Prediction of Growth and Mortality of Oregon White Oak in the Pacific Northwest

Peter J. Gould, David D. Marshall, and Constance A. Harrington

ABSTRACT

We developed new equations to predict Oregon white oak (*Quercus garryana* Dougl. ex Hook.) development within ORGANON, a stand-development model that is widely used in the Pacific Northwest. Tree size, competitive status, crown ratio, and site productivity were statistically significant predictors of growth and mortality. Three scenarios were projected with the new equations, the previous ORGANON model, and the Forest Vegetation Simulator. Compared with the two other models, the new equations predicted greater diameter growth in oak woodland and a greater effect of conifer removal in a conifer-oak stand. The new equations, which are based on considerably more information than previous equations, should give forest managers greater confidence in the ability of ORGANON to estimate the impacts of silvicultural treatments on oaks.

Keywords: *Quercus garryana*, Garry oak, ORGANON, modeling, Washington, Oregon

Oregon white oak (*Quercus garryana* Dougl. ex Hook.; also known as Garry oak) is an important tree species in the Pacific Northwest, both for its contribution to the region's biodiversity and for its importance in culturally significant landscapes. Oregon white oak woodlands, savannas, and associated prairies host a range of species that are uncommon in the region's forests, which are mostly dominated by conifers (Chappell and Crawford 1997, Thysell and Carey 2001, Wilson and Carey 2001). In much of its historic range, Oregon white oak was maintained at low densities through frequent burning by Native Americans (Thilenius 1968). Most of these areas have been converted to other land uses through urban and agricultural development and much of what remains has been impacted by the encroachment of native conifers and the establishment of exotic herbaceous and shrub species (Crawford and Hall 1997, Thysell and Carey 2001). Active management is necessary in many cases to maintain the open character of oak stands or to restore those that have been invaded by conifers (Foster and Shaff 2003).

Forest growth models are typically used to evaluate the effects of silvicultural treatments on forest productivity and development. They are often also the best tools available for evaluating restoration alternatives and successional trends. Currently, there are two models that include Oregon white oak: ORGANON (Hann 2005) and the Forest Vegetation Simulator (FVS) (Donnelly and Johnson 1997). Oregon white oak is not a primary species in either model and only a small number of observations of Oregon white oak were used to develop the oak equations for these models: 12 trees for FVS and 37 trees for ORGANON (Donnelly and Johnson 1997, Hann and Hanus 2002). There is a need for more accurate predictions of the growth and survival of Oregon white oak across a range of stand conditions to help guide conservation efforts.

In this article, we describe new diameter growth and mortality equations for Oregon white oak that were incorporated recently into ORGANON (download at www.cof.orst.edu/cof/fr/research/organon/downld.htm). Equations also were developed to predict total tree height (Ht; as a function of diameter), and height to live crown. We chose to develop new equations because the equations in the previous ORGANON model were based on very few observations and initial analyses of diameter growth data from Oregon and Washington indicated that they consistently underpredicted diameter growth. The new equations, which are based on a much larger data set, should improve estimates of Oregon white oak development across a range of stand conditions. In addition, the equations should provide greater insight into how factors such as initial diameter, site index (SI), crown ratio (CR), and stand basal area (BA) affect oak growth and mortality. The long-term development of oak woodland and a conifer-oak stand (with and without conifer removal to restore it to a low-density oak stand) were projected to illustrate two common conditions. Projections also were performed using the previous ORGANON model and FVS to compare the results of these models with those obtained with the new equations.

Methods

Data Collection

Data from five sources were used to fit the four equations (Table 1). Data were collected in most of the counties where Oregon white oak occurs in Oregon and from two counties in Washington (Figure 1). Oaks in the USDA Forest Service Forest Inventory and Analysis (FIA), Oregon State University McDonald-Dunn Forest, and Release (experimental plots at Fort Lewis, Washington) data sets were on permanent plots that were measured on two occasions. The period between measurements ranged from 4 to 14 years (mean, 8.5 years) for the diameter growth model and 3 to 20 years (mean, 9.5

Received September 21, 2006; accepted December 21, 2006.

Peter J. Gould (pgould@fs.fed.us), David D. Marshall, and Constance A. Harrington, US Forest Service, Pacific Northwest Research Station, 3625 93rd Avenue SW, Olympia, WA 98512-9193. *The authors thank Tara Barrett with the US Forest Service, Pacific Northwest Forest Inventory and Analysis, for providing FIA data for western Oregon and Debra Johnson for providing inventory data from Oregon State University's McDonald-Dunn Forest. The authors also are grateful to David Hann for providing data and for incorporating the new equations into ORGANON.*

Table 1. Number of observations by data set and sources used to develop diameter growth, mortality, height-to-crown base, and Ht equations for Oregon white oak.

		Number of observations per equation			
Data set	Source	Diameter growth	Mortality	Ht to CB	Ht
FIA	Forest Service FIA for western Oregon	221	238	NA	323
SWO	OSU, SWO, original ORGANON data set	37	NA	53	53
Open	OFSL, southwest Washington	40	NA	40	40
OSU	OSU, western Oregon, McDonald-Dunn Forest	242	518	455	583
Release	OFSL, southwest Washington	125	287	209	300
Total		665	1,043	757	1,299

NA, not applicable; OFSL, Olympia Forestry Sciences Laboratory, US Forest Service, Pacific Northwest Research Station; OSU, Oregon State University.

Figure 1. The geographic distribution of Oregon white oak (shaded; Little [1971]) and the counties where the modeling data were collected (outlines).

years) for the mortality model. Different numbers of observations were used to fit the equations because of missing or inconsistent data and variable period lengths (e.g., observations were not used to fit the diameter growth equation when they indicated negative growth of more than 0.05 in.). Repeat-measurement data were not used to fit the static Ht and height-to-crown base models. Increment cores were extracted from trees in southwest Oregon (SWO) and open (open-grown trees in southwest Washington) data sets and 5-year diameter increments were reconstructed. Competitor tree attributes were backdated for the SWO data set to the beginning of the growth period (Hann and Hanus 2002). Open-grown oaks were measured for the open data set; therefore, no data were collected on competitors. On plots where competitors were measured, Douglas-fir made up about 48% of BA (range, 0–99) and Oregon white oak made up about 42% (range, less than 1–100).

The tree-level variables used for modeling were dbh, total Ht, and live CR (Table 2). Stand-level variables that relate to stand density and the target tree's competitive status were stand BA, stand BA in trees larger than the target tree diameter (BAL), and crown competition factor in trees larger than the target tree diameter (CCFL). All variables were measured at the start of the growth period. CCFL is calculated in ORGANON as a function of the maximum expected crown areas of trees larger than the target tree (Krajicek et al. 1961) using the maximum crown-width equations of Paine and Hann (1982). Douglas-fir SI (base age, 50 years) was estimated from site trees for stands in Oregon (King 1966). SI estimates published in county soil surveys were used for stands in Washington (Natural Resources Conservation Service 2002). Douglas-fir SI may not be the optimal measure of site productivity for Oregon white oak; however, it is used in ORGANON to project the growth of all species.

Data Analysis

The new equations, with the exception of the mortality equation, were fit using the same equation forms (with new coefficient estimates), weights, and modeling approach used for the previous equations in ORGANON (Hanus et al. 1999, 2000, Hann and Hanus 2002). Indicator variables were used to account for differences in SI

Table 2. Means (minimum–maximum) for the independent variables used to develop diameter growth, mortality, height-to-crown base, and Ht equations for Oregon white oak.

	Equation			
Variable[a]	Diameter growth	Mortality	Ht to CB	Ht
BA (ft^2/ac)	126.0 (0–300)	—	122.7 (0–324)	—
BAL (ft^2/ac)	81.8 (0—281)	100.0 (0–282)	—	—
CCFL (%)	—	—	92.0 (0–313)	—
CR	0.45 (0.05–1.00)	0.41 (0.05–1.00)	—	—
dbh (in.)	12.4 (2.0–58.7)	12.0 (0.8–58.7)	13.2 (0.2–58.7)	12.8 (0.2–58.7)
Ht (ft)	—	—	52.5 (5.5–115.0)	—
SI_{50} (ft)	109.6 (55–140)	112.6 (58–140)	114.2 (55–140)	—

[a] See text for descriptions of variables.

Table 3. Coefficient estimates (with standard errors) for diameter growth, mortality, height-to-crown base, and total height equations for Oregon white oak.

	Equation			
Coefficient	Diameter growth	Mortality	Ht to CB	Ht
a_0	−7.81267986	−6.00031085	1.05786632	4.69753118
	(1.95997531)	(0.24901452)	(0.11266406)	(0.12760012)
a_1	14.05616529	−0.10490823	0	−3.51586969
	(3.32521396)	(0.00527257)		(0.15706069)
a_2	−6.03105850	−0.99541909	−0.00183283	−0.57665068
	(1.67827638)	(0.10161383)	(0.00047958)	(0.07409663)
a_3	0.64286007	0.00912739	−0.28644547	—
	(0.15341591)	(0.00136382)	(0.02862691)	
a_4	10.37687142	0.87115652	0	—
	(3.71925599)	(0.04101712)		
a_5	0	—	0	—
a_6	−7.87012218	—	—	—
	(1.94517583)			

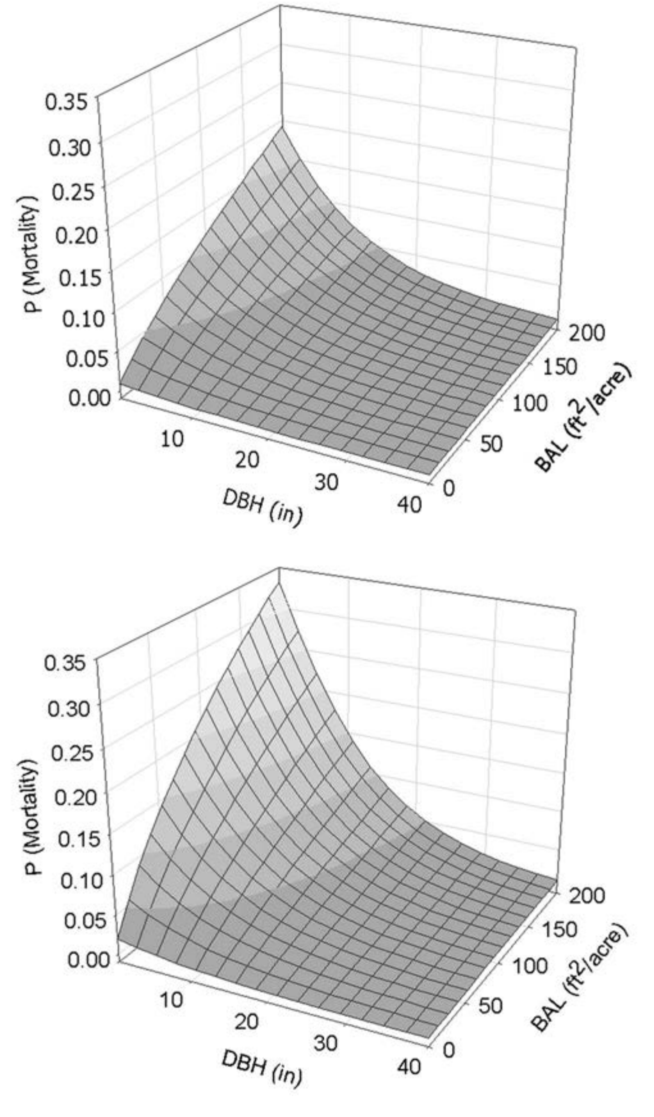

Figure 2. Three-dimensional plots of the mortality equation when SI is 100 ft and CR is 1.00 (top) and 0.25 (bottom). The *y*-axes show the 5-year probability of mortality for individual oaks. The *x*-axes are dbh and BA in trees with greater diameters than the target tree (BAL).

definitions, CR measurements, and plot types in some of the data sets (Hann et al. 2006). Indicator variables isolate the potential effects of different measurement techniques by estimating a separate addition to a model coefficient that reflects the difference between a given data set and the rest of the data used to fit the model. The indicator variables are subsequently dropped from the coefficient estimates. The SAS statistical software (PROC NLIN) was used to fit the coefficients using the GAUSS optimization option (SAS Institute, Cary, NC).

The equations[1] are

$$\begin{aligned}\text{diameter growth (in.)} &= \exp[a_0 + a_1 \cdot \ln(\text{dbh} + 5)/10 + a_2 \cdot \text{dbh}/100 \\ &\quad + a_3 \cdot \ln((\text{CR} + 0.2)/1.2) + a_4 \cdot \ln(\text{SI} - 4.5)/10 \\ &\quad + a_5 \cdot \text{BAL}/(1{,}000 \cdot \ln(\text{dbh} + 2.7)) + a_6 \cdot \text{BA}^{0.5}/100]\end{aligned}$$

$$\begin{aligned}\text{height to crown base (ft)} &= \text{Ht}/\{1 + \exp[a_0 + a_1 \cdot \text{Ht} + a_2 \cdot \text{CCFL} \\ &\quad + a_3 \cdot \ln(\text{BA}) + a_4 \cdot \ln(\text{dbh}/\text{Ht}) + a_5(\text{SI} - 4.5)]\}\end{aligned}$$

$$\text{total height (ft)} = 4.5 + \exp(a_0 + a_1 \cdot \text{dbh}^{a_2})$$

The previous ORGANON mortality equation was modified by replacing the BAL term with natural log (BAL + 5.0) and dropping the dbh^2 term to improve model behavior. The modified equation is

$$\begin{aligned}\text{mortality (trees/ac)} &= \text{EXPFAC} \cdot \{1 - 1/[1 + \exp(a_0 + a_1 \cdot \text{dbh} + a_2 \cdot \text{CR} + a_3 \cdot \text{SI} \\ &\quad + a_4 \cdot \ln(5.0 + \text{BAL}))]\}\end{aligned}$$

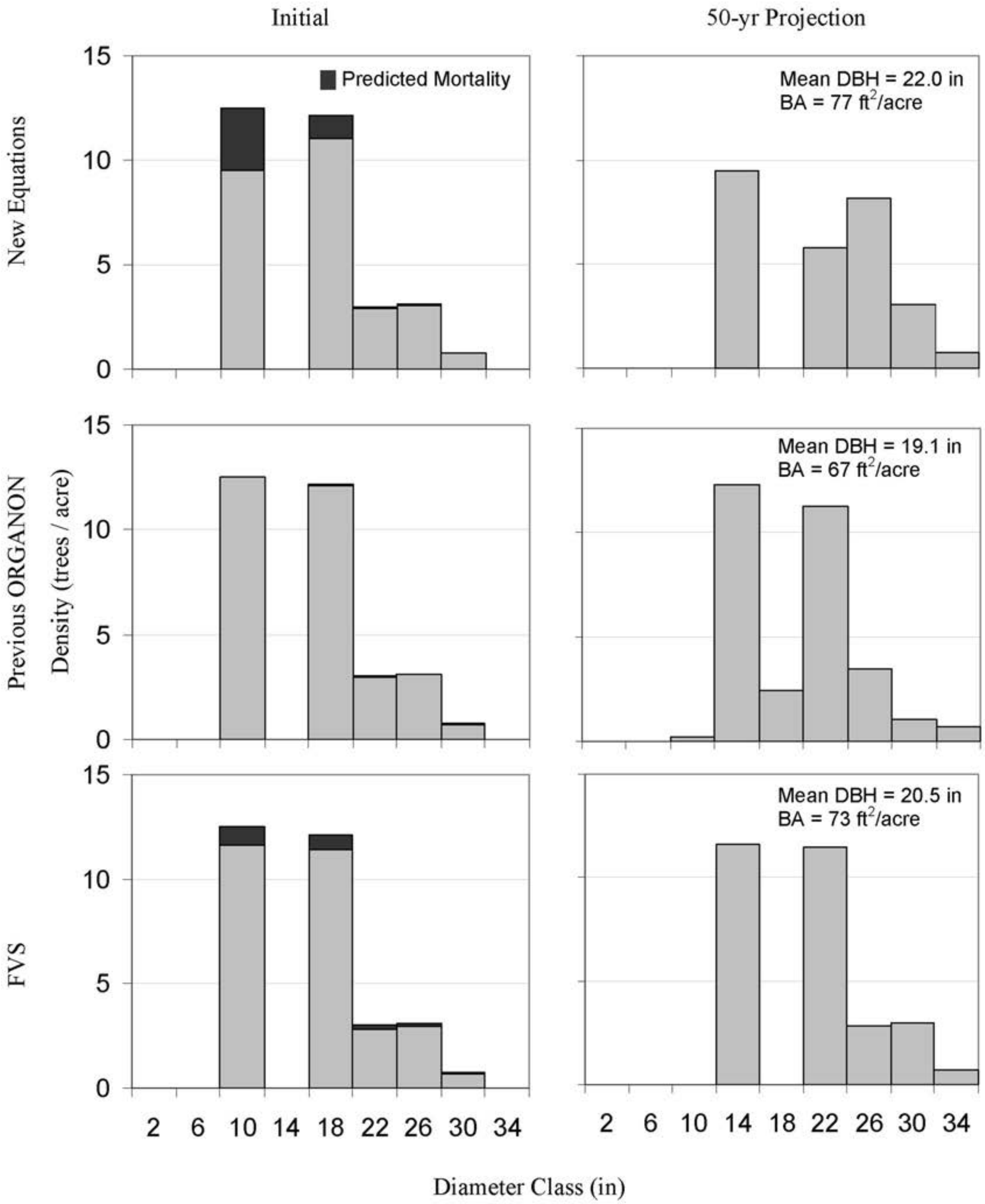

Figure 3. Initial (left) and projected diameter distributions (right) for Oregon white oak in stand 1 estimated with the new equations (top), the previous ORGANON model (middle), and FVS (bottom). Black bars in the initial diameter distributions indicate oaks that were projected to die during the 50-year period.

where EXPFAC is the expansion factor—the trees per acre that a sampled oak represents because of the sampling approach used in data collection (e.g., from fixed-area or variable-radius plots).

The new equations were incorporated into ORGANON and the development of two stands located at Fort Lewis in southwestern Washington was projected using the new version of ORGANON, the previous version of ORGANON, and the Westside Cascades variant of FVS. Some of the data used to refit the equations were collected in nearby stands but not in the projected stands. Stand 1 was an open oak woodland where conifer encroachment had been prevented (31 trees/ac, 51 ft^2/ac of BA, mean CR of 0.80, and mean diameter of 16.3 in.). Stand 2 was a conifer-oak stand that had a total BA of 242 ft^2/ac (201 ft^2/ac of Douglas-fir). The BA, density, mean CR, and mean diameter of Oregon white oak were 36 ft^2/ac, 45 trees/ac, and 0.25 and 11.5 in., respectively. Douglas-fir 50-year SI was 110 ft in both stands (King 1966). Projections for the conifer-oak stand were run without any management and with the removal of Douglas-fir (conifer removal) at the beginning of the projection period to restore the low stand density that was characteristic of oak stands in this area.

Results

Nearly all the coefficient estimates for the equations were significantly different from zero (Table 3). The BA term in the diameter growth equation (a_5) was not significant when it was estimated in an equation containing BAL, but it was significant when the BAL term

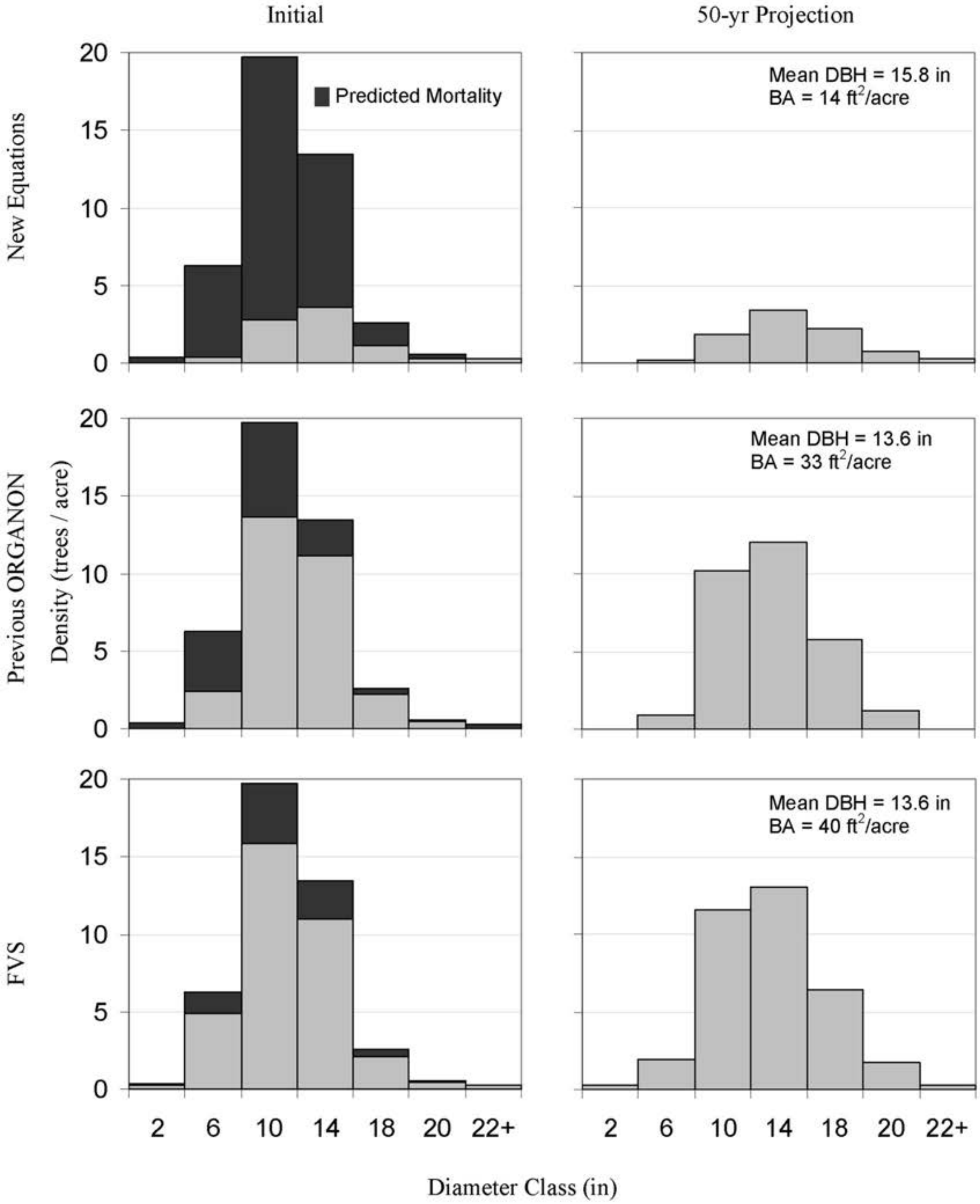

Figure 4. Initial (left) and projected diameter distributions (right) for Oregon white oak without conifer removal in stand 2 estimated using the new equations (top), the previous ORGANON model (middle), and FVS (bottom). Black bars in the initial diameter distributions indicate oaks that were projected to die during the 50-year period.

was dropped. The BAL term was dropped in favor of the BA term in the final equation based on a comparison of residuals between models containing either a BAL or BA term. Three terms that were not statistically significant were dropped from the height-to-crown base equation before the final equation was fit. In the diameter growth equation, CR and SI have a positive relationship with predicted growth, BA has a negative relationship, and dbh has a curvilinear relationship with the maximum predicted growth at 18.3 in. The maximum predicted diameter growth of an open-grown oak (SI, 100) is 1.27 in./5years under the new equation, which is much greater than the maximum predicted growth under the previous ORGANON model (0.43 in./5 years; Hann and Hanus 2002).

Expected mortality is particularly important to forest managers when evaluating management alternatives. Tree size (dbh) and competitive status (BAL) strongly influence the predicted 5-year probability of mortality (Figure 2). Small oaks growing in stands with larger trees have a high probability of mortality. For example, the 5-year probability of mortality for a 5-in. oak is less than 0.01 when it is growing in the open (BAL, 0; CR, 1.00; and SI, 100), but the probability of mortality increases to 0.10 when BAL is 150 ft^2/ac. Mortality also increases with decreasing CR. When BAL is 150 ft^2/ac and CR is 0.25, the 5-year probability of mortality for a 5-in. oak increases to 0.19. In addition, the probability of mortality increases with increasing SI (not shown). The probability of mortality

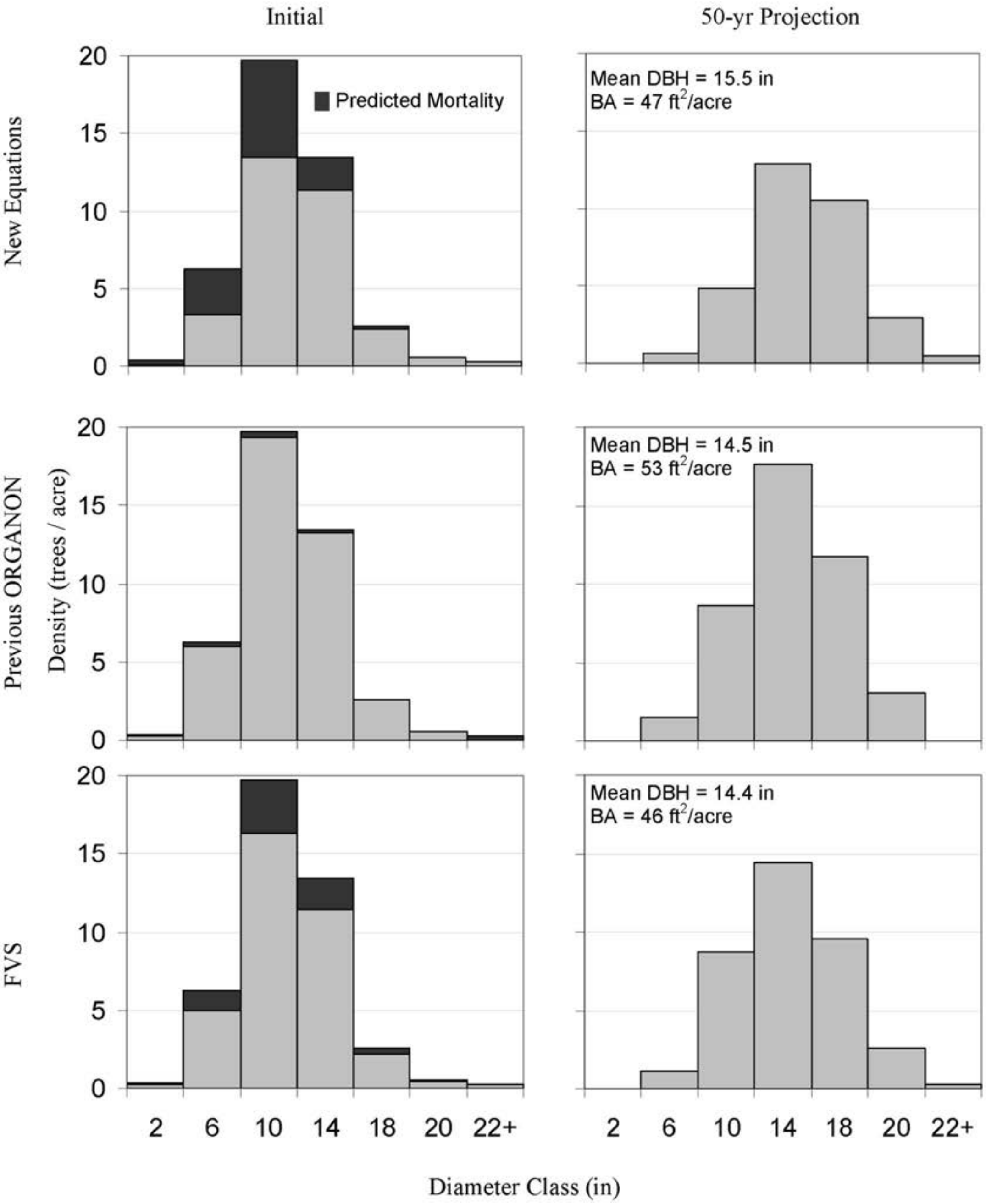

Figure 5. Initial (left) and projected diameter distributions (right) for Oregon white oak after conifer removal in stand 2 estimated using the new equations (top), the previous ORGANON model (middle), and FVS (bottom). Black bars in the initial diameter distributions indicate oaks that were projected to die during the 50-year period.

for larger oaks generally is low. For a 20-in. oak, the 5-year probability of mortality is 0.02 when BAL is 150 ft^2/ac and CR is1.00. Reducing the CR to 0.25 increases the 5-year probability of mortality to 0.05.

In stand 1, the new version of ORGANON predicted greater mortality, greater diameter growth of surviving trees, and greater BA growth over the 50-year projection period than the previous ORGANON model and FVS (Figure 3). About 13% of oaks were expected to die, mostly from the smallest diameter classes. Predicted mortality was lower in FVS (6%) and nearly zero in the previous ORGANON model. The predicted mean diameter growth of oaks that survived the 50-year projection period was 6.5 in. for the new version of ORGANON, 4.2 in. for FVS, and 2.8 in. for the previous ORGANON model. The new version of ORGANON predicted oak BA would increase by 70%, and the previous ORGANON model and FVS predicted increases of 31 and 43%, respectively.

The new version of ORGANON predicted that 80% of the oaks in stand 2 would die over the projection period (3.1% annual mortality) if conifers were not removed (Figure 4). The predicted high mortality rate caused oak BA to decline by 58%. Mortality decreased with increasing diameter; only about 30% of oaks in the largest two diameter classes were predicted to die. FVS and the previous ORGANON model predicted much lower mortality without conifer removal (19 and 30%, respectively) across all diameter classes. BA was projected to increase slightly under FVS and decrease by only

12% under the previous ORGANON model. The previous ORGANON model predicted high mortality both in smaller oaks and in the largest diameter class, and FVS predicted mortality almost proportionally across all diameter classes. The new version of ORGANON predicted the greatest mean dbh at the end of the projection period, largely because of the high mortality of small oaks. FVS predicted the greatest mean diameter growth of surviving oaks (2.0 in.), followed by the new version of ORGANON (1.9 in.) and the previous version of ORGANON (1.5 in.).

The new version of ORGANON predicted a much greater effect of conifer removal in stand 2 than the previous ORGANON model or FVS (Figure 5). With the new equations, conifer removal reduced projected mortality to 27% (0.6% annually) and very little mortality was predicted in the largest three diameter classes. Predicted mortality also decreased slightly under FVS (to 17%) and it decreased to almost zero under the previous version of ORGANON. Predicted diameter growth of surviving oaks was greatest under the new version of ORGANON (4.3 in.), followed by the previous ORGANON model (3.1 in.) and FVS (2.8 in.). The new and previous versions of ORGANON predicted that oak BA would increase by about 41% over the projection period, while FVS predicted a smaller increase in oak BA (26%).

Discussion

The development of the new equations provided insight into the factors that influence the growth and survival of the Oregon white oak. Oregon white oak often is classified as intolerant to very intolerant of shade, particularly in competition with overtopping conifers (Stein 1990). The sensitivity of Oregon white oak to competition is reflected in the new mortality equation, which predicts a sharp increase in the probability of mortality with increasing competition. The mortality of small oaks, which are likely to be overtopped in closed-canopy stands, is predicted to be particularly high. CR and SI are important factors also. Predicted growth and survival both increase with increasing CR. However, CRs typically will be low in many current oak stands other than savannas or relatively open woodlands. Predicted growth increases with increasing SI, but the probability of mortality increases also. Not surprisingly, the greatest growth and survival of Oregon white oak is predicted to occur in open stands or savannas on productive sites. The overall vigor of Oregon white oak under such conditions also is reflected in their acorn production, which is highest in low-density stands on more mesic sites (Peter and Harrington 2002). The new equation predicts greater diameter growth of open-grown oaks than the previous ORGANON model. The maximum 5-year growth rate predicted by the new equation (1.27 in.) is consistent with maximum growth rates reported elsewhere. Previously reported 5-year growth rates in Washington range from 1.4 to 2.0 in. (Witt 1979, Stein 1990). Thilenius (1964) reported a somewhat lower maximum 5-year growth rate (1.0 in.) for forest-grown oaks in the Willamette Valley, Oregon.

The new version of ORGANON predicts a much greater impact of conifer removal on oaks in conifer-oak stands (e.g., stand 2) than FVS or the previous ORGANON model. The major difference between models was in projected mortality, which changed relatively little with conifer removal under the previous ORGANON model and FVS. In contrast, the new mortality equation suggests that oaks will decline rapidly without management intervention in stands that have been invaded by conifers. Long-term growth data for Oregon white oak were not available to evaluate the accuracy of the new equation, but the mortality rate without conifer removal (3.1% annually) appears to be reasonable when compared with mortality for other oaks in closed-canopy stands. The combined annual mortality of scarlet (*Quercus coccinea* Muench.) and black oak (*Quercus velutina* Lam.), which are classified as very intolerant and intermediate, respectively (Johnson 1990, Sander 1990), was estimated to range from 0.9% under low competition to 7.3% under heavy competition (Shifley et al. 2006). The annual mortality rate for post oak (*Quercus stellata* Wangenh.), a shade-intolerant species (Stransky 1990), ranged from 3.4 to 23.2% over 34 years in maturing stands (Huddle and Pallardy 1996). The new equation also predicted greater mortality than the two other models under less competition (i.e., after conifer removal and in the oak woodland), particularly in the smaller diameter classes. The mortality equation can be validated and refit if necessary as additional data become available. Mortality within oak sprout groups, which can be high even with a low overall stand density (Gardiner and Helmig 1997), may need to be considered as a special case.

The equations presented here are based on considerably more information than those used in previous models and should, consequently, provide better estimates of growth and survival over a range of stand conditions. Many forest managers in the Northwest are already familiar with ORGANON, which is used primarily to estimate the effects of silvicultural treatments on productivity in conifer stands. The new equations can give managers greater confidence in the ability of ORGANON to estimate the impact of silvicultural treatments on oaks or weigh the cost of inaction as stands previously classified as oak woodlands or savannas are invaded and dominated by conifers.

Endnote

[1] All ORGANON equations use English units. Users with metric measurements must convert before entering data into the model.

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