Predicting Root Biomass of Burned and Unburned White Oak Advance Reproduction from Diameter and Height

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ABSTRACT: *The size, especially the root size, of advance oak (*Quercus *spp.) reproduction provides the best indication of the growth potential after release or top-kill. This study examined the relationship between the size of the root system and various diameter/height measurements for small (<60 cm) white oak (*Q. alba *L.) seedlings. Diameters measured at the top of the litter and humus layers and at the root collar were tested for their ability to predict root biomass on burned and unburned sites. Despite their close physical proximity, separate equations were required for burned and unburned sites when predicting root biomass from diameters measured at the humus and root collar locations, as well as height and diameter/height combinations. On burned sites, all diameter measures were good predictors, accounting for 75 to 86% of the total variance of root biomass. On the unburned site, the best predictor was the diameter measured at the root collar, accounting for 85% of the total variance of root biomass. Diameter at the litter level accounted for only 55% of the total variance of root biomass whereas diameter at the top of the humus layer accounted for 53%. When dealing with stands of unknown disturbance history, the diameter measured at the root collar should be used to predict root biomass for small seedlings. South. J. Appl. For. 30(1):40–45.*

Key Words: Allometric relationships, oak regeneration, root collar diameter.

Successful regeneration of oak (*Quercus* spp.)-dominated forest stands is a serious challenge facing foresters today (Smith 1992). It is widely acknowledged that the presence of advance reproduction is a prerequisite for oak regeneration success (Sander 1972, Hannah 1987, Johnson 1992, Johnson et al. 2002). However, its presence by no means guarantees the eventual dominance of oaks in the canopy, especially on mesic or good quality sites. Unlike their competitors, such as red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), or yellow-poplar (*Liriodendron tulipifera* L.), oaks proportionally allocate more resources to root growth and less to shoot growth during regeneration stages (Kolb and Steiner 1990). Because of their inherent slower shoot growth and lower shade tolerance, understory oak seedlings are at a disadvantage when competing with shade-tolerant species (e.g., red maple and American beech). Severe competition often prevents advance oak reproduction from achieving a competitive size under a closed canopy condition (Sander 1972, Hannah 1987). In the event of canopy removal, most advance oak reproduction that has not achieved a competitive size would fail to become a canopy species because they would be out-competed by very fast growing shade-intolerant species (e.g., yellow-poplar) or advance reproduction of shade-tolerant species of larger size.

Oaks are more tenacious sprouters than other hardwood species (Waldrop et al. 1987) and they maintain a high root-to-shoot ratio even under limited light conditions (unpublished data). After each top-kill or dieback, oak seedling sprouts re-establish their shoots while continuing to grow their root systems. Consequently, advance oak reproduction commonly possesses root systems that are much older than the stems (Merz and Boyce 1956, Tyron and Powell 1984). Large root systems serve as carbohydrate reserves and enhance absorption of water and nutrients, which account for rapid shoot growth after dieback, top-kill, or release (Cobb et al. 1985).

Accelerated shoot growth after canopy release is essential for oak seedlings or sprouts to successfully overcome intense competition. On release from the overstory, the growth potential of advance oak reproduction is primarily dependent on the size of the root system (Johnson et al.

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2002), which, unfortunately, cannot be measured without destructive sampling. Consequently, diameter and/or height before release from the overstory are used to predict the growth potential after release (Sander 1972, Loftis 1990, Belli et al. 1999). However, the relationship between postrelease growth and prerelease diameter or height has not been very strong (Loftis 1990). Because of recurrent dieback, diameter, and/or height may not be good surrogate measures of root biomass, and thus postrelease growth potential.

The objectives of this study were to test if root biomass of white oak (*Q. alba* L.) advance reproduction can be reliably predicted by various diameter measures and/or height, and if burning history affects the strength of this prediction. Root size predictions should allow foresters to better estimate growth potential of advance reproduction and the probability to achieve canopy status after release.

Materials and Methods

Study Site

The study was conducted on the Clemson University Experimental Forest (CUEF) (latitude 34.68 N, longitude 82.84 W) within the Piedmont physiologic province in northwestern South Carolina. CUEF has a humid temperate climate, with an average high of 25° C in July, an average low of 7° C in Jan., and an average annual precipitation of 1,310 mm. It is characterized by rolling topography with soil associations dominated by Pacolet-Madison-Wilkes and Cecil-Hiawassee-Catuala (Byrd 1972). Soils are strongly acidic, firm, and clayey and are derived from gneiss, mica schist, hornblende schist, and schist parent materials (Smith and Hallbeck 1979). Similar to other areas of the Piedmont, CUEF land was farmed intensively until the 1930s for corn, cotton, and other row crops. Massive soil erosion resulted from these early agricultural practices (Trimble 1974).

Study Design

A mature hardwood stand containing a large component of white oak was selected for the study. The stand was divided into three areas that had similar amounts of white oak seedlings growing under comparable conditions. One area of the stand had been treated with prescribed fire in 1990, and a second area was prescribe-burned in 1992. A third, unburned area remained as a control (Watt 1992). Therefore, it can be assumed that many of the oak seedlings had experienced dieback at some point, from either the prescribed fire or natural suppression. The resulting reproduction was composed of a combination of seedlings and seedling sprouts (all referred to as seedlings hereafter).

In the summer of 2003, two transect lines were randomly located across each of the three study areas. Sampled seedlings were randomly selected from all those that fell within 50 cm on either side of the transect lines. In total, there were 132 oak seedlings excavated from the treatment sites, with 34 seedlings coming from the first burned section, 36 seedlings coming from the second, and the remaining 62 from the unburned site (control). Samples from the burned areas were pooled together for a total of 70 burned seedlings. Before excavation, three positions along each stem were marked: at the top of the litter level, at the top of the humus level, and at the mineral soil level. Each selected seedling was carefully excavated, labeled, and then put into plastic bags and brought back to the laboratory.

Data Collection

The root collar of each collected seedling was identified after the root system was washed in the laboratory. The root collar is where the stem and roots come together and is identified by Brose and Van Lear (2004) as a ring of callous tissue and dormant buds. Diameters were measured at the top of the litter (D_1) and at the top of the humus (D_2), as well as just above and below the root collar using a digital caliper. Diameters above and below the root collar were then averaged to give a root collar diameter (RCD) measurement that was used in data analysis. Depth of the root collar in mineral soil was measured and a depth of zero was recorded if the root collar was located above the mineral soil. Height from the litter (H) was measured for each seedling. Seedlings were dried in an oven at 80° C to a constant mass, and aboveground biomass and root biomass (RB) were then determined. Summary statistics of sampled seedlings for the burned and unburned sites are given in Table 1. Due to lack of larger seedlings or saplings, all sampled seedlings were less than 60 cm in height.

Data Analysis

Scatterplots with locally weighted smooth curves were used to explore relationships between root biomass and various aboveground variables, based on which the following model was selected:

$$\text{Log } Y = a + b \text{ Log } X, \qquad (1)$$

where Y is root biomass, X is the aboveground variable, and a and b are model parameters to be determined. Linear regression analysis was performed to determine the relationship between the root biomass and various aboveground variables, including D_1, D_2, RCD, H, $[D_1^2H]$, $[D_2^2H]$, and $[RCD^2H]$. Other models tested include exponential functions, transformations including square roots and inversions, and the addition of height as a second independent variable

Table 1. Means and standard deviation (in parentheses) of the measurements taken from sampled seedlings on the burned (n = 70) and control (n = 62) sites.

Variable	Burned	Control
Diameter at litter (mm)	3.23	2.98
	(1.25)	(0.79)
Diameter at humus (mm)	3.93	3.97
	(1.46)	(1.43)
Root collar diameter (mm)	5.42	5.23
	(2.18)	(1.95)
Depth of root collar in mineral soil (mm)	0.78	0.35
	(1.01)	(0.77)
Height (cm)	22.30	21.10
	(12.80)	(7.20)
Root biomass (g)	5.78	3.90
	(6.59)	(4.77)
Total biomass (g)	9.07	6.10
	(10.15)	(6.07)

with diameter. These models did not perform as well as model [1].

To test if separate models were necessary for burned and unburned sites, extra sum of squares F-tests were conducted based on full and reduced models (Neter et al. 1985, Huang 1997, Huang et al. 2000):

$$F = \frac{\mathrm{SSE}(R) - \mathrm{SSE}(F)}{(df_{\mathrm{R}} - df_{\mathrm{F}}) * \mathrm{MSE}_{\mathrm{F}}}, \qquad (2)$$

where $SSE(R)$ and $SSE(F)$ are the sum of square errors for the reduced and full models, respectively, df_R and df_F are degrees of freedom for reduced and full models, respectively, and MSE_F is the full model mean square error. The reduced model fit model [1] to the entire data (all 132 seedlings) whereas the full model incorporated both site types into model [1] by using indicator variables, as specified in the following:

$$\mathrm{Log}\ Y = (a + (bZ)) + ((c + dZ)(\mathrm{Log}\ X)), \qquad (3)$$

where Y is root biomass, Z is the site type indicator (1 = burned, 0 = unburned), X is the aboveground variable, and a, b, c, and d are model parameters to be determined. A significant F-test indicates that two separate equations should be used for burned and unburned sites. All statistical analyses were conducted using SYSTAT Version 10.2 (SYSTAT Software Inc., Richmond, CA).

Results

F-tests based on results from fitting full and reduced models indicate that separate models for the burned and unburned sites were needed for predicting root biomass from D_2, RCD, H, [D_1^2H] [D_2^2H], and [RCD^{2}H], but not for D_1. The P values from the extra sum of squares test and R^2 values of the appropriate models are given in Table 2. Although the extra sum of squares test indicated a single model is appropriate for D_1, separate models were also developed to show large differences in R^2 values between burned and unburned sites (Table 2).

Excluding RCD, aboveground variables were much better predictors of root biomass on the burned sites when compared to the unburned site (Table 2). On the burned sites, H was slightly better than D_2 but inferior to other variables in predicting root biomass. All three diameter measures predicted root biomass very well, with 75 to 86% of the total variance in root biomass explained (Table 2, Figure 1). Incorporating H into each of the diameter measures only slightly improved root biomass prediction, raising R^2 for D_1 from 0.85 to 0.86, R^2 for D_2 from 0.75 to 0.83, and R^2 for RCD from 0.86 to 0.88 (Table 2).

Table 2. R^2 values from regression analyses (Log $Y = a + b$ Log X; Y = root biomass (g); X = aboveground variable; a and b are model parameters) for burn and control sites together as well as separately.

Independent variablea	Burn and control	Burned	Control	P value
D_1	0.73	0.85	0.55	0.0726
D_2		0.75	0.53	0.0014
RCD	^{b}	0.86	0.85	0.0009
H	^{b}	0.77	0.47	0.0063
D_1^2H	^{b}	0.86	0.56	0.0136
D_2^2H	^{b}	0.83	0.62	0.0011
RCD^2H	^{b}	0.88	0.83	<0.0001

All equations are statistically significant ($P < 0.001$). P values are for the extra sum of squares test of full versus reduced models for burned and unburned sites.

[a] D_1 = diameter at litter (mm); D = diameter at humus (mm); RCD = root collar diameter (mm); H = height (cm).

[b] Separate equations are needed for the burned and control sites based on the extra sum of squares method.

On the unburned site, H was inferior to each of the diameter measurements in predicting root biomass. RCD was the best predictor among all three diameter measures, with 85% of the total variance in root biomass explained (Table 2, Figure 2). D_1 and D_2 were both poor predictors of root biomass, with only 55% and 53% of total variance explained, respectively (Table 2, Figure 2). Incorporating H into RCD did not improve root biomass prediction, with R^2 reduced from 0.85 to 0.83. Incorporating H into D_1 and D_2 marginally improved root biomass prediction, with R^2 increased from 0.55 to 0.56 and from 0.53 to 0.62, respectively.

Discussion

In stands where advance oak reproduction exists, accurate assessment of its growth potential after disturbance or canopy release is critical to sustainable management of oak ecosystems. Previous studies have suggested that the size of the root system determines postrelease growth performance of advance oak seedlings (Loftis 1990, Johnson et al. 2002). However, the size of the root system may not be well represented by the aboveground size of the seedling due to repeated top dieback under the canopy. Our study was designed to test if simple allometric relationships could reliably predict root biomass of small advance oak reproduction. Our results indicate height and various diameter measures were significantly related to root biomass of white oak advance reproduction. We also found that the strength of these relationships differed depending on past disturbance (burned versus unburned) history.

Among the three diameter measures taken in the study, RCD was expected to be the best predictor of root size because it is measured at a position closest to the root system. Understory oak advance reproduction experiences repeated top dieback (Merz and Boyce 1956), with the majority of resprouting buds at or above the point of this measurement. As a result, stems at the root collar are of the same age as the roots while the sprouts above the root collar may be much younger. Results from our study indicated that RCD was the most consistent predictor, regardless of the disturbance history, with $R^2 = 0.86$ for burned and $R^2 = 0.85$ for unburned sites. However, because of the method of germination of oaks, their root collars are buried in the soil (Burns and Honkala 1990). To measure RCD, a few centimeters of mineral soil may need to be removed to expose the root collar. Among the 132 seedlings sampled in our study, the root collars of 36% of the seedlings were buried in the mineral soil, with 22% on the unburned site and 47% on the burned sites. However, the average burying depth of

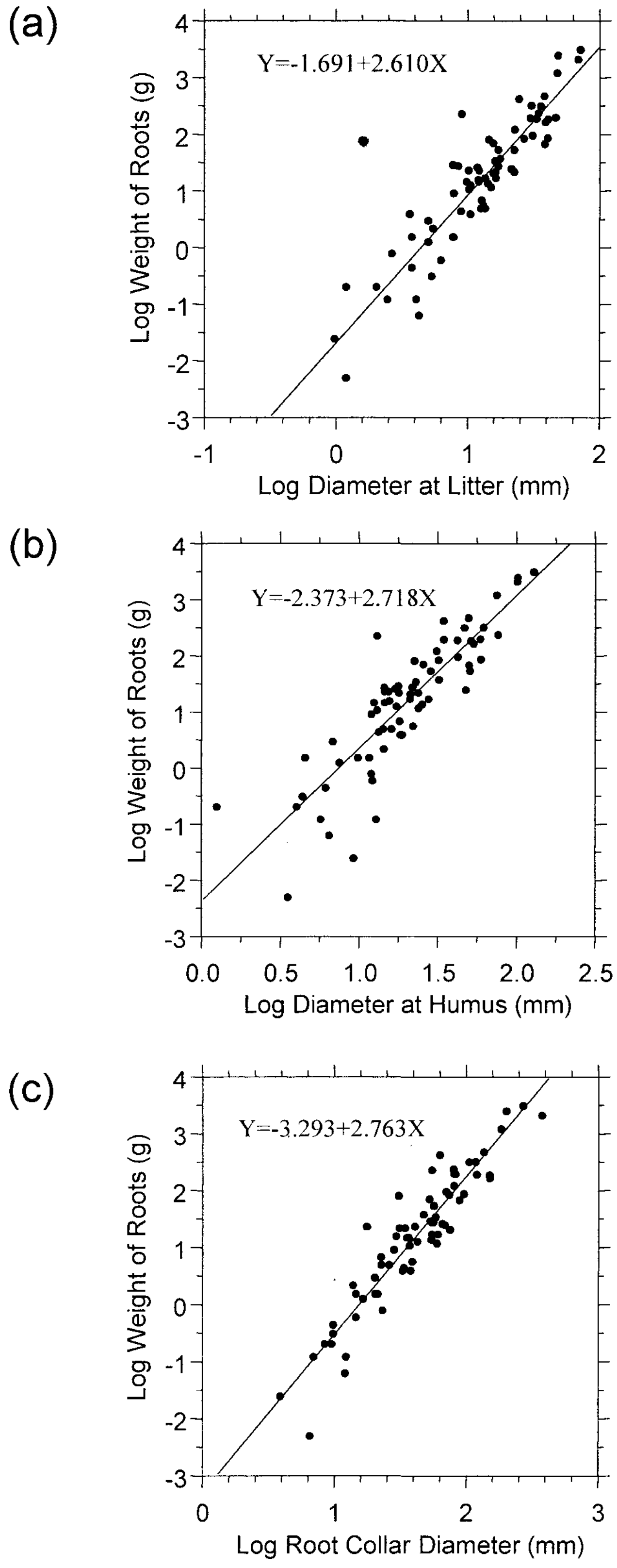

Figure 1. Scatterplots of root biomass versus diameters measured at litter (a), humus (b), and root collar (c) on the burned sites. Regression lines are superimposed on scatterplots.

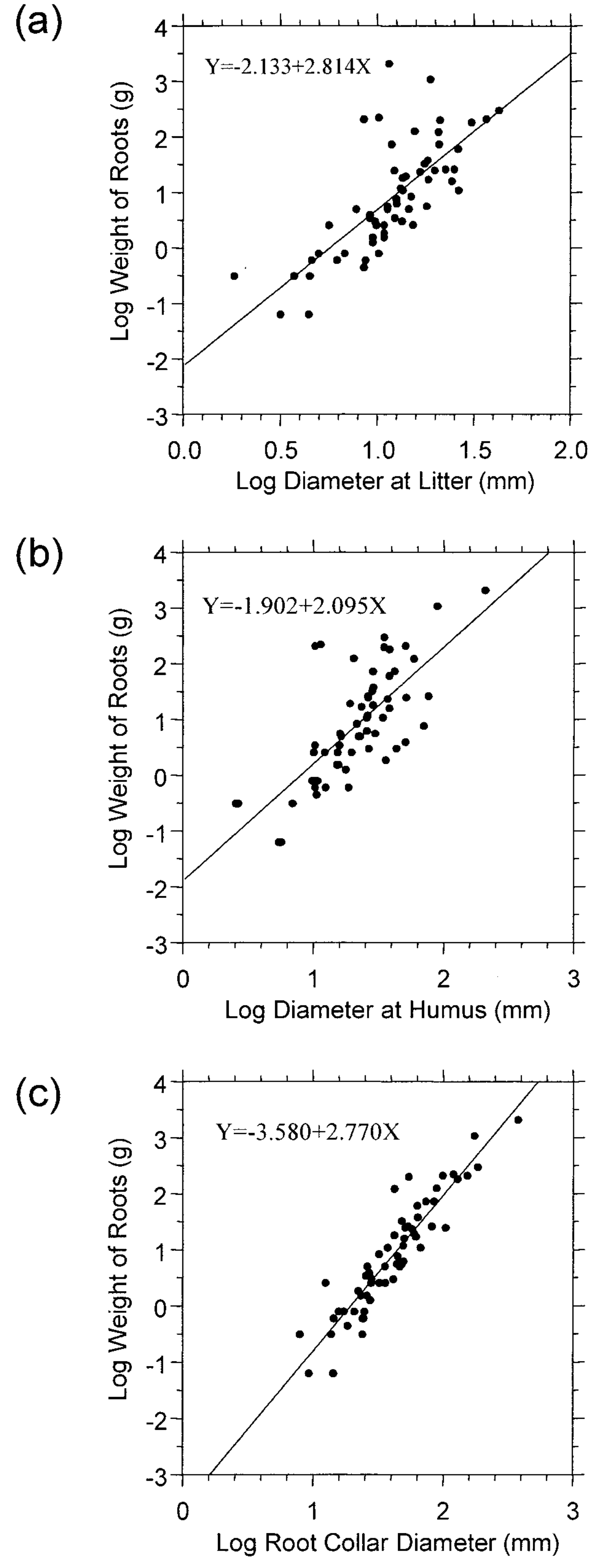

Figure 2. Scatterplots of root biomass versus diameters measured at litter (a), humus (b), and root collar (c) on the unburned site. Regression lines are superimposed on scatterplots.

the root collar was less than 1 cm, with a maximum of 4 cm. The average on the unburned site, where root collar measurements are more important for prediction, was only 0.35 cm (Table 1). It is, therefore, feasible to measure RCD in the field.

The ability of other diameter variables to predict root biomass depended on disturbance history. On the burned sites, all diameter measurements (D_1, D_2, and RCD) were adequate predictors, with 75 to 86% of the total variance in the root biomass explained. Thus, the routine measurement of diameter (i.e., diameter measured at litter level—D_1) provides an adequate indicator of root biomass without digging down to the root collar. Diameter measured at the humus level yielded a slightly lower R^2 value, while the root collar measurement resulted in only slight improvement in biomass prediction. In contrast, on the unburned site the location of the diameter measurement had much to do with the reliability of root biomass prediction. Only the diameter closest to the root system (RCD) predicted root biomass as reliably as on the burned sites. There was little improvement when height was added to diameter measurements, suggesting that diameter alone, when measured at the appropriate position on the stem, is sufficient to predict root biomass.

An unforeseen result of our study was the strong difference in allometric relationships in oak advance reproduction between burned and unburned sites, despite their close physical proximity. The sites were burned more than 10 years ago, with no other recent disturbance or notable site differences, suggesting that a single burn can have lasting effects on a stand. Burning in mixed hardwood stands reduces the midstory and allows advance oak reproduction to resprout vigorously (Brose and Van Lear 1998), with the stored carbohydrates in the roots supplying the necessary starches for rapid shoot growth (Hodges and Gardiner 1992). Because these sprouts started regrowth at the same time and had been growing under similar postburn conditions, the growth of each individual was strongly influenced by the amount of carbohydrates stored in their respective root systems. As a result, it was not surprising to find that all three diameter measures (D_1, D_2, and RCD) on the burned sites were closely related to the size of the root system.

In contrast, advance oak reproduction on the unburned site had been growing under a closed canopy condition for a longer period before sampling. Because the growth potential of oak seedling sprouts is not expressed until release (Johnson et al. 2002), these seedlings had not had the opportunity to sprout proportionately to the root system. Although dieback and resprouting can be assumed to have occurred, these events were not likely synchronized among individuals throughout the stand. Consequently, oak advance reproduction on the unburned site was at various stages of regrowth. In addition, these sprouts could not fully use the carbohydrate reserves in their root systems because of the growth-inhibiting shade from the canopy (Sander 1971, Johnson et al. 2002). As a result, aboveground measurements were not consistent in reflecting root size on the unburned site.

We acknowledge that the seedlings sampled in the study were generally small in size (Table 1), as large seedlings were not found in our study sites. Consequently, we are not sure if the strong influence of disturbance history on predicting root biomass detected in our study would persist for larger seedlings. Additionally, the study was limited to one stand for seedling selection. The lack of repetition in comparing burned and unburned sites limits what conclusions can be drawn about the effect of burn history on root biomass prediction. However, this study provides strong evidence that burn history affects root biomass prediction and should be explored more thoroughly in future research.

Conclusion

Root biomass, an indicator of the potential for regeneration success, of white oak advance reproduction less than 60 cm tall can be fairly accurately predicted from aboveground measurements. Although the root collar diameter yields the best prediction regardless of site history, burning of advance reproduction appears to affect the root biomass prediction of other measurements. Root biomass estimates of burned reproduction can be obtained from logarithmic regressions using diameter measurements taken at the top of the litter layer. Unburned reproduction, however, requires the diameter measurement to be taken at the root collar. Because root collars are either above the mineral soil or buried up to a few centimeters in the mineral soil, the root collar diameter could be easily measured in the field. Given the fact that stand disturbance history may not be readily known, we recommend that the root collar diameter be used to predict root biomass. Root biomass increases with increasing root collar diameter, implying an increase in the growth potential of advance reproduction. Improved ability in predicting root biomass should help foresters to time release treatments according to the growth potential of advance white oak reproduction.

Literature Cited

BELLI, K.L., C.P. HART, J.D. HODGES, AND J.A. STANTURF. 1999. Assessment of the regeneration potential of red oaks and ash on minor bottoms of Mississippi. South. J. Appl. For. 23(3):133–138.

BROSE, P.H., AND D.H. VAN LEAR. 1998. Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands. Can. J. For. Res. 28(3):331–339.

BROSE, P.H., AND D.H. VAN LEAR. 2004. Survival of hardwood regeneration during prescribed fires: The importance of root development and root collar location. P. 123–127 *in* Upland oak ecology symposium: History, current conditions, and sustainability. Spetich, M.A. (ed.). Southern Research Station, Asheville, NC.

BURNS, R.M., AND B.H. HONKALA. 1990. Silvics of North America, Vol. 2, Hardwoods. Agriculture Handbook 654, USDA For. Serv. Washington, DC. 877 p.

BYRD, H.S. 1972. Soil survey of Pickens county, South Carolina. USDA, Soil Conservation Service in cooperation with the South Carolina Agricultural Experiment Station. USGPO, Washington, DC. 70 p.

COBB, S.W., A.E. MILLER, AND R. ZAHNER. 1985. Recurrent shoot flushes in scarlet oak stump sprouts. For. Sci. 31(3):725–730.

HANNAH, P.R. 1987. Regeneration methods for oaks. North. J. Appl. For. 4(2):97–101.

HODGES, J.D., AND E.S. GARDINER. 1992. Ecology and physiology of oak regeneration. P. 54–65 *in* Oak regeneration: Serious problems, practical recommendations, Loftis, D.L. and C.E. McGee (eds.). Southeastern Forest Experiment Station, Knoxville, TN.

HUANG, S. 1997. Development of a subregion-based compatible height-site index-age model for black spruce in Alberta. For. Manage. Res. Note No. 5, Pub. No. T/352, Edmonton, Alberta. 56 p.

Huang, S., D. Price, D. Morgan, and K. Peck. 2000. Kozak's variable-exponent taper equation regionalized for white spruce in Alberta. West. J. Appl. For. 15(3):75–85.

Johnson, P.S. 1992. Sources of oak reproduction. P. 112–131 *in* Oak regeneration: Serious problems, practical recommendations. Loftis, D.L. and C.E. McGee (eds.). Southeastern Forest Experiment Station, Knoxville, TN.

Johnson, P.S., S.R. Shifley, and R. Rogers. 2002. The ecology and silviculture of oaks. CABI Publishing, New York, NY. 503 p.

Kolb, T.E., and K.C. Steiner. 1990. Growth and biomass partitioning of northern red oak and yellow-poplar seedlings—effects of shading and grass root competition. For. Sci. 36(1):34–44.

Loftis, D.L. 1990. Predicting post-harvest performance of advance red oak reproduction in the Southern Appalachians. For. Sci. 36(4):908–916.

Merz, R.W., and S.G. Boyce. 1956. Age of oak "seedlings." J. For. 54(11):774–775.

Neter, J., W. Wasserman, and M.H. Kutner. 1985. Applied linear statistical models: Regression, analysis of variance, and experimental design (2nd Ed.) Irwin, Homewood, IL. 1127 p.

Sander, I.L. 1971. Height growth of new oak sprouts depends on size of advance reproduction. J. For. 69(11):809–811.

Sander, I.L. 1972. Size of oak advance reproduction: Key to growth following harvest cutting. USDA For. Serv. Res. Pap. NC-79. North Central Forest Experiment Station. 6 p.

Smith, D. 1992. Oak regeneration: The scope of the problem. P. 40–52 *in* Oak regeneration: Serious problems, practical recommendations. Loftis, D.L. and C.E. McGee (eds.). Southeastern Forest Experiment Station, Knoxville, TN.

Smith, B.R., and D.C. Hallbeck. 1979. General soil map, South Carolina. SC Agricultural Experimental Station, Clemson University, Clemson, SC.

Trimble, S.W. 1974. Man-induced soil erosion on the Southern Piedmont, 1700–1970. Washington, DC. Soil Conservation Society of America. 180 p.

Tyron, E.H., and D.S. Powell. 1984. Root ages of advanced hardwood reproduction. For. Ecol. Manage. 8(3/4):293–298.

Waldrop, T.A., D.H. Van Lear, F.T. Lloyd, and W.H. Harms. 1987. Long-term studies of prescribed burning in loblolly pine forests of the southeastern Coastal Plain. USDA For. Serv. Gen. Tech. Rep. SE-45. Asheville, NC. 23 p.

Watt, J. M. 1992. The response of oak ecosystems to prescribed fire in the Piedmont of South Carolina. MSc thesis, Clemson Univ., Clemson, SC. 79 p.