Growth of Blue Oak on California's Hardwood Rangelands[1]

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***Abstract**. An individual tree basal area increment model was developed for blue oak (*Quercus douglasii *Hook. & Arn.) in California, an important woodland tree for wildlife habitat. Box-Cox regression based on 895 increment cores that showed current basal area and the relative size of the tree crown were significant variables. Models to link basal area changes over time with tree height and crown cover were developed to provide initial estimates of stand structure dynamics. Relative tree crown characteristics, site index, and diameter at breast height (DBH) were significant variables in predicting tree height. Individual tree basal area, basal area competition in trees larger than the subject tree, and tree height were significant in predicting crown cover. Use of these models for assessing projected changes in stand structure under different levels of management is demonstrated.*

Blue oak (*Quercus douglasii* Hook. & Arn.) is a widely distributed tree species on California rangelands, occurring in more or less pure woodland or savanna stands on 1.2 million ha of California's 3.0 million ha of hardwood rangelands, and in mixed stands on another 360,000 hectares (Bolsinger 1988). Blue oak woodlands have an understory of annual grasses and occasional native perennial grasses, and are found in association with foothill pine (*Pinus sabiniana* Dougl.), coast live oak (*Quercus agrifolia* Nee), and interior live oak (*Quercus wislizenii* A. DC.). Good ecological descriptions of these areas are found in Bartolome (1987), Griffin (1977), and Holmes (1990). Livestock grazing is the predominant land use on these areas, 75 percent of which are privately owned (Bolsinger 1988).

Historically, little attention was given to tree growth on blue oak woodlands because they are classed as "noncommercial" by USDA Forest Service standards (average annual growth less than 1.4 cubic m per ha per year), they have little commercial use other than for firewood, and they inhibit forage production for livestock on some areas. In recent years, however, it has been recognized that blue oak rangelands are a rich source of biological diversity. The valley-foothill hardwood and valley-foothill hardwood conifer habitat types, of which blue oak woodlands are a principal component (Mayer and Laudenslayer 1988), have 278 vertebrate species of wildlife, which rely on these lands for at least part of their habitat needs (Airola 1988). Watershed protection and esthetics are other important public values supplied by blue oak woodlands. Concern about long-term sustainability of blue oak woodlands has been expressed by policy makers, resource mangers, and the general public because regeneration failure has been documented in some areas (Bolsinger 1988, Muick and Bartolome 1987, Standiford and others 1991).

To evaluate blue oak woodland environmental values, managers need to be able to assess changes in tree cover and stand structure over time. Blue oak stand structure is closely correlated with the quality of wildlife habitat (Block and Morrison 1991, Wilson and others 1991). To date, the only information on growth and yield available for assessing blue oak stand dynamics is a whole stand model of volume, basal area, and crown cover developed for use in economic optimization of multiple resource management on blue oak woodlands (Standiford and Howitt 1993). However, this is not adequate for assessing stand structure changes over time and their effects on habitat values. The objective of this study is to develop preliminary individual blue oak tree models to allow managers to assess stand structure changes over time.

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Individual Tree Growth Models

Individual tree growth models have become increasingly important for natural resource management decision making (Holdaway 1984, Wensel and others 1987, Wycoff and others 1982). Individual tree growth is affected by tree size (height, diameter), crown characteristics (live crown ratio, crown diameter), site factors (site index, soils, habitat type), and competition with adjacent trees.

Tree competition has been modelled in a variety of ways. Crown competition factor (Krajicek and others 1961), individual tree crown radius (Curtis 1970) and the relative proportion of total crown closure at 66 percent of a tree's total height (Wensel and others 1987) are examples of crown factors used to model competition in different growth studies. A percentile distribution of basal area (Stage 1973) and the summation of basal area per hectare in larger trees, known as BAL (Wycoff 1990), are examples of basal area factors used to model competitive effects of adjacent trees.

Many blue oak stands are fairly open with varying crown diameters. The size of individual crowns or basal area in relationship to other trees in the stand are expected to closely follow the competitive impacts interacting with the tree. Open grown or widely spaced trees and trees with large crowns would be expected to have higher diameter and volume growth than closely spaced trees or trees with narrow crowns.

Methods

Seven representative study locations were selected covering a wide geographic range throughout the extent of the hardwood range area of the state. One location was at the northern end of the Sacramento Valley, two locations were in the Sierra Nevada foothills, three locations were in the Coastal Range, and one location was at the extreme southern end of the San Joaquin Valley. At each study location, 3 to 22 0.04-ha plots were randomly chosen in stands of pure blue oak, mixed blue oak and interior live oak, and mixed blue oak and coast live oak. These study locations covered a broad range of stand density, species composition, and site quality. Study sites were confined to areas that had at least 50 percent blue oak basal area. Sixty-six of the 81 study plots were pure blue oak stands.

Individual tree data collected at each plot included diameter at breast height (1.4 meters), total tree height, tree crown diameter, and 5- and 10-year radial growth. Blue oaks represented 895 of the 972 individual trees measured in this study. The sample size for non-blue oak trees was too small to be included in the analysis.

The following was calculated for each of the 81 sample plots from the individual tree data: stand volume in m^3/ha using merchantable firewood volume equations (Pillsbury and Kirkley 1984, stand basal area in m^2/ha, stand crown cover percent, site index (Standiford and Howitt 1988), and periodic annual volume and basal area growth over the previous 5- and 10-year periods.

Competition was evaluated by comparing two different indices. The basal area per ha in larger trees, BAL (Wycoff 1990), was used. It was hypothesized that as BAL increases, representing more competition from other trees in the stand, growth rate would decrease.

Another competition factor evaluated was a modification of CC_{66} (Wensel and others 1987). Instead of calculating relative crown area at 66 percent of a tree's height, relative crown area was calculated at the base of each tree by dividing projected crown area of a tree by total crown area per hectare of all trees. The formula used to calculate this crown index, RELCROWN, is shown in equation (1).

$$\text{RELCROWN}_j = \frac{CA_j}{\sum_{i=1}^{n} CA_i}$$

where: RELCROWN_j = relative crown index for tree j
CA_i = Projected crown area for tree i
CA_j = Projected crown area for tree j
n = total number of trees/ha

The size of an individual tree crown in relationship to other trees in the stand would closely follow the competitive impacts on the tree. As RELCROWN increases, a tree has more dominance in a stand, and would be expected to grow more rapidly than a tree with a smaller RELCROWN.

Since this is the first widespread growth study of individual oak tree growth on hardwood rangelands, data on height and crown growth from costly stem analysis or long-term permanent growth plots were not available. The main growth parameter which could be evaluated in this study was periodic basal area increment, determined for each tree by subtracting tree basal area 10 years ago determined from increment cores, from the current tree basal area.

The functional form of basal area increment was not known. Studies of production functions often evaluate several forms, ranging from a Cobb-Douglas logarithmic form to a linear form. Rather than imposing one of these two forms, it was decided instead to let the data itself determine the form of the basal area increment production function by using the Box-Cox transformation (Zarembka 1974). The form of the Box-Cox transformation, (λ), is shown in equations (2) through (4) below.

$$y^{(\lambda)} = \frac{y^{\lambda} - 1}{\lambda} \quad \text{for: } \lambda \neq 0 \tag{2}$$

$$= \ln(y) \quad \text{for: } \lambda = 0$$

$$y^{(\lambda)} = a_0 + a_1 x^{(\lambda)} + a_2 x_2^{(\lambda)} + \ldots + a_n x_n^{(\lambda)} + \varepsilon \tag{3}$$

$$\frac{y^{\lambda} - 1}{\lambda} = a_0 + a_1 \frac{x_1 \lambda - 1}{\lambda} + a_2 \frac{x_2 \lambda - 1}{\lambda} + \ldots + a_n \frac{x_n \lambda - 1}{\lambda} + \varepsilon \tag{4}$$

Both the dependent variable, y, and the independent variables, x_i, are transformed with the lambda relationship shown in equation (4). The Box-Cox process solves for the coefficients, a_i, as well as for λ using a maximum likelihood process. Noncollinearity of the independent variables, additivity of the error term with a zero mean and constant variance, and symmetry of the residuals are required for unbiased estimates of the coefficients (Zarembka 1974). If λ equals zero, the relationship is a Cobb-Douglas production model. If λ equals one, the relationship is linear.

Results

The Box-Cox transformation was used to evaluate the effect of tree size, competition, and site on basal area increment. Tree size was represented by tree basal area at the beginning of the growth period. Both BAL and RELCROWN competition indices were evaluated; however, only RELCROWN was significant at the 0.10 level in the Box-Cox analysis. Site index was not a significant variable at the 0.10 level when tree size and competition factors were included. The low correlation of site with individual tree growth (R = 0.011) was surprising, given the high correlation of site index with whole stand growth (Standiford and Howitt 1988).

The basal area increment model for blue oak is shown in equation (5). Basal area increment is for growth inside bark. All variables are significant at the 0.01 level.

$$BAINC_i^{(\lambda)} = a_0 + a_1 BA_i^{(\lambda)} + a_2 RELCROWN_i^{(\lambda)} \qquad R^2 = 0.64 \tag{5}$$

where:

$BAINC_i$ = 10-year basal area periodic increment for tree i (square meters)

BA_i = Current basal area of tree i in m^2

$RELCROWN_i$ = Relative crown cover of tree i expressed as decimal

$\lambda = 0.11$

$a_0 = -2.9011$

$a_1 = 0.3963$

$a_2 = 0.0413$

$^{(\lambda)}$ = Box-Cox transformation (see equation (2) above)

Homoskedasticity was demonstrated across the range of independent variables using the Glejser (1969) test. Multi-collinearity was evaluated by inspection of the correlation matrix of independent variables. Since the correlation coefficient between BA and RELCROWN was less than 0.6, multi-collinearity was rejected. The mean of error term was equal to zero, and skewness of the residuals was not significantly different than zero, showing the required symmetry for unbiased estimates.

Equation (5) can be converted to (6) to directly calculate 10-year blue oak basal area increment.

$$BAINC = [\lambda(a_0 + a_1 \frac{BA^{\lambda} - 1}{\lambda} + a_2 \frac{RELCROWN^{\lambda} - 1}{\lambda}) + 1]^{1/\lambda} \tag{6}$$

Height growth was not evaluated directly in this initial study of dynamics. Height growth will be estimated by using the correlation between tree height and diameter for dominant trees from the site index relationship (Standiford and Howitt 1988). As diameter increases as determined by equation (6), height changes can also be estimated as a first approximation until permanent height growth data can be collected and analyzed.

Equation (7) shows the form of the height-diameter site index equations for dominant trees developed for hardwood rangelands (Standiford and Howitt 1988).

$$\ln(SITE) = [\ln(HT_{dom}) - .3103] + 7.882 \times \frac{1}{DBH_{dom}} \tag{7}$$

where:

HT_{dom} = total tree height in meters for dominant trees in stand

SITE = site index

DBH_{dom} = diameter at breast height (1.4 m) in centimeters for dominant trees

If site index and DBH are known, the height for dominant trees in a stand can be determined by rearranging the equation to give equation (8).

$$HT_{dom} = e^{(\ln(SITE) - 7.882 * (1/DBH_{dom}) + .3103)} \tag{8}$$

It is assumed that the height-dbh relationship for trees in lower crown classes is modified by competition level. The competition index used in (6), RELCROWN, together with (8) was used in a Box-Cox transformation to predict height for any tree in the stand, however skewness of the residuals showed that the assumption for unbiased coefficients was violated. Nonlinear regression was used to develop a height prediction relationship by assuming a logistic crown competition relationship multiplied by the transformed site index equation (8) to give:

$$HT = \frac{1}{1+e^{(a_1 RELCROWN)}}[e^{(\ln(SITE)-7.882*(1/DBH)+.3103)}] \quad (9)$$

The initial nonlinear regression was run to solve for a_1. Given this starting value and the values of the site index relationship, the entire height-diameter equation was solved for a_1, a_2, and a_3 using nonlinear regression for equation (10). All regression coefficients were significant at the 0.01 level.

$$HT = \frac{1}{1+e^{(a_1 RELCROWN)}}[e^{(\ln(SITE)+a_2*(1/DBH)+a_3)}] \quad (10)$$

where:

a_1 = -0.8177

a_2 = -10.396

a_3 = 0.7566

Changes in canopy cover over time are also of interest to hardwood rangeland managers. Just as with height growth above, this initial study of blue oak dynamics did not have permanent growth plot or stem analysis data on changes in individual crown cover available. Changes in crown characteristics were assumed to be correlated with basal area increment. Individual tree crown cover in square meters was evaluated as a function of tree size, site and competition. The results of the Box-Cox regression are shown in equation (11). Both tree height and basal area were significant at the 0.01 level. The competition index, BAL, was also significant at the 0.01 level. There was no evidence of collinearity, since the correlation coefficient between the three independent variables was less than 0.45. Conditions of symmetry were met, as skewness was not significantly different than zero. The Glejser (1969) test revealed uniform variability across the range of independent variables in the study.

$$CROWNCOV_i^{(\lambda)} = a_0 + a_1 BA_i^{(\lambda)} + a_2 BAL_i^{(\lambda)} + a_3 HT_i^{(\lambda)} \quad R^2 = 0.60 \quad (11)$$

where:

$CROWNCOV_i$ = Crown cover of tree i (m^2)

BA_i = Current basal area of tree i in m^2

BAL_i = Square meters of basal area per ha in trees larger than tree i

HT_i = Current total height of tree i in m

λ = 0.20

a_0 = 10.096

a_1 = 2.7036

a_2 = -0.0733

a_3 = 0.1581

Discussion

Given initial values for dbh, height, and crown cover for individual blue oak trees in a stand and the relationships for basal area increment (6), tree height-diameter correlation (10), and crown cover (11), projections of stand structure changes can be made. As 10-year basal area increment is estimated, height, crown, and dbh for each individual tree is updated using these relationships.

As an example of the use of this system of equations in modelling stand structure dynamics, a blue oak woodland in California's central coast with 988 stems per ha, site 12, and a 53 percent crown cover was evaluated over a 30-year period. Actual individual tree data collected from 0.04-ha plots in this stand were evaluated. Projections of stand changes over time are shown in *table 1*, assuming no mortality or regeneration. Crown cover is expected to increase from 53 to 81 percent over the 30-year simulation period, and basal area is expected to increase from 9.3 to 15.5 m^2/ha.

Table 1—Projected changes in stand characteristics for a blue oak woodland, site 12

Time	Average DBH	Basal area per ha	Volume per ha	Crown cover
yr from present	*cm*	*sq m*	*cubic m*	*pct*
0	10.9	9.3	30.6	53
10	11.9	11.2	37.1	62
20	13.0	13.3	45.1	71
30	14.2	15.5	54.5	81

A key advantage of an individual tree model is to evaluate how diameter distribution by size class changes over time. *Figure 1* shows the diameter distribution of the 988 trees per hectare over a 30-year simulation period. These changes in diameter distribution can be related to habitat suitability over time.

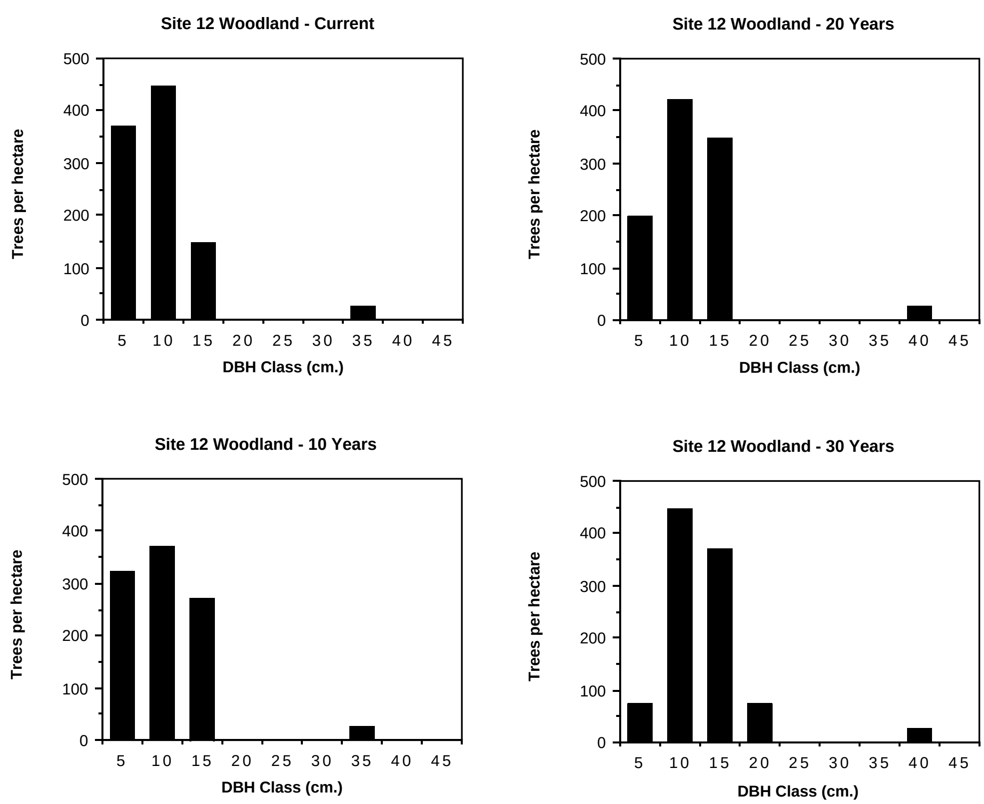

Figure 1—Example of 30-year changes in diameter distribution for a pure blue oak woodland with 988 stems per ha, site index 12, and 53 percent crown cover.

Another important structural feature that can be evaluated is oak tree cover. For a blue oak woodland in the central Sierra Nevada on site 9, with 200 stems per ha and a basal area of 7.8 m^2/ha, current oak canopy cover is 36 percent. *Figure 2* shows how the canopy of eight trees in a 0.04-ha sample plot increases over a 30-year simulation period to 45 percent cover.

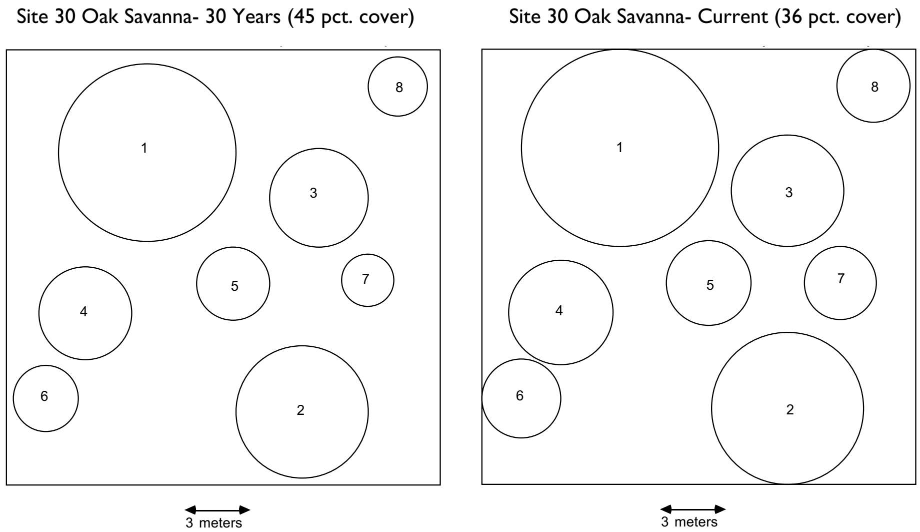

Figure 2—Example of 30-year changes in crown cover in a pure blue oak woodland with 200 stems per hectare, site index 9, and 36 percent crown cover.

Conclusion

This study provided the first individual tree model for blue oaks on hardwood rangelands in California. This modelling effort is based upon basal area increment and its correlations with crown and height over time. Future work will be needed to establish permanent plots to collect data needed to develop specific height and crown growth functions.

It was somewhat surprising that the site index relationship used for whole stand models was poorly correlated with individual tree growth. Future work will be needed to determine which site factors influence individual tree growth to refine the relationships developed in this preliminary study.

A long-term sustainability evaluation of blue oak stands requires good estimates of mortality and regeneration, in addition to site-specific growth relationships. Mortality functions can be derived from permanent growth plots. Preliminary relationships for natural oak regeneration probability have been developed (Standiford and others 1991).

This study concentrated on growth relationships for blue oak, one of the most important hardwood rangeland species in the state. Future work will be needed to develop more complete information on associated species.

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