (j=1,2,...,$n$) at time $t$. The column vector $\mathbf{h}_t = [h_{ijt}]$ represents the number of trees of species group $i$, diameter class $j$ that are cut at time t. $\mathbf{G}$, the state-dependent growth matrix, describes how the trees that are not cut grow or die between $t$ and $t$+1. The state-dependent vector $\mathbf{R}$ represents the number of trees recruited in the smallest diameter class of each species group, between $t$ and $t$+1, and $\boldsymbol{\varepsilon}_t$ is a vector of random shocks. $\mathbf{G}$ and $\mathbf{R}$ are defined as:

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & & & \\ & \mathbf{G}_2 & & \\ & & \ddots & \\ & & & \mathbf{G}_m \end{bmatrix}, \mathbf{G}_i = \begin{bmatrix} a_{i1} & & & & \\ b_{i1} & a_{i2} & & & \\ & \ddots & \ddots & & \\ & & b_{i,n-2} & a_{i,n-1} & \\ & & & b_{i,n-1} & a_{in} \end{bmatrix}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_1 \\ \mathbf{R}_2 \\ \vdots \\ \mathbf{R}_m \end{bmatrix}, \quad \mathbf{R}_i = \begin{bmatrix} R_1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \qquad (2)$$

where $a_{ij}$ is the probability that a tree of species group $i$ and diameter class $j$ stays alive and in the same diameter class between $t$ and $t$+1, $b_{ij}$ is the probability that it stays alive and grows into diameter class $j$+1, and $R_i$ is the recruitment rate, i.e. the number of trees of species group $i$ that enter the smallest diameter class between $t$ and $t$+1. $a_{ij}$, is related to $b_{ij}$, and the probability , $m_{ij}$, that a tree of species group $i$ and diameter class $j$ dies from $t$ to $t$+1, by:

$$m_{ij} = 1 - a_{ij} - b_{ij} \qquad (3)$$

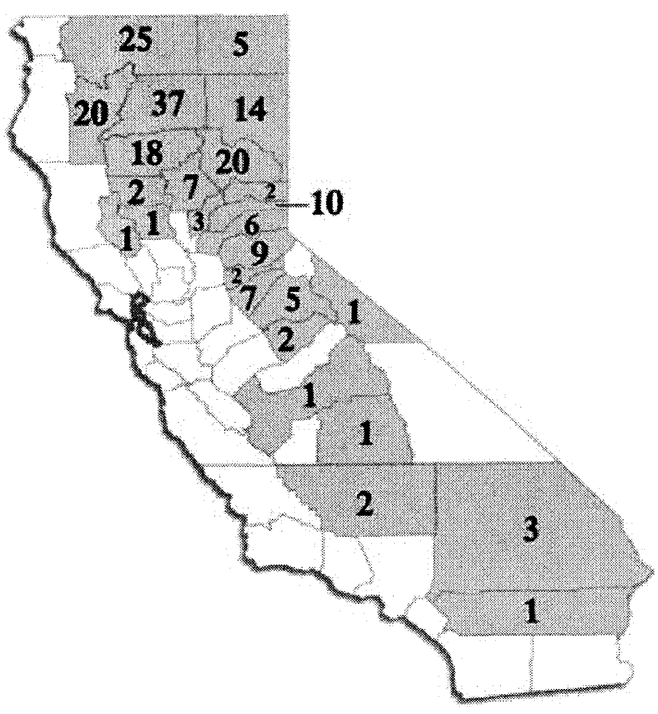
where $b_{ij}$ and $m_{ij}$ are species-dependent functions of tree and stand characteristics. $R_i$ is a species-dependent function of stand characteristics.

## DATA

The data came from permanent plots in the California mixed conifer type. The plots were measured during the last two periodic inventories conducted by the Pacific Northwest Research Station's Forest Inventory and Analysis (FIA) Program (PNW FIA 2000). The surveys were done in the 1980's and 1990's on forested lands outside of National Forests and parks.

The 205 plots used to calibrate the model were in the mixed-conifer forest type, and in uneven-aged stands. Uneven-aged stands were defined as stands in which more than 70 percent of the trees differed by more than 30 years in age (Hiserote and Waddell 2003). Most of the plots were in northern California (Figure 1). About 70% of the

FIGURE 1 *Number of plots by California County*




plots were on industry lands 25% belonged to other private owners, the rest were on public lands (Table 1).

Trees were grouped as softwoods and hardwoods, and into nineteen 5.08 cm diameter classes, from diameter class 10 cm (trees 7.6 to 12.7 cm in diameter) to diameter

TABLE 1 *Distribution of sample plots, by ownership*

| Ownership | Number of plots | (%) |
|---|---|---|
| Industry with mills | 95 | (46.2) |
| Industry without mills | 50 | (24.4) |
| Miscellaneous private | 48 | (23.4) |
| Farmer owned | 4 | ( 2.0) |
| Bureau of Land Management | 4 | ( 2.0) |
| State owned | 3 | ( 1.5) |
| County/Municipal | 1 | ( 0.5) |
| Total | 205 | ( 100) |

class 102 cm (trees 99.1 cm in diameter and larger). White fir (*Abies concolor*), a shade-tolerant conifer (Seidel 1981), was the most abundant softwood on the plots (Table 2). The moderately shade-tolerant California black oak (*Quercus kellogii*) and canyon live oak (*Quercus chrysolepus*) were the most abundant hardwoods. The average number of trees per unit area over all the plots decreased exponentially as tree diameter increased (Figure 2).

Most plots were on lands with site indices between 15 and 24 m (Figure 3). Site index was based on the height of the dominant tree on the plot at age 50 (Hanson et al 2002), and there was only one site index per plot. The

TABLE 2 *Average number of trees per hectare by species, on the 205 plots*

| Scientific name[1] | Common name | 1st Inventory | 2nd Inventory |
|---|---|---|---|
| | Softwoods | | |
| *Abies concolor* | White fir | 152.49 | 163.78 |
| *Libocedrus decurrens* | Incense-cedar | 109.06 | 128.32 |
| *Pseudotsuga menziesii* | Douglas-fir | 106.54 | 121.51 |
| *Pinus ponderosa* | Ponderosa pine | 71.41 | 73.70 |
| *Pinus lambertiana* | Sugar pine | 24.52 | 27.01 |
| *Pinus jeffreyii* | Jeffrey pine | 12.35 | 14.44 |
| *Abies magnifica* | California red fir | 8.40 | 13.06 |
| *Pinus contorta* | Lodgepole pine | 2.67 | 2.25 |
| *Juniperus occidentalis* | Western juniper | 0.86 | 0.86 |
| *Taxus brevifolia* | Pacific yew | 1.09 | 0.69 |
| *Pinus monticola* | Western white pine | 0.69 | 0.69 |
| *Pinus coulteri* | Coulter pine | 0.54 | 0.54 |
| *Pinus attenuata* | Knobcone pine | 0.64 | 0.35 |
| *Sequoia gigantea* | Giant sequoia | 0.32 | 0.32 |
| *Torrey californica* | California-nutmeg | 0.22 | 0.22 |
| *Pinus sabiniana* | Gray pine | 0.05 | 0.05 |
| *Pinus albicaulis* | Whitebark pine | 0.02 | 0.02 |
| *Pseudotsuga macrocarpa* | Bigcone Douglas-fir | 0.02 | 0.02 |
| *Abies magnifica v. s.* | Shasta red fir | 0.00 | 0.00 |
| Total | | 491.93 | 547.83 |
| | Hardwoods | | |
| *Quercus kelloggii* | California black oak | 46.173 | 44.963 |
| *Quercus chrysolepi* | Canyon live oak | 27.407 | 30.716 |
| *Acer macrophyllum* | Bigleaf maple | 6.444 | 12.444 |
| *Lithocarpus densiflorus* | Tanoak | 7.704 | 11.556 |
| *Arbutus menziesii* | Pacific madrone | 3.481 | 6.568 |
| *Umbellularia californica* | California-laurel | 2.889 | 4.296 |
| *Cornus nutallii* | Pacific dogwood | 0.000 | 4.049 |
| *Quercus wislizeni* | Interior live oak | 1.481 | 3.852 |
| *Alnus rhombifolia* | White alder | 1.728 | 1.975 |
| *Alnus rubra* | Red alder | 0.617 | 0.914 |
| *Castanopsis chrysophylla* | Golden chinkapin | 0.519 | 0.519 |
| *Quercus garryana* | Oregon white oak | 0.296 | 0.296 |
| *Salix* spp. | Willow | 0.123 | 0.123 |
| *Quercus lobata* | California white oak | 0.049 | 0.049 |
| *Populus tremuloides* | Quaking aspen | 0.099 | 0.000 |
| Total | | 99.037 | 122.321 |

[1] Nomenclature per Little (1979).

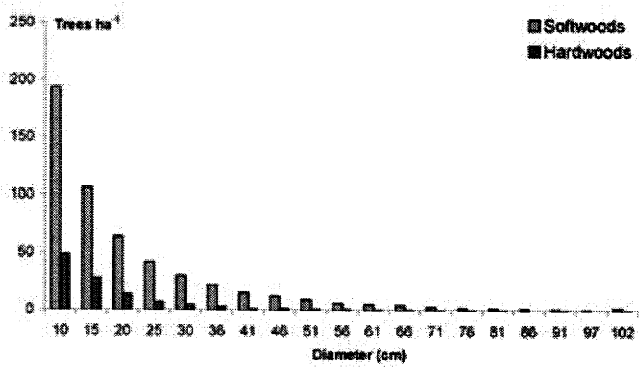



FIGURE 2 *Average number of trees per hectare over the 205 plots, between the two inventories*

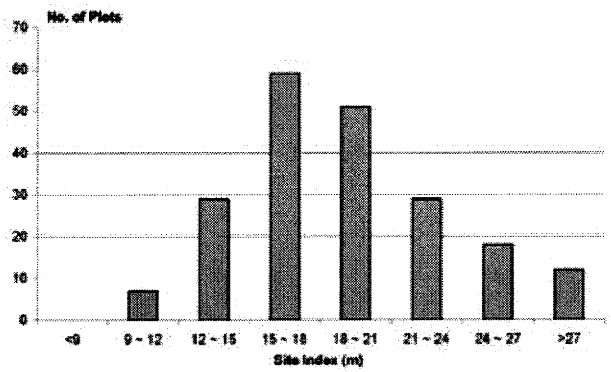



FIGURE 3 *Distribution of plots by site index class (205 plots in total, site index measured by dominant tree height at age 50 y)*

mean recruitment rate over all plots was higher for softwoods than for hardwoods (Table 3a). On average, softwood trees grew at twice the rate of hardwood trees, and the mean mortality rate was 5 times higher for hardwoods than for softwoods. The superior recruitment rate and the lower mortality rate of softwoods explain the five to one dominance of softwoods in the stands, in terms of number of trees. The average volume of individual softwood trees was twice that of hardwood trees (Table 3b).

## PARAMETER ESTIMATION

The equations of growth, mortality, and recruitment, and the equations of tree volume were chosen based on three criteria: 1) Agreement with the expected biological response, for example, the effect of basal area on diameter growth should be negative (Schulte and Buongiorno 2004); 2) goodness of fit, statistical significance of the parameters, and distribution of residuals (Draper and

TABLE 3a *Summary statistics for stand data on the 205 plots*

| | Trees ha$^{-1}$ [a] | | Recruitment (tree ha$^{-1}$ y$^{-1}$) | | Site Index (m) | Basal area [a] (m$^2$ ha$^{-1}$) | Years between inventories |
|---|---|---|---|---|---|---|---|
| | Softwoods | Hardwoods | Softwoods | Hardwoods | | | |
| *Mean* | 519.88 | 110.67 | 11.06 | 3.06 | 26.80 | 28.92 | 10.88 |
| *S.D.* | 340.17 | 195.16 | 12.42 | 8.25 | 4.90 | 13.74 | 0.62 |
| *Max* | 1731.56 | 1332.44 | 74.22 | 65.04 | 40.54 | 69.17 | 12.00 |
| *Min* | 15.95 | 0.00 | 0.00 | 0.00 | 10.06 | 3.04 | 8.17 |
| *n* | 205 | 205 | 205 | 205 | 205 | 205 | 205 |

[a] Average over the two inventories.

TABLE 3b *Summary statistics for individual tree data on the 205 plots*

| | Diameter growth [a] (cm y$^{-1}$) | | Probability of dying between inventories | | Tree Volume [a] (m$^3$ tree$^{-1}$) | | Diameter [a] (cm) | |
|---|---|---|---|---|---|---|---|---|
| | Softwoods | Hardwoods | Softwoods | Hardwoods | Softwoods | Hardwoods | Softwoods | Hardwoods |
| *Mean* | 0.46 | 0.20 | 0.07 | 0.34 | 1.63 | 0.72 | 42.06 | 36.07 |
| *S.D.* | 0.30 | 0.14 | 0.25 | 0.47 | 2.87 | 1.69 | 25.60 | 24.64 |
| *Max* | 2.45 | 1.08 | 1.00 | 1.00 | 54.72 | 20.45 | 214.30 | 119.51 |
| *Min* | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 7.75 | 7.85 |
| *n* | 3836 | 559 | 4124 b | 845 b | 3836 | 559 | 3836 | 559 |

[a] Average between the two inventories.
[b] Live and dead trees.

Harry 1998); and 3) simplicity and parsimony. The following equations were selected by fitting various functional forms to data from 177 calibration plots, drawn randomly from the 205 plots. The remaining 28 plots were used for further testing and verification.

**Diameter growth equations**

The probability that a survivor tree moved from one diameter class to the next was calculated as:

$$b_{ij} = \frac{1}{d} g_{ij} \quad (4)$$

where $d$ is the width of each diameter class, and $g_{ij}$ is the expected annual diameter growth of a survivor tree of species group $i$ and diameter class $j$, obtained by converting periodic growth to annual growth by linear interpolation. The expected annual diameter growth was predicted by:

$$\ln g_{ij} = \alpha_i + \beta_i \ln D_j + \gamma_i (\ln D_j)^2 + \delta_i \ln B + \varphi_i \ln S \quad (5)$$

where $D_j$ is the tree diameter, $B$ is the stand basal area, and $S$ is the site index. The parameters of equation (5) were estimated by ordinary least squares. The logarithmic transformation was used to obtain homoskedastic residuals. The data came from the 3,334 live softwood trees and 485 live hardwood trees on the 177 calibration plots.

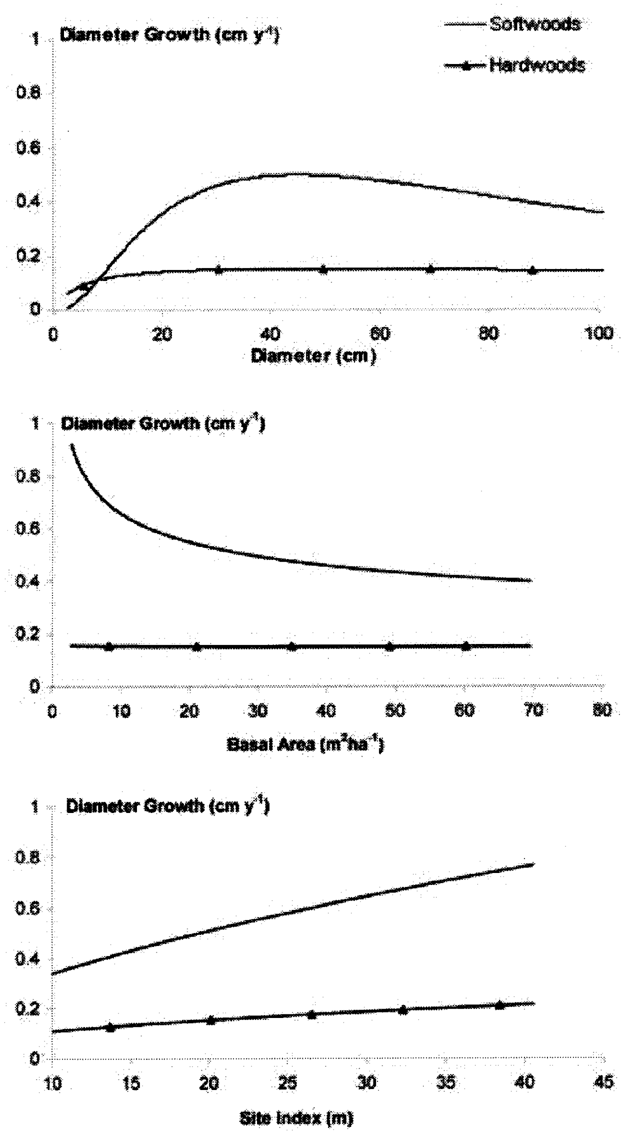
TABLE 4 *Parameters of diameter growth rate equations, estimated from individual trees on 177 calibration plots*

| | Coefficient of Independent Variable | | | | |
|---|---|---|---|---|---|
| | ln*D* | ln*D*² | ln*B* | ln*S* | Constant |
| Softwoods | | | | | |
| | 3.96 | -0.52 | -0.26 | 0.58 | -9.07 |
| *SE* | 0.18 | 0.03 | 0.03 | 0.05 | 0.33 |
| *t* | 22.43 | -20.47 | -9.97 | 10.95 | -27.43 |
| *P* | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $R^2$ | 0.25 | | | | |
| *SEE* | 0.68 | | | | |
| *dF* | 3329 | | | | |
| Hardwoods | | | | | |
| | 0.84 | -0.11 | 0.01 | 0.48 | -4.85 |
| *SE* | 0.47 | 0.07 | 0.08 | 0.17 | 0.96 |
| *t* | 1.77 | -1.52 | 0.19 | 2.86 | -5.03 |
| *P* | 0.08 | 0.13 | 0.85 | 0.00 | 0.00 |
| *SEE* | 0.71 | | | | |
| $R^2$ | 0.04 | | | | |
| *dF* | 480 | | | | |

Dependent variable = logarithm of annual diameter growth.
*SE* = standard error.
*t* = Student's t ratio.
*P* = area in two tails of distribution outside ± *t* - value.
$R^2$ = coefficient of determination.
*SEE* = standard error of estimates.
*dF* = degrees of freedom.

The parameter estimates and related statistics are in Table 4. Figure 4 shows the partial effect of each variable on the predicted growth rate, holding the others constant at their sample mean. For softwoods, the growth rate increased with tree diameter up to 40 cm, and then declined. For hardwoods, it increased more slowly up to 40 cm, and then remained constant. Higher stand basal area reduced significantly the growth rate of softwoods, but not that of hardwoods. Softwoods grew significantly faster on higher sites, but hardwoods did not. The low $R^2$'s of the equations show that the independent variables explained only a small part of the variability in diameter growth. For hardwoods in particular, the expected diameter growth was nearly constant. Nevertheless, the standard errors of the resulting transition probabilities (equation

FIGURE 4 *Effect of each explanatory variable on the expected tree growth rate, with other variables being held constant at their sample mean*



(4)) were small: 0.002 for softwoods, and 0.006 for hardwoods. A further test of these equations is the accuracy of the complete model of which they are a part, examined in section 5.1.

**Mortality equations**

The expected annual mortality rate was calculated as:

$$m_{ij} = \frac{1}{\bar{T}} M_{ij} \tag{6}$$

where $M_{ij}$ was the expected mortality rate between the two inventories and $\bar{T}$ was the average interval between inventories, in years. Because mortality rates are small, this linear interpolation is practically identical to an exponential interpolation. $M_{ij}$ was modeled with a probit equation:

$$M_{ij} = P(y_{ij} = 1 | D_j, B, T) = \Phi(\eta_i + \kappa_i D_j + \lambda_i D_j^2 + \mu_i B + \theta_i T) \tag{7}$$

where $y_{ij} = 1$ if a tree of species group $i$ and diameter class $j$ died, and $y_{ij} = 0$ otherwise. $\Phi$ is the standard normal cumulative distribution function (Wooldridge 2000). The parameters were estimated by maximum likelihood with individual tree data.

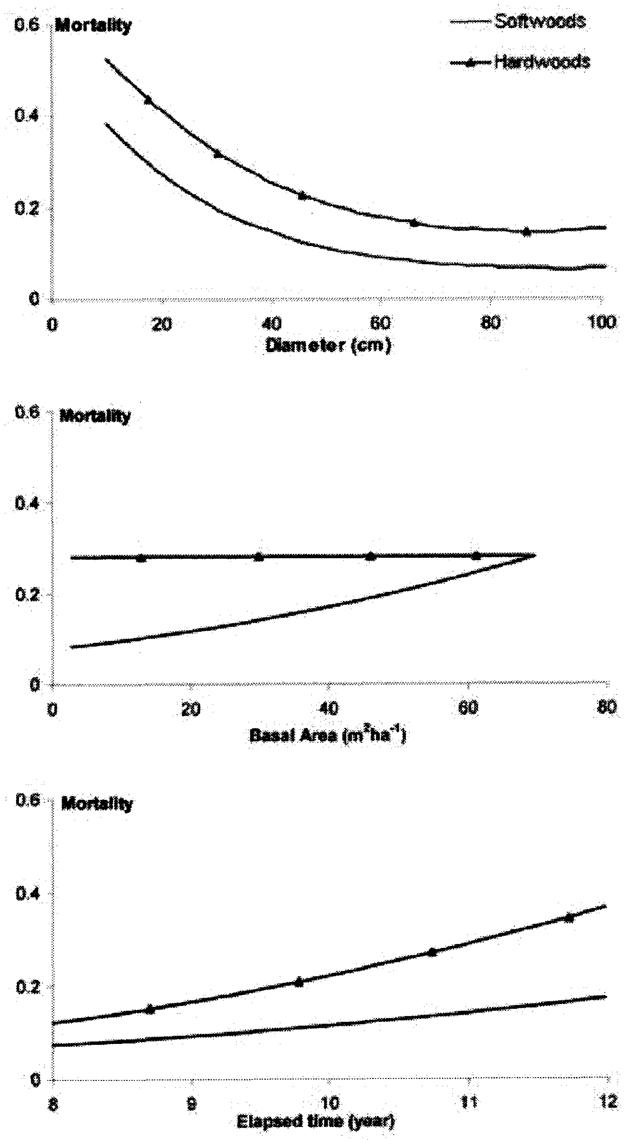
The parameter estimates and related statistics of the mortality equations are in Table 5, and Figure 5 shows the partial effect of each variable on the predicted annual mortality rate while other variables were held constant at their sample mean. For both softwoods and hardwoods, the predicted mortality rate decreased rapidly with diameter. It increased with stand basal area for softwoods, but not for hardwoods. The mortality rate also increased with the time interval between inventories. Other things being equal, the expected mortality rate was higher for hardwoods than for softwoods.

TABLE 5 *Parameters of probit mortality rate equations estimated from individual trees on the 177 calibration plots*

| | Coefficient of Independent Variable | | | | |
|---|---|---|---|---|---|
| | $D$ | $D^2$ | $B$ | $T$ | Constant |
| Softwoods | | | | | |
| | -0.058 | 0.00026 | 0.020 | 0.238 | -3.141 |
| *SE* | 0.004 | 0.00003 | 0.006 | 0.068 | 0.739 |
| *Z* | -13.02 | 6.66 | 3.56 | 3.50 | -4.25 |
| *P* | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| *L* | -659.9 | | | | |
| *n* | 3570 | | | | |
| Hardwoods | | | | | |
| | -0.054 | 0.00026 | 0.0003 | 0.357 | -3.268 |
| *SE* | 0.009 | 0.00011 | 0.0008 | 0.095 | 1.029 |
| *Z* | -5.97 | 2.27 | 0.04 | 3.77 | -3.18 |
| *P* | 0.000 | 0.023 | 0.97 | 0.000 | 0.001 |
| *L* | -363.2 | | | | |
| *n* | 716 | | | | |

Dependent variable = mortality rate between inventories taken at $T$ year interval.
$SE$ = standard error.
$Z$ = analog for Student t ratio for probit model.
$P$ = probability that the coefficient has this sample value if the null hypothesis is true.
$L$ = log-Likelihood value.
$n$ = Total number of observations of the response variable.

FIGURE 5 *Effect of each explanatory variable on the expected mortality rate between the two inventories, with other variables being held constant at their sample mean*




**Recruitment equations**

There was no recruitment for softwoods on 52 of the 177 calibration plots, and no recruitment for hardwoods on 144. A Tobit model was therefore used to represent recruitment. The Tobit model combines the probability that there is recruitment with the expected recruitment if there is any, to obtain the unconditional expected recruitment:

$$R_i = \Phi(\boldsymbol{\beta}_i \mathbf{x}_i / \sigma_i)\boldsymbol{\beta}_i \mathbf{x}_i + \sigma\phi(\boldsymbol{\beta}_i \mathbf{x}_i / \sigma_i) \quad (11)$$

where $\Phi$ and $\phi$ are respectively the standard normal cumulative and density functions, $\sigma$ is the standard deviation of the residuals (Wooldridge 2000). Only the stand basal area and the number of trees of the same species group per unit area were found to significantly influence recruitment, specifically:

$$\boldsymbol{\beta}_i \mathbf{x}_i = \omega_i + \rho_i B + \tau N_i \quad (12)$$

where $N_i$ is the number of trees of species group $i$ per unit area in the stand.

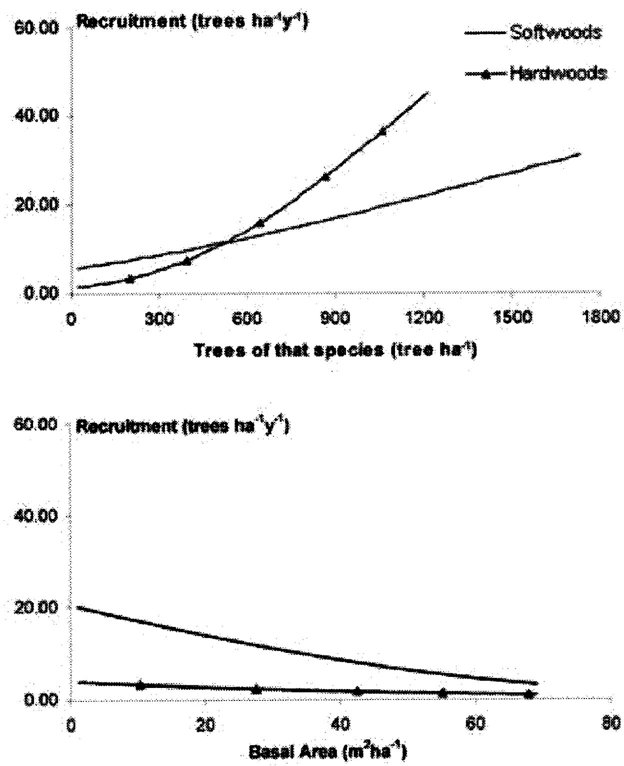
The maximum likelihood estimates of the parameters of the recruitment equations are in Table 6. Figure 6 shows the effect of variations in the stand basal area and number of trees on the predicted recruitment, other things being equal. Recruitment was affected positively and significantly by the density of trees of the same species group, especially for hardwoods. Recruitment decreased as the stand basal area increased, more so for softwoods than for hardwoods.

TABLE 6 *Parameters of Tobit recruitment equations estimated from the 177 calibration plots*

| | Coefficient of Independent Variable | | | |
|---|---|---|---|---|
| | *B* | *N* | Constant | $\sigma$ |
| Softwoods | | | | |
| | -0.38 | 0.018 | 10.54 | 14.09 |
| *SE* | 0.09 | 0.004 | 2.60 | 0.95 |
| $\chi^2$ | 16.52 | 20.54 | 16.47 | |
| *P* | 0.00 | 0.000 | 0.00 | |
| *L* | -552.58 | | | |
| *n* | 177 | | | |
| Hardwoods | | | | |
| | -0.25 | 0.06 | -18.24 | 8.69 |
| *SE* | 0.19 | 0.01 | 6.41 | 1.25 |
| $\chi^2$ | 1.66 | 20.05 | 8.10 | |
| *P* | 0.20 | 0.00 | 0.00 | |
| *L* | -197.96 | | | |
| *n* | 177 | | | |

Dependent variable = trees ha$^{-1}$ y$^{-1}$.
$\sigma$ = standard deviation of residuals.
*SE* = standard error.
*P* = probability that the coefficient has this sample value if the null hypothesis is true.
*L* = log-Likelihood value.

FIGURE 6 *Effect of each explanatory variable on the expected annual recruitment rate, with other variables being held constant at their sample mean*




**Tree volume equations**

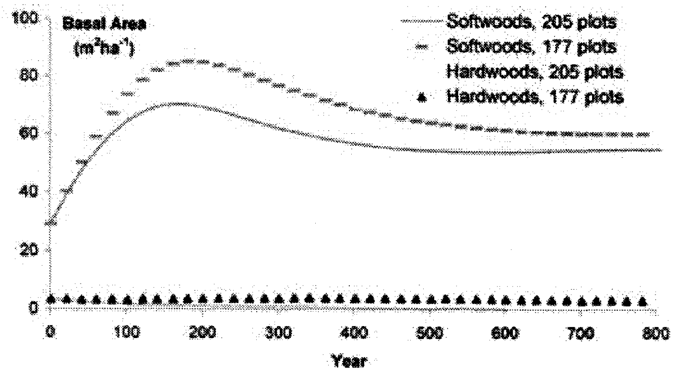
The following equation was used to estimate the expected volume per tree:

$$\ln v_{ij} = \varsigma_i + \ln D_j + \psi_i \ln B + \zeta_i \ln S \quad (13)$$

where $V_{ij}$ is the expected volume, in m$^3$, of a tree of species group $i$ and diameter class $j$. The parameters were estimated by ordinary least squares, with data from all live trees measured at both inventories. The results of estimation for the tree volume equations are in Table 7.

Tree diameter, stand basal area and site index all had a positive and statistically significant effect on tree volume, at the 0.05 level, based on the $t$ ratios. Tree volume was most sensitive to tree diameter, as expected. The volume of hardwood trees was more sensitive to basal area than that of softwood trees. Variations in site index had a similar effect on the tree volume of hardwoods and softwoods. Other things being equal, softwood trees had more volume than hardwoods.

FIGURE 8 *Long-term basal area predicted with parameters estimated with data from all 205 plots, or from a subset of 177 plots*




state of 60 to 70 m$^2$ ha$^{-1}$. This is consistent with the "normal" basal area of 65 and 75 m$^2$ ha$^{-1}$ for mixed conifers on average site at age 100 years (Lawrence 1997). But the diameter distribution of trees in old growth plots measured by Sudworth at the beginning of the last century, from a much more limited area, (McKelvey and Johnston 1992) implied an average basal area of about 102 m$^2$ ha$^{-1}$.

The steady state predicted by the model had 54 tree ha$^{-1}$, of which 46% were in diameter class 99.1 + cm. In comparison, the Sudworth's old-growth plots had 115 tree ha-1, of which 42% were in diameter class 99.1+ cm. Thus, the model seems to predict correctly the proportion of trees in the largest size class in old growth stands, but to underestimate the total number of trees.

Still, the predicted steady state was within the interim minimum standards for old-growth mixed-conifer forests in California, which specifies "two or more species with a wide age range and full range of tree sizes," with at least 20 tree ha$^{-1}$ of diameter above 81 cm (Old Growth Definition Task Group 1986).

To check the sensitivity of these results to the data, the calculations were repeated with parameters estimated from all 205 plots, instead of the 177 calibration plots only. The paths of basal area had the same shape for the two sets of parameters, and the steady states were very similar, both in total basal area and in tree distribution by diameter class. However, the predicted basal area during the intermediate years of the simulation was substantially lower with the parameters based on the entire 205 plot data. Since the parameters based on 205 plots represented more information, they were used in the following application. The results of these long-term predictions and steady-state computations must be taken cautiously, since they depend on a model calibrated with data that span no more than twelve years. Still, they do not contradict previous ecological knowledge, hence it seems reasonable to use the model in management applications.

## MANAGEMENT APPLICATION

The effect of management on the growth of uneven-aged mixed conifer stands can be projected by applying equation (1) recursively to predict the expected growing stock, $\mathbf{y}_t$, given an initial stand state, $\mathbf{y}_0$, and a management regime defined by the magnitude and timing of harvests, $\mathbf{h}_t$. The CalPro software (Liang *et al.* 2004, available at http://www.forest.wisc.edu/facstaff/buongiorno/index.htm) facilitates this kind of application.

CalPro is a spreadsheet add-in program based on the growth and volume equations presented above. Stands are described by the number of trees per unit area in each of 19 diameter classes, in softwoods and hardwoods. CalPro allows year-by-year predictions of stand development for many decades from an initial state. Management regimes are defined by the interval between harvests (cutting cycle) and a target distribution of trees left after harvest. Tabulated and graphic results show diameter distributions, basal area, volumes, income, net present value, and indices of tree size diversity and tree species diversity.

Alexander and Edminster (1976) indicated that the choice of intensity of silviculture and length of cutting cycle depends on the growth rate of the stand (embedded here in the growth model) and on the economic and other

TABLE 8 *Tree volume and harvest unit values by species group and size*

| Diameter | Softwoods | | Hardwoods | |
|---|---|---|---|---|
| (cm) | m$^3$ | \$ m$^{-3}$ | m$^3$ | \$ m$^{-3}$ |
| 7.6 – 12.7 | 0.0 | 4.3 | 0.0 | 12.5 |
| 12.7 – 17.8 | 0.1 | 7.1 | 0.1 | 12.5 |
| 17.8 – 22.9 | 0.1 | 7.1 | 0.2 | 12.5 |
| 22.9 – 27.9 | 0.2 | 108.1 | 0.3 | 13.6 |
| 27.9 – 33.0 | 0.4 | 163.6 | 0.4 | 14.8 |
| 33.0 – 38.1 | 0.6 | 163.6 | 0.6 | 14.8 |
| 38.1 – 43.2 | 0.9 | 207.6 | 0.9 | 14.8 |
| 43.2 – 48.3 | 1.2 | 207.6 | 1.2 | 14.8 |
| 48.3 – 53.3 | 1.6 | 207.6 | 1.6 | 14.8 |
| 53.3 – 58.4 | 2.1 | 207.6 | 2.0 | 14.8 |
| 58.4 – 63.5 | 2.6 | 207.6 | 2.5 | 14.8 |
| 63.5 – 68.6 | 3.3 | 207.6 | 3.0 | 14.8 |
| 68.6 – 73.7 | 4.0 | 207.6 | 3.7 | 14.8 |
| 73.7 – 78.7 | 4.9 | 207.6 | 4.4 | 14.8 |
| 78.7 – 83.8 | 5.8 | 207.6 | 5.1 | 14.8 |
| 83.8 – 88.9 | 6.8 | 207.6 | 6.0 | 14.8 |
| 88.9 – 94.0 | 8.0 | 207.6 | 6.9 | 14.8 |
| 94.0 – 99.1 | 9.2 | 207.6 | 7.9 | 14.8 |
| 99.1 + | 10.6 | 207.6 | 9.0 | 14.8 |

Notes: Tree volume is for a stand of 28.92 m2ha-1 of basal area, and a site index of 18.90 m. For a given diameter, the tree volume is a function of site and stand basal area. Unit values are adapted from California State Board of Equalization (2003), Harvest Values Schedule, 07/2003~12/2003.

constraints. The following example summarizes CalPro results in predicting the effects of a management strategy designed to maintain the current stand state, over the forest area represented by the plots in this study. Accordingly, the initial state was defined by the average number of trees by species group and diameter class on the 205 sample plots (Figure 2). The average site index was 27 m.

The number of trees harvested per unit area, $h_{ijt}$, depended on the current stand state, and on the desired stand state, as follows:

$$h_{ijt} = \max(0, y_{ijt} - y_{ijt}^*) \qquad (14)$$

where $y_{ijt}^*$, the desired number of trees of species group $i$, diameter $j$, in year $t$. In this particular example of application, $y_{ijt}^*$ was set equal to the observed initial number of trees. The cutting cycle was either ten or twenty years, but a harvest would occur only if $h_{ijt}$ was not zero, according to equation (14).

The expected individual tree volume calculated from the volume equations, $v_{ij}$, and the corresponding harvest value per unit of volume, by species group and diameter, $p_{ij}$, are in Table 8. Net present values were computed with a real (net of inflation) interest rate of 3% $y^{-1}$, with the formula:

$$NVP = \sum_{k=0}^{K} \frac{h_{ijt} v_{ij} p_{ij}}{(1+r)^{kc}} \qquad (15)$$

where $r$ was the interest rate, and $c$ was the cutting cycle, in years. The land expectation value was then *NPV* minus the value of the initial growing stock. This land expectation value could then be compared with the land expectation value of an even-aged stand, starting from bare land.

Figure 9 shows the expected stand basal area with this target distribution for ten-year and twenty-year cutting cycles over 100 years. The basal area was practically the same for both cutting cycles during the first decade after each harvest. However, the twenty-year cutting cycle maintained a substantially higher level of basal area than the ten-year cutting cycle over the following decade.

Both the annual basal area and the annual volume harvested over 100 years were higher with the ten-year cutting cycle than with the twenty-year cutting cycle (Table 9). The ten-year cutting cycle was financially superior, giving a 14% higher present value of harvests than the twenty-year cycle. Nevertheless, with either cutting cycle, the return to the land was negative, indicating that the simulated management which aimed at maintaining the current tree distribution was very costly, even compared with the alternative that would harvest the entire stand immediately, without any future benefit.

Expected stand diversity was measured with Shannon's index (Magurran 1988), based on the proportion of basal area by species group or diameter class. Tree size diversity decreased at each harvest, and then increased over the cutting cycle (Figure 10). In contrast, species diversity increased at each harvest, because the harvest took mostly softwood trees and then declined over the cutting cycle, as the softwood basal area increased while the hardwoods basal area remained almost constant.

Tree size diversity was practically the same for both cutting cycles, during the first decade after each harvest. But the twenty-year cutting cycle maintained a more diverse stand structure in the following decade because it let some of the trees grow bigger (Figure 10).

TABLE 9 *Predicted average productivity and financial returns obtained by using the current tree distribution as target distribution in the California mixed conifer forest type, over 100 years*

| | | Cutting cycle (years) | |
|---|---|---|---|
| | Unit | 10 | 20 |
| Total Basal area | $m^2\ ha^{-1}y^{-1}$ | 0.60 | 0.53 |
| Total Volume | $m^3\ ha^{-1}y^{-1}$ | 6.00 | 5.57 |
| Softwoods volume | $m^3\ ha^{-1}y^{-1}$ | 5.87 | 5.46 |
| Hardwoods volume | $m^3\ ha^{-1}y^{-1}$ | 0.12 | 0.11 |
| Present value of harvests | $\$\ ha^{-1}$ | 36,647 | 32,030 |
| Value of initial stock | $\$\ ha^{-1}$ | 45,970 | 45,970 |
| Land expectation value | $\$\ ha^{-1}$ | -9,323 | -13,940 |

FIGURE 9 *Expected basal area in softwood and hardwoods in managed mixed conifer stands, for two different cutting cycles. The average tree distribution on the 205 plots is the initial state and also the post-harvest target state*

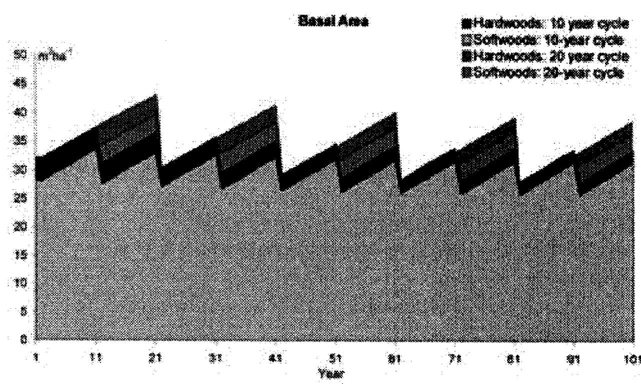
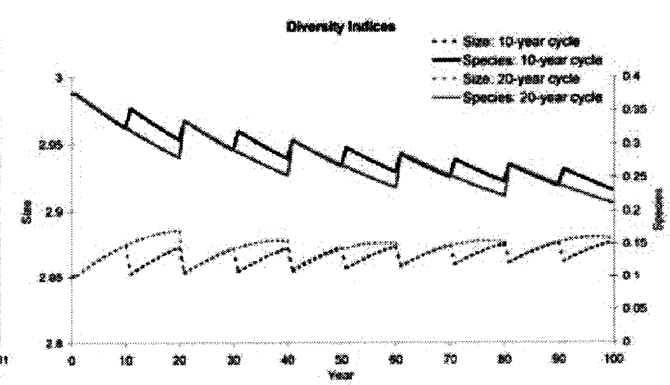



FIGURE 10 *Projected expected diversity of tree size and tree species group in managed mixed conifer stands. The average tree distribution on the 205 plots is the initial state and also the post-harvest target state*



## SUMMARY AND CONCLUSION

A stand growth model was developed for mixed-conifers in California, based on permanent plot data from private lands and unreserved public lands outside of national forests and parks. One advantage of the method was to use the information available by pooling many different plots. Consequently, despite its simple underlying structure, the model was capable of predicting accurately stand growth over a wide geographic area. The underlying diameter growth, mortality, and recruitment equations were consistent with prior knowledge. Predictions of the growth on plots not used for model calibration appeared to be unbiased. The introduction of a recruitment equation allowed for long term predictions of stand development. Predictions exceeding a century were plausible. The long-term stand state did not depend on the initial stand state, but it was sensitive to the data used to estimate the parameters.

The application investigated the effects of cutting back the stand to the current stand state, at intervals of ten or twenty years. The predicted productivity was 5 to 6 $m^3$ $ha^{-1}$ $y^{-1}$ on site 27 m, for a stand of average initial condition. This is similar to the maximum mean annual increment of 5 $m^3$ $ha^{-1}$ $y^{-1}$ of even-aged pure Douglas-fir stands on lands of similar site index (McArdle *et al.* 1961). Thus, the productivity of uneven-aged management may well match that of even-aged systems. Both productivity and financial performance could be improved substantially by choosing less conservative target distributions (Ralston *et al.* 2004).

With the target tree distribution set equal to the current distribution, a twenty-year cutting cycle gave higher productivity and higher tree size diversity than a ten-year cycle, though lower species diversity. The ten-year cutting cycle produced a higher present value of harvests. Further analysis is needed to document the economics of different target distributions coupled with different cutting cycles, and their consequences for stand structure and species composition.

This paper has concentrated on model development and testing. Many more varied applications than the few reported here are possible. Numerous management regimes with various cutting cycles, and target distributions could be studied either by simulation (e.g. Ralston *et al.* 2004), or optimization (e.g. Buongiorno 2001). Though inherently difficult due to non-linearity of the model, optimization is also a potentially fruitful area of future research to determine the ecological and economic consequences of different managements in the mixed conifer forests of California.

## ACKNOWLEDGEMENTS

The research leading to this paper was supported in parts by the USDA Forest Service, Pacific Northwest Forest and Range Experiment Station (Forest Inventory and Analysis, and Human and Natural Resources Interaction programs); NRICGP grant 2001-35108-10673; and by the School of Natural Resources, University of Wisconsin, Madison. We thank Jeremy Fried for his help in obtaining the forest plot data, and for reviewing an earlier draft of this paper. We are also grateful to John Helms and Keith Gilless for reviewing the initial results, and for providing data on old growth mixed conifers.

## REFERENCES

ADAMS, D.M., EK, A.R. 1974. Optimizing the management of uneven-age forest stands. Canadian Journal of Forest Research. 4 274-287.

ALEXANDER, R.R., EDMINSTER, C.B. 1976. Regulation and control under uneven-aged management. USDA For. Serv. Uneven-aged silvilculture and management in the United States. 25 pp.

AMBUEL, B., TEMPLE, S.A.,1983. Area-dependent changes in the bird communities and vegetation of S. Wisconsin forests. Ecology. 64 1057-1068.

BARBOUR, M.G., MAJOR, J., eds 1977. Terrestrial vegetation of California. John Wiley and Sons, New York. 1002 pp.

BIGING, G. S., MEERSCHAERT, W., ROBARDS, T. A., and TURNBLOM, E. C. 1991. The Forest Stand Generator (STAG) User's Guide, Version 4.0. Northern California Forest Yield Cooperative Research Note No. 34. URL: http: //www.cnr.berkeley.edu/~wensel/cactos/stag/stag.htm.

BUONGIORNO, J. 2001. Quantifying the implications of transformation from even to uneven-aged forest stands. For. Ecol. Manage. 151 121-132.

BUONGIORNO, J., MICHIE., B.R. 1980. A matrix model of uneven-aged forest management. For. Sci. 26(4), 609-625.

CALIFORNIA STATE BOARD OF EQUALIZATION 2003. Harvest values schedule, effective July 1,2003 through December 31 2003. California State Board of Equalization, Sacramento, CA. 6 pp.

DRAPER, N.R., HARRY, S. 1998. Applied regression analysis. John Wiley & Sons, Inc. Third Edition. 706 pp.

EWING, R.A., TOSTA, N., TUAZON, R., HUNTSINGER, L., MAROSE, R., NIELSON, K., MOTRONI, R., and TURAN, S. 1988. California's forest and rangelands: growing conflict over changing uses. California Department of Forestry and Fire Protection. 348 pp.

GULDIN, J.M. 1996. The role of uneven-aged silviculture in the context of ecosystem management. Western Journal of Applied Forestry 11(1), 4-12.

HAIGHT, R. G., MONSERUD, R. A. 1990. Optimizing any-aged management of mixed-species stands: II. Effects of decision criteria. Forest Science 36(1) 125-144.

HANSEN, A.J., SPIES, T.A., SWANSON, F.J., OHMANN, J.L. 1991. Conserving biodiversity in managed forests: lessons from natural forests. BioScience 41(6), 382-292.

HANSON, E.J., AZUMA, D.L., HISEROTE, B.A. 2002. Site index equations and mean annual increment equations for Pacific Northwest Research Station Forest Inventory and Analysis 1985-2001. USDA Forest Service, PNW Research Station, Portland. Research note PNW-RN-533. 24 pp.

HISEROTE, B., WADDELL, K. 2003. The PNW-FIA integrated database user guide. A database of forest inventory information for California, Oregon and Washington, V 1.3. FIA PNW Station, Portland, Oregon. 10 pp.

LAWRENCE, J.A. 1997. Opinion in appeal No. 97-05-00-0044- A215. File Code: 1570-1/2430-2. http://www.fs.fed.us/r5/ecoplan/appeals/1997/fy97_0044.htm

LIANG, J., BUONGIORNO, J., MONSERUD, R.A. 2004. CalPro: A spreadsheet program for the management of California mixed conifer stands. USDA Forest Service, PNW Research State, General Technical Report PNW-GTR-619. 32 pp.

LITTLE, E.L. 1979. Checklist of United States trees (native and naturalized). United States Department of Agriculture Handbook 541.Washington, DC. 375 pp.

MAGURRAN, A.E. 1988. Ecological diversity and its measurement. Princeton University Press, Princeton. 179 pp.

MCKELVEY, K.S., JOHNSON, J.D. 1992. Historical perspectives on forests of the Sierra Nevada and the Transverse Ranges of Southern California: Forest Conditions at the Turn of the Century. pp. 225-246 *in* Verner, J., McKelvey, K.S., Noon, B.R., Gutierrez, R.J., Gould, Jr., G.I., and Beck, T.W. Technical coordinators. The California Spotted Owl: A technical assessment of its current status. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-133. 285 pp.

MCARDLE, R.E., MEYER, W.H., BRUCE, D. 1961. The yield of Douglas-fir in the Pacific Northwest. Technical Bulletin No. 201. USDA Forest Service, Washington, D.C. 74 pp.

OLD GROWTH DEFINITION TASK GROUP 1986. Interim definitions for old-growth Douglas-fir and mixed-conifer forests in the Pacific Northwest and California. USDA Forest Service PNW Research Station, Research Note PNW-447. 7 pp.

PNW FIA 2000. California Inventory Data, June 19 2000. CD. USDA Forest Service, PNW Research Station, Portland.

RALSTON, R.E., BUONGIORNO, J., and FRIED, J.S. 2003. Non-linear matrix modeling of forest growth with permanent plot data: The case of uneven-aged Douglas-fir stands. International Transactions in Operations Research. 10, 461-482.

RALSTON, R.E., BUONGIORNO, J., and FRIED, J.S. 2004. Potential yield, return, and tree diversity of managed, uneven-aged Douglas-fir stands. Silva Fennica 38(1) 1-14.

RITCHIE, M. W. 1999. A compendium of forest growth and yield simulators for the Pacific Coast states. Gen. Tech. Rep. PSW-GTR-174. Albany CA: Pacific Southwest Research Station, Forest Service, U. S. Department of Agriculture. 59 pp.

RITCHIE, M. W. 2003. User's Guide and Help System for CONIFERS: A Simulator for Young Mixed-Conifer Stands Version 1.80. USDA Forest Service, Pacific Southwest Research Station. http://www.fs.fed.us/psw. 127 html pp.

RITCHIE, M. W., POWERS, R. F. 1993. User's guide for SYSTUM-1 (Version 2.0): a simulator of growth trends in young stands under management in California and Oregon. Gen. Tech. Rep. PSW-GTR-147. Albany, CA, Pacific Southwest Research Station, Forest Service, U. S. Department of Agriculture. 45 pp.

ROY, D.F., MCDONALD, P.M. 1973. Silvicultural systems for the major forest types of the United States: California mixed conifers. USDA Forest Service, Agriculture Handbook No. 445 28-30.

SARGENT, R.G. 1984. A tutorial on verification and validation of simulation models. Proceedings of the 1984 Winter Simulation Conference. IEEE 84CH2098-2 115-122.

SCHULTE, B.J., and BUONGIORNO, J. 2004. A growth and yield model for naturally-regenerated mixed shortleaf pine forests in the southern United States of America. International Forestry Review 6(1):19-29.

SEIDEL, K.W. 1981. Silviculture of mixed conifer forests in eastern Oregon and Washington. Gen. Tech. Rep. PNW-121. 70 pp.

TECK, R., MOEUR, M., ADAMS, J., eds, 1997. Proceedings: Forest Vegetation Simulator Conference. General Technical Report INT-GTR-373, USDA Forest Service Intermountain Research Station. 222 pp.

U.S. DEPARTMENT OF COMMERCE 2001. Regional Economic Information System Database. U.S. Department of Commerce, Washington, DC.

WENSEL, L.C., BIGING, G.S. 1987. The CACTOS system for individual-tree growth simulation in the mixed conifer forests of California. In: Ek, A.R.; Shifley, S.R.; Burk, T.E. (eds) Forest Growth Modeling and Prediction. IUFRO conference, Minneapolis, MI, V. 1 175-183.

WOOLDRIDGE, J.M. 2000. Introductory econometrics: A modern approach. South-Western College, Cincinnati. 824 pp.

WYKOFF, W.R., CROOKSTON, N.L., and STAGE, A. R., 1982. User's guide to the stand prognosis model. GTR-INT-133. Ogden, UT: Intermountain For. Range Exp. Sta, Forest Service, U.S. Department of Agriculture. 113 pp.