Forest Science, Vol 36, No 4, pp 908–916

Predicting Post-Harvest Performance of Advance Red Oak Reproduction in the Southern Appalachians

DAVID L. LOFTIS

ABSTRACT. Models are presented for predicting: (1) height growth of red oak advance reproduction after clearcutting, and (2) the probability of stems becoming dominants or codominants in new stands as a function of preharvest size of advance reproduction and site quality. The second model permits silviculturists to predict, prior to harvest, the contribution to a new stand of an existing population of advance red oak reproduction. FOR. SCI. 36(4):908–916.

ADDITIONAL KEY WORDS. Regeneration, logistic regression.

REGENERATING UPLAND OAKS on more productive sites is frequently cited as a management problem in eastern hardwood forests (McLintock 1979, Merritt 1979). In Southern Appalachian mixed hardwood forests, red oak (*Quercus rubra* L.) is not being consistently regenerated by even-aged methods (Beck 1970, Beck and Hooper 1986, Loftis 1983b, McGee and Hooper 1970). Red oak regeneration failures have occurred over a broad range of sites below 4,000 ft elevation where red oak was a prominent component of the previous stand. High-quality wood, rapid diameter growth, and mast production for many wildlife species make red oak a desirable component of regenerated stands.

Failures to regenerate the species indicate that sources of red oak regeneration capable of competing successfully with associated species were not present on that site prior to overstory removal. Advance reproduction is usually considered to be the most important source of regeneration (Beck 1980, Carvell and Tryon 1961, Loftis 1983a, Sander and Clark 1971).

The objectives of the study reported here are (1) to examine the relationship between attributes of advance red oak reproduction prior to harvest and its performance after harvest, and (2) to develop a method for predicting the likelihood of successfully regenerating red oak based on the population distribution of these attributes of the advance red oak reproduction. In the absence of such a tool, the silviculturist has no basis for prescribing cultural practices to maintain a component of red oak in regenerated stands.

SOURCES OF HARDWOOD REGENERATION

Natural regeneration after a harvest cut comes from new seedlings established at or after the time of the harvest cut, from older seedlings established prior to the harvest cut (advance reproduction), and from sprouts from stumps or roots of the harvested trees (Beck 1980). For some species, such as yellow-poplar (*Lirio-*

dendron tulipifera L.), the primary source of reproduction may be new seedlings from seed stored in the forest floor, or from a combination of new seedlings and sprouting of cut trees. For other species, such as black locust (*Robinia pseudoacacia* L.), the primary source of regeneration is root-suckering after the harvest of existing stems. For the upland oaks, including red oak, new seedlings are not a viable source of regeneration (Beck 1970, McQuilken 1975, Sander 1972). Newly established seedlings grow much too slowly to compete successfully with associated species after overstory removal. Stump sprouts of upland oaks do grow rapidly enough after overstory removal, but the probability that an oak stump will produce a sprout which will become a dominant or codominant stem decreases with increasing tree diameter and tree age (Johnson 1977). In mature stands on productive sites in the Southern Appalachians, very few small-diameter stems are present. Consequently, stump sprouts can rarely be relied upon to regenerate red oak after overstory removal (Loftis 1983a).

Advance reproduction, then, is the primary source of future dominant and codominant red oak stems. The importance of advance oak reproduction has been stressed by a number of researchers and has become a tenet of upland oak silviculture (Carvell and Tryon 1961, Merritt 1979, Sander 1971, Sander and Clark 1971).

The mere presence of red oak advance reproduction, however, does not ensure that red oak will be a component of the succeeding stand. In studies where inventories of advance reproduction were made prior to overstory removal, red oak has usually been present. But dominant or codominant red oaks occur infrequently in the new stands (Beck and Hooper 1986, Loftis 1983b, McGee and Hooper 1970).

Sander (1971, 1972) found that growth of advance reproduction following overstory removal is strongly related to its size prior to harvest. This relationship provides a possible explanation for the red oak regeneration failures observed in the Southern Appalachians. In a study where advance reproduction was inventoried by size class (Loftis 1983b), almost all of the oak advance reproduction was less than 1.0 ft tall.

Sander developed guidelines for evaluating the adequacy of advance reproduction to regenerate fully stocked oak stands where oak site index is 70 and below in the Missouri Ozarks (Sander et al. 1976, Sander et al. 1984). No such guidelines exist for the higher quality, productive sites in the Southern Appalachians.

METHODS

In 1978 and 1979, six study sites were located on the Bent Creek Experimental Forest near Asheville, NC. The primary criterion for site selection was the presence of a range of sizes of advance red oak reproduction under a mature overstory. An attempt was also made to locate areas representing the range of site qualities on which red oak occurs. At each site a center stake was established, and all red oak advance reproduction 2.0 in. or less in basal diameter (at groundline) within 20–30 ft of the center stake was located. From 40 to 50 seedlings per site were marked. The red oak advance reproduction was mapped by azimuth and distance from the center stake. A metal pin, with numbered tag attached, was placed by each seedling. Groundline diameter to the nearest 0.1 in., height to the nearest 0.1 ft, and a subjective assessment of degree of apical dominance were recorded for each stem. Apical dominance was rated on a scale of 1 to 3, with 3 designating strong apical dominance (strong central leader), 1 designating no apical dominance (a "flat-topped" seedling), and 2 designating an intermediate form. Oak site index (base age = 50 years) was determined on each plot based on 3 dominant or codominant trees (Doolittle 1958, Olson 1959).

After the trees were mapped, tagged, and measured, the mature stands occupying the sites were clearcut, with the clearcut boundary extending at least 50 ft beyond the most distant red oak seedling. Residual trees were felled with chainsaws. This treatment mimics the clearcutting method as commonly applied in the Southern Appalachians.

After clearcutting, tagged trees at each site, a total of 249 trees across all sites, were observed annually through 1986. Observations include height and competitive position of the red oak seedlings (whether the seedling is free-to-grow or not), stem origin (whether the advance red oak stem retained its original top or initiated a new sprout), and origin (sprout or seedling) and species of each red oak stem's principal competitor.

RESULTS AND DISCUSSION

HEIGHT

Heights of the 167 red oak seedlings that survived eight growing seasons ($HT8$) were analyzed using ordinary least squares, setting

$$HT8 = F(HT, BD, APDOM, SI)$$

where

HT = height of advanced red oak prior to overstory removal

BD = basal diameter of advanced red oak prior to overstory removal

$APDOM$ = assessment of apical dominance of advanced red oak prior to overstory removal

SI = oak site index (base age 50 years).

Several model forms and variable transformations were used to examine the relationships between dependent and independent variables.

The model that best described the relationship between height at age 8 and the independent variables was:

$$HT8 = 29.9656 - (2.2099/BD) - (3.2886/HT) - (688.8281/SI)$$

It accounted for only 42% of the variation in the response variable, but was highly significant ($P < 0.01$). Parameter estimates for each of the independent variables were also highly significant. The relatively low coefficient of determination is not surprising. The aboveground measures of preharvest plant size are imperfect indicators of the capacity of the root system to sustain growth of a top after release from the overstory (Sander 1972). Another source of variation in height growth is competition—many of the red oak stems have been overtopped by competing individuals since overstory removal while others have been free to grow since overstory removal. Adding the free-to-grow status at age 5 or age 8 to the model as an indicator variable (1 or 0) increased the coefficients of determination to 0.51 and 0.52, respectively. The parameter estimate for age 8 free-to-grow status, significant at the 0.01 level, shows that free-to-grow stems with a given site index, initial basal diameter, and initial height are 3.37 feet taller than overtopped stems.

In contrast to Carvell's (1967) findings, apical dominance did not prove to be a good predictor of performance after harvest in the present study. One reason is that fewer than half of the advance red oak stems in the study retained their original tops after the first growing season. A primary cause of top mortality was logging damage. Tops of some advance stems died for no apparent reason, and a new sprout was initiated. On other advance stems a pre-existing basal sprout suppressed the original top. This combination of conditions rendered the original assessment of apical dominance nonsignificant.

The current work is consistent with Sander's (1971, 1972) findings that growth after harvest is strongly related to preharvest size of advance oak reproduction.

PROBABILITY

A prediction of growth, per se, does not indicate what the competitive status of a stem will be. Silviculturists need to predict how many dominant and codominant oaks will result from an observed population of advance oak reproduction, if the overstory is harvested.

If the height, at age 8, of oak stems that eventually become dominants and codominants were known, then the statistics from the regression of height growth on preharvest basal diameter, preharvest height, and site index could be used to estimate the proportion of advance stems of a given basal diameter-height-site index combination that would be expected to be as tall or taller than this known height. This proportion could be viewed as an estimate of the probability that an advance oak stem with given preharvest attributes will become dominant or codominant after clearcutting. However, a stem that attains the expected height may, in fact, be suppressed by faster growing competitors. Furthermore, the regression of 8-year height on preharvest attributes and site index predicts heights of survivors. A separate estimate of mortality would be necessary.

Fortunately, a more direct method of estimating the probability of a stem becoming dominant or codominant (hence called "dominance probability") is available. The condition of being or not being dominant or codominant can be treated as a binary or dichotomous response variable. The expected value of the response variable in the regression of a binary response variable on a set of independent variables is the probability that the response variable equals 1. In this case, the expected value is the probability that a stem is dominant or codominant—the dominance probability. To overcome the problems of nonnormal error terms and nonconstant error variance when the response variable is binary, a weighted regression analysis is used, with the weight equal to the inverse of the error variance. Furthermore, the logistic model is frequently used to constrain the expected value of the response variable to values between 0 and 1 (Neter and

Wasserman 1974). This method has been applied to provide dominance probabilities for oak stump sprouts and advance reproduction in the Missouri Ozark oak forests (Johnson 1977, Sander et al. 1984).

In the present study, a red oak stem was considered dominant (response variable = 1) at age 8 if (1) it was free-to-grow, and (2) its height was equal to or greater than 8/20 of the height at age 20 as indicated by site index curves (Olson 1959). This second criterion assumes a linear growth rate from age 0 to age 20, and is probably fairly realistic. For site index 67, the lowest site index in the study, a stem would have to be at least 13.8 ft tall to satisfy the second criterion; for site index 90, the highest site in the study, a stem would have to be at least 18.6 ft tall. The two criteria together restrict dominant stems to those growing at a rate that would place them among the dominant and codominant stems at age 20, and those whose present competitive position in the stand (free-to-grow) provides the potential for future growth free of overtopping competition. Stems that do not meet both criteria include those which have died since overstory removal. Mortality is, therefore, accounted for in the dominance probability estimates.

The 8-year-data were analyzed by nonlinear regression (SAS 1982) with a logistic model. The set of independent variables to be included in the model was evaluated by comparing residual sums of squares among models, and by ensuring that the 95% asymptotic confidence interval for the parameter (coefficient) estimates did not include 0. The results were verified using a specialized logistic regression procedure (PROC LOGIST) that provides fit statistics for the model, as well as chi-square tests of significance of parameter estimates for variables included in the model (SAS 1986).

The model chosen

$$P8 = \frac{e^{(6.05546\,BD - 0.081889SI)}}{1 + e^{(6.05546\,BD - 0.081889SI)}}$$

where

BD = preharvest basal diameter
SI = oak site index of the stand
$P8$ = dominance probability at age 8
e = base of the natural logarithms

resulted in the smallest residual sums of squares of all models for which all parameter estimates were significantly different from 0. Including preharvest height or composite variables of preharvest height and basal diameter, e.g., *BD* squared × height, in the model resulted in nonsignificant parameter estimates for these variables.

The inverse relationship between site quality and dominance probability (Figure 1) is consistent with a similar study of oak advance reproduction in the Missouri Ozarks (Sander et al. 1984). Even though, in the present study, this relationship may seem the natural consequence of using the height criterion adjusted for site index, the same relationship holds when the "free-to-grow" criterion alone is used

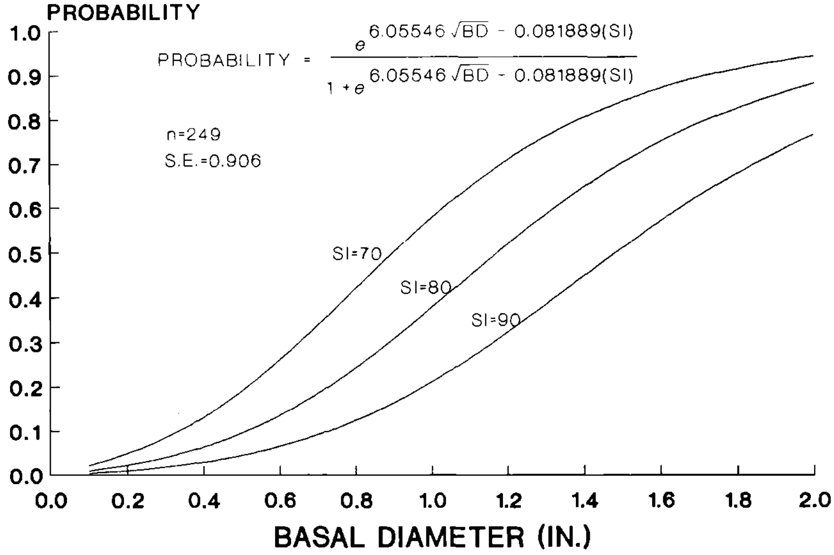

FIGURE 1. Dominance probability at age 8 estimated by logistic regression on basal diameter (at groundline) and oak site index.

to define dominance. As in the Missouri study, this relationship may be attributed to severe competition characteristic during early stand development on higher quality sites.

An estimate generated by this model is the probability that an advance red oak stem of a given preharvest basal diameter on a site of a given quality will be dominant or codominant 8 years after overstory removal. To be useful to silviculturists, it is necessary to extrapolate these probability estimates to a point in stand development, say 20 years, at which a stem's competitive status is more meaningful, and when the application of intermediate cuttings can be expected to be effective in shaping the composition of the stand to be carried to rotation age. The limited data available (Beck and Hooper 1986) suggest that, as even-aged stands mature, the number of dominant and codominant stems at age 20 will be about one-half the number of dominant and codominant stems at age 8. Multiplying the probabilities estimated for age 8 times 0.5 provides estimates of the probabilities at age 20 (*P*20). Implicit in this procedure are the assumptions that the rate of diminution in numbers of dominant and codominant red oak stems over time will be the average rate for all species, and that, over all preharvest basal diameters and site indexes, the rate of diminution in numbers will be the same. The validity of these assumptions can only be tested as the present study approaches age 20.

With these probabilities (Table 1) and a target number of dominant and codominant red oak stems desired at age 20, the silviculturist can use an inventory (sample) of the preharvest population of advance red oak reproduction (by basal diameter) and a measure of oak site index to determine if the current population of advance red oak reproduction in the stand would meet the regeneration goal if the overstory were removed immediately (clearcut). The expected number of dominant and codominant stems is given by:

$$N = n_{ij}P20_{ij}$$

TABLE 1.

Dominance probabilities at age 20 for northern red oak advance reproduction.

Basal diameter[a] of advance reproduction (in.)	Oak site index[b]		
	70	80	90
0.1	0.01	0.00	0.00
0.2	0.02	0.01	0.00
0.3	0.04	0.02	0.01
0.4	0.06	0.03	0.01
0.5	0.09	0.04	0.02
0.6	0.13	0.06	0.03
0.7	0.17	0.09	0.04
0.8	0.21	0.12	0.06
0.9	0.25	0.15	0.08
1.0	0.29	0.18	0.11
1.1 to 1.5	0.38	0.29	0.19
1.6 to 2.0	0.46	0.41	0.34

[a] Basal diameter at groundline.
[b] Olson (1959).

where

N = the expected number of dominant and codominant red oaks at age 20

n_{ij} = the number of advance red oak in the ith size class on the jth site index class

$P20_{ij}$ = probability of advance red oak in the ith size class on the jth site index class becoming dominant or codominant.

For example, suppose sampling indicates that a mature stand with an oak site index of 80 ft contains 1,500 advance red oak stems per acre distributed as follows:

Basal diameter (in.)	Number/ac
0.1	1000
0.2	400
0.3	100

If the stand were clearcut immediately, the expected number of dominant and codominant red oak stems at age 20 would be:

$$\begin{array}{r} 1000 \times 0.00 = 0.0 \\ 400 \times 0.01 = 4.0 \\ \underline{100 \times 0.02 = 2.0} \\ 6.0 \end{array}$$

If six dominant or codominant red oak trees per acre at age 20 are adequate to meet the regeneration goal, clearcutting would be the appropriate regeneration method. If six trees per acre are not adequate, another regeneration method should be considered (Loftis 1983a, 1988).

CONCLUSIONS

The models presented in this paper allow silviculturists to predict, prior to harvest, the performance of advance red oak reproduction after harvest both in terms of height growth and, more importantly, in terms of the probability of attaining a favorable competitive position in a new stand which develops after overstory removal. They can determine if immediate clearcutting, given the extant population of advance red oak reproduction, would be the appropriate silvicultural prescription to meet regeneration goals for red oak.

Given the age of the study on which the models are based, the results are tentative. However, the models should allow the silviculturist to recognize, at the very least, those stands where the current regeneration potential for red oak is clearly inadequate to meet his goals. In these cases, goals must be modified, or cultural practices must be imposed that will result in a population of large advance reproduction. As the study ages, and the model is refined, more confidence can be placed in the predicted number of dominant and codominant red oak stems in the new stands.

LITERATURE CITED

BECK, D. E. 1970. Effect of competition on survival and height growth of red oak seedlings. USDA For. Serv. Res. Pap. SE-56. 7 p.

BECK, D. E. 1980. Natural regeneration of southern hardwoods. P. 132–142 *in* R. L. McElwee and N. H. Bell (eds.). Regenerating the southern forest, Tenth For. Wildl. Forum. Virginia Poly. Inst. & State Univ., Blacksburg.

BECK, D. E., and R. M. HOOPER. 1986. Development of a Southern Appalachian hardwood stand after clearcutting. South. J. Appl. For. 10(3):168–172.

CARVELL, K. L. 1967. The response of understory oak seedlings to release after partial cutting. West Virginia Univ. Agric. Exp. Stn. Bull. 553. 10 p.

CARVELL, K. L., and E. H. TRYON. 1961. The effect of environmental factors on the abundance of oak regeneration beneath mature oak stands. For. Sci. 7:98–105.

DOOLITTLE, W. T. 1958. Site index comparisons for several forest species in the Southern Appalachians. Soil. Sci. Soc. Am. Proc. 22(5):455–458.

JOHNSON, P. S. 1977. Predicting oak stump sprouting and sprout development in the Missouri Ozarks. USDA For. Serv. Res. Pap. NC-149. 11 p.

LOFTIS, D. L. 1983a. Regenerating red oak on productive sites in the Southern Appalachians: a research approach. P. 144–150 *in* Jones E. P., Jr. (ed.). Proc. 2nd Bienn. South. Silvic. Res. Conf., Gen. Tech. Rep. SE-24.

LOFTIS, D. L. 1983b. Regenerating Southern Appalachian mixed hardwoods with the shelterwood method. South. J. Appl. For. 7(4):212–217.

LOFTIS, D. L. 1988. Regenerating red oak in the Southern Appalachians: Predictive models and practical applications. Ph.D. diss., North Carolina State Univ., Raleigh.

MCGEE, C. E., and R. M. HOOPER. 1970. Regeneration after clearcutting in the Southern Appalachians. USDA For. Serv. Res. Pap. SE-70. 12 p.

MCLINTOCK, T. F. 1979. Research priorities for eastern hardwoods. Hardwood Res. Counc., Nashville, TN. 70 p.

MCQUILKEN, R. A. 1975. Growth of four types of white oak reproduction after clearcutting in the Missouri Ozarks. USDA For. Serv. Res. Pap. NC-116. 5 p.

MERRITT, C. 1979. An overview of oak regeneration problems. P. 1–10 *in* Holt, H. A., and B. C. Fischer (eds.). Regenerating oaks in upland hardwood forests, 1979 John S. Wright For. Conf., Purdue Res. Found. Lafayette, IN.

NETER, J., and W. WASSERMAN. 1974. Applied linear statistical models. Richard D. Irwin, Homewood, IL. 842 p.

OLSON, D. F., JR. 1959. Site index curves for upland oaks in the southeast. USDA For. Serv. Southeast. Stn. Notes 25. 2 p.

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

SANDER, I. L. 1972. Size of advance reproduction: Key to growth following harvest cutting. USDA For. Serv. Res. Pap. NC-79. 6 p.

SANDER, I. L., and F. B. CLARK. 1971. Reproduction of upland hardwood forests in the central states. Agric. Handb. 405. USDA For. Serv., Washington, DC. 25 p.

SANDER, I. L., P. S. JOHNSON, and R. ROGERS. 1984. Evaluating oak advance reproduction in the Missouri Ozarks. USDA For. Serv. Res. Pap. NC-251. 16 p.

SANDER, I. L., P. S. JOHNSON, and R. F. WATT. 1976. A guide for evaluating the adequacy of oak advance reproduction. USDA For. Serv. Gen. Tech. Rep. NC-23. 7 p.

SAS INSTITUTE INC. 1982. SAS user's guide: Statistics, 1982. SAS Inst. Inc., Cary, NC. 584 p.

SAS INSTITUTE INC. 1986. SUGI supplemental user's guide, Version 5. SAS Inst. Inc., Cary, NC. 662 p.

Manuscript received February 24, 1989.

AUTHORS AND ACKNOWLEDGMENTS

David L. Loftis is Research Forester, USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC 28806.