Competitive Capacity of *Quercus rubra* L. Planted in Arkansas' Boston Mountains

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ABSTRACT. Results of an 11 yr study of the growth and survival of planted northern red oak (*Quercus rubra* L.) seedlings (2-0 bare-root) are presented. More than 4,000 seedlings were planted under shelterwood overstories that were harvested 3 yr after planting. Results are expressed as planted-tree dominance probabilities. Dominance probability is the probability that a planted tree will live to attain a favorable competitive position (i.e., at least 80% of the mean height of dominant competitors) at a specified year. We interpret the resulting probability as a measure of the competitive capacity of an individual seedling, i.e., its potential of attaining dominance in a specified environment. Based on logistic regression analysis, dominance probabilities increase with time after shelterwood overstory removal for any given environment and initial seedling characteristics. At any specified time, dominance probabilities depend on initial seedling basal diameter before planting (stem caliper 2 cm above the root collar), site quality, intensity of weed control, and shelterwood percent stocking. Dominance probabilities increase with decreasing shelterwood stocking, increasing initial stem caliper, and increasing intensity of weed control. Other factors being equal, top clipped seedlings have higher dominance probabilities than unclipped seedlings. The reciprocals of the dominance probabilities provide silviculturally useful estimates of the numbers of trees that would need to be planted to obtain, on the average, one competitively successful tree. For example, if clipped seedlings averaging 6 mm in caliper were planted where oak site index was 24 m, shelterwood stocking was 80%, and the site was given no weed control before or after planting, obtaining one competitively successful tree 11 yr after planting (8 yr after shelterwood removal) would require planting 144 seedlings. Other factors remaining the same, increasing initial caliper to 22 mm would require planting only 5 trees to obtain 1 competitively successful tree. For the same size (22 mm) and type of seedling planted on site index 18 m under a shelterwood at 40 to 60% stocking and given two weed control treatments, only 1.4 trees would need to be planted. Results emphasize the sensitivity of competitive capacity, and thus the silvicultural potential, of planted northern red oaks in the Boston Mountains of Arkansas to the joint effects of field environment and initial seedling characteristics. For. Sci. 48(3):504–517.

Key Words: Dominance, probabilities, competitive capacity, northern red oak, shelterwood.

OAKS ARE KEYSTONE SPECIES in the forests of the eastern United States. Oak-dominated forests represent 51% of the eastern U.S. forests including 49.8 million ha of oak-hickory forest, 19.3 million ha of oak-pine forest, and 12.1 million ha of oak-gum-cypress forest (Forest Maps of the United States RPA Program 1993). In addition to their value to society for wood products, oaks produce acorns that are an important food source (Martin et al. 1951, p. 308) for over 100 wildlife species (Van Dersal 1940). Fluctuations in wildlife populations such as these often follow fluctuations in oak mast production (Nixon et al. 1975, Wentworth et al. 1990, McShea and Schwede 1993).

Early in the 20th century, regeneration of oak was not perceived as a problem. However, according to Lorimer (1989), "by the 1970s, oak regeneration was recognized as one of the most serious silvicultural problems of the eastern United States." The decline of oak as a dominant species in eastern forests has altered species composition of many stands (Johnson et al. 1973, Cho and Boerner 1991, and Shotola et al. 1992). For instance, in an old-growth mixed mesophytic forest in Indiana that was protected from fire since 1926 and in which every tree ≥10 cm dbh had been periodically stand mapped, a dramatic shift in the regeneration pool had occurred by the late 20th century. In 1926, regenerating oak (from 10 to 25 cm dbh) represented 14%, and sugar maple (*Acer saccharum* Marsh.) represented 12% of standing biomass in that diameter range. However, by 1992, oak represented only 1%, and sugar maple had increased to 43% (Spetich and Parker 1998). There are also many other examples of the successional displacement of oak (e.g., Abrams and Downs 1990, Dodge 1997, Shotola et al. 1992, McGee 1986, Johnson et al. 1973).

Although northern red oak can be planted in clearcuts, dominance probabilities are lower there than in shelterwoods. Johnson (1989) found that only 37% of half-inch caliper seedlings planted in Missouri clearcuts would be competitively successful 8 yr after planting. However, 61% of those planted under a shelterwood and released 3 yr later would be competitively successful 8 yr after planting. The 3 yr period between planting and final overstory removal in the shelterwood allows seedlings to recover from lifting and planting shock and to develop more substantial root systems (Dey and Parker 1996, 1997b) before competition becomes prolific.

Planting oaks under shelterwoods offers an important but often overlooked tool for maintaining and restoring oaks in eastern forests. Studies in several regions have demonstrated the potential usefulness of the method (Dey and Parker 1996, 1997a, Johnson 1984, Weigel and Johnson 1998a, 1998b, 2000, Teclaw and Isebrands 1993a, 1993b). However, the long-term success of this planting method depends on the growth and survival of planted trees relative to competing vegetation, i.e., their competitive capacity.

We define a tree's competitive capacity as its ability to survive and grow at a rate sufficient to attain and maintain dominance among its competitors. The concept is applied to northern red oaks that have been planted among existing trees and other naturally occurring forest vegetation. Competitive capacity is quantitatively expressed as the probability that a planted tree will attain dominance among competitors after a specified period. These probabilities take into account a planted tree's initial characteristics together with its growing environment. The latter includes site quality and environmental changes resulting from silvicultural practices such as weeding and thinning before and after planting. To be silviculturally useful in this context, the derived probabilities must reflect potential changes in the relative competitive position of both the planted trees and the competing naturally regenerated trees. The relative competitive position among species and individual trees changes over time (through succession), and rates of change may vary among ecosystems. Outcomes of the interspecific competition between planted trees and natural vegetation occur as a function of site factors, associated differences in growth rates of co-occurring species, the genetics of plant populations, and the state of the vegetation complex when silviculturally prescribed or naturally imposed disturbances occur. The competitive capacity of a species, therefore, may vary as those factors vary in time and space. The objective of this study was to evaluate the competitive capacity of northern red oaks planted under shelterwoods from which they were released 3 yr after planting.

We evaluated the competitive capacity of these planted oaks through logistic regression. The full power, versatility, and relevance of logistic regression to analyze dichotomous data first gained recognition in the 1960s (Hosmer and Lemeshow 1989, p. vii). Since then, researchers have utilized this method to examine everything from human health issues to the growth and survival of naturally regenerated trees (Lowell et al. 1987). Here we use it to examine growth and survival of planted trees.

Methods

Site Description

Northern red oak seedlings were planted in five upland hardwood shelterwood stands in the Boston Mountains on the Buffalo Ranger District of the Ozark National Forest in northern Arkansas. These sites were located on north and northeast facing mountain slopes and benches (Graney 1977), the most difficult sites to regenerate oak (Graney and Rogerson 1985, Sander and Graney 1993, Graney and Murphy 1997). The mountains are an uplifted peneplain surface that has been dissected through the process of erosion. These mountains consist of mountaintops that are relatively level to gently rolling, while mountainsides are an alternating series of steep slopes and gently sloping benches (bench and bluff topography). This is the southernmost lobe of the central hardwood region (Merritt 1980, p. 108) and the Boston Mountain Section (M222A) of the Hot Continental Division (220) of Bailey's ecoregions (Bailey et al. 1994).

Plot Establishment, Study Variables, Site Character, Planting Stock and Treatments

A total of 4,320 2-0 seedlings, which were undercut the first year in the nursery, were hand-planted with a mattock

in early April, 1987, at a 2.4 × 2.4 m spacing in a split-split plot experimental design with five replicates (locations). However only 4,128 seedlings were available for study because of the loss of two main plots. Site index for red oaks (northern red and black oaks) ranged from 18.3 to 24.1 m at 50 yr based on indirect estimation from soil and topographic factors (Graney 1977). Planted trees and competitors were measured after the first, third, fourth, sixth, eighth, and eleventh growing seasons. This article summarizes the 11 yr performance (8 yr free of the shelterwood) of planted trees.

Designed study variables fall into two categories: (1) those related to planting environment, and (2) those related to nursery production. The former include initial harvest residual overstory density (expressed as stocking percentage) and weed control treatments. The latter include time of lifting and shoot clipping. The study also incorporated four local seed sources. The designed study variables included three overstory densities, three weed control treatments, three shoot clipping treatments, two seedling lifting times, and four seed sources and are described in detail in Table 1.

Plots were located on predominantly north to northeast facing aspects. Each plot was marked for thinning to a randomly selected residual stocking level (from among 40, 60, and 80% levels) with the objective of thinning from below. This was accomplished by marking trees for thinning beginning with the smallest diameter trees (> 3.9 cm) and progressively moving to larger diameter trees until the prescribed stocking level was obtained and a relatively uniform canopy of residual trees remained.

Prior to thinning, the mean overstory characteristics consisted of 1,095 trees/ha, 27.3 m²/ha of basal area, a quadratic mean stand diameter of 18.0 cm and 93% stand stocking. After thinning: the number of trees/ha were 168,

282, and 566 for the 40, 60, and 80% stocking treatments respectively; basal area/ac was 13.1, 19.5, and 24.1 m²/ha for the 40, 60, and 80% stocking treatments respectively; and quadratic mean dbh was 32.0, 30.2, and 24.1 cm for the 40, 60, and 80% stocking treatments respectively.

All trees were felled with a chainsaw during the fall of 1986. Stumps of overstory trees removed in thinning were sprayed with herbicide during December 1986, and January 1987, on all plots designated for one (W1) or two (W2) weed control treatments (see Table 1). During March 1987, the first herbicide treatment was applied. At that time, woody stems ≥30 cm tall were cut and treated. Naturally occurring oaks were treated as any other competitor during weed control treatments.

Acorns were collected in fall of 1984 from 4 local stands in the Ozark National Forest. Stands were no larger than 64.7 ha and were at least 8 km apart. Within each stand acorns were collected from at least 5 parent trees. No fewer than 2,500 acorns were collected from each stand. Viability estimates were made of each set of acorns so that at least 2,000 sound acorns were obtained. After nursery planting, all seedlings were undercut June 21, 1985 (first growing season) with a Fobro lifting machine with the blade set to a 15 cm depth. After lifting but before planting, taproots and lateral roots of all seedlings were pruned to a common length of 20 cm. Lifting and shoot clipping descriptions and dates can be found in Table 1.

Trees were hand-planted with mattocks by a six-person crew during the period March 30 through April 9, 1987. Nursery stock was removed from cold storage on an as-needed basis.

The second herbicide treatment (W2) and the final overstory removal were applied during the winter of 1990. Cut stems of all overstory trees were treated with herbicide (see Table 1 for details).

Table 1. Designed study variables defined (independent variables). The dependent variable is the dominance probability that a planted tree will live to attain a favorable competitive position (i.e., at least 80% of the mean height of dominant competitors) at a specified year.

Variable category	Independent variable name (design level)	Variable description
Planting environment	Preharvest overstory stocking—stocking after thinning from below (shelterwood creation) (main plots)	Three levels: shelterwoods were thinned to 40, 60, or 80% stocking (D40, D60 or D80, respectively) before planting. The overstory was removed 3 years after planting.
Planting environment	Weed control treatments (main plots)	Three levels: (1) W0—control*; (2) W1—one-herbicide treatment (the winter before spring planting) + mechanical weeding (trees ≥30 cm [1 ft] tall were cut the winter before overstory removal); (3) W2—two-herbicide treatments. In both W1 and W2, the first herbicide application (Tordon 101R or Roundup) was applied to stumps of cut overstory trees (trees ≥3.9 cm dbh) and to cut stems of understory trees ≥30 cm tall the winter prior to planting. In W2, the second herbicide application (Garlon-4) was applied the winter before overstory removal† to cut stems of trees ≥30 cm tall.
Nursery production	Shoot clipping treatments (subplots)	Three levels: C0—shoots not clipped; C1—shoots clipped 20 cm (8 in.) above the root collar in the fall (Nov.–Dec.) before planting; C2—shoots clipped 20 cm above the root collar in the spring (Mar.) before planting.
Nursery production	Time of lifting (subplots)	Two levels: L1—seedlings lifted in November; L2—seedlings lifted in March.
Nursery production	Seed source (sub-subplots)	Four sources: collected from local stands distributed across the Buffalo ranger district of the Ozark National Forest

* Stems ≤3.8 cm dbh not treated, however stems >3.8 cm dbh were cut with the overstory and treated with Roundup.
† Overstory shelterwood removal occurred during the winter of 1989–1990.

Measurements

In addition to the designed study variables, initial basal stem diameter (caliper) of each seedling was measured 2 cm above the root collar to 0.1 mm. Initial caliper averaged 11 mm and ranged from 4 to 22 mm. At each remeasurement, the height of the dominant (tallest) woody competitor was measured to the nearest cm using a height pole on a 3.14 m² plot centered at every fourth planted tree location. We define these as the competition plots. The dominant competitor species, most abundant competitor species, and the density of all tree reproduction ≥30 cm tall also were recorded for each competition plot. All planted living trees on all plots also received a height measurement to the nearest cm using a height pole each measurement year. Naturally occurring oak were also considered competitors to the planted trees, receiving the same treatments and measured as any other competitor.

Analysis

To assess the competitive status of planted oaks, we compared their heights to those of dominant competitors in years 6 through 11. We defined a successful planted tree as one that attained at least 80% of the mean height of dominant competitors (RH80). Trees attaining that height typically occupy a position of dominance or codominance. This approach thus integrates survival and growth responses into a single measure of the proportion of planted trees that attain a specified relative height. We then estimated dominance probabilities for individual trees using logistic regression. A dominance probability is defined accordingly as the estimated probability that an individual planted tree will survive and attain a dominant or codominant crown position at time y. This is our measure of competitive capacity. Probability estimates were based on the RH80 success criterion.

Logistic regression was used to estimate probabilities for dominance of planted northern red oak, dominance of competitors, and survival of planted trees. We used the model building approach recommended in Hosmer and Lemeshow's (1989, p. 82) text on applied logistic regression. There is also an excellent summary of this method in Weigel and Peng (2002). Logistic regression has been used in studies to predict growth and success of regenerated oak stems (Lowell et al. 1987), to estimate the contribution of planted hardwoods to future stocking (Johnson and Rogers 1985), and to model regeneration of oak stands (Dey et al. 1996).

Designed independent variables included three levels of overstory stocking, three levels of weed control, three levels of shoot clipping, two times of lifting seedlings, and four seed sources (Table 1). Other independent variables included site index, initial seedling caliper, and years since planting. The dependent variable is the dominance probability, except in the case of one model where it was the probability of survival.

Although the observed value of the dependent variable is binary (0 or 1) in logistic regression, the resulting probability estimates are continuous and restricted to the interval 0 to 1. To prepare for logistic regression analysis, each tree was assigned either 1 (successful) or 0 (unsuccessful). For example, dominance probability (competitive capacity) success was based on the RH80 criterion above, where trees ≥RH80 were coded 1 and those < RH80 were coded 0. Mortality of an individual stem prior to the measurement year was also considered a failure.

For categorical independent variables, standard logistic regression dummy variables were used (Hosmer and Lemeshow 1989). For instance, because there were three weed control treatments, two dummy variables were needed, where the no weed control (W0) was coded 0, 0; one weed control (W1) was coded 1, 0; and two weed control treatments (W2) was coded 0, 1. For categorical variables with only two outcomes, only one dummy variable was used, coded either 0 or 1.

To evaluate logistic regression model performance, we selected predictors with a P value of 0.05 or less based on the chi-square distribution with one degree of freedom. We used the Hosmer-Lemeshow goodness-of-fit statistic (Hosmer and Lemeshow 1989, p. 140) to test the null hypothesis that the equation described the data. For Hosmer-Lemeshow, goodness-of-fit P values of 0.05 or less (indicating a poor fit of the equation to our data), the null hypothesis was rejected. It is therefore important to note that predictor P values of 0.05 or less have a different interpretation than the Hosmer-Lemeshow goodness-of-fit P values of 0.05 or less.

Results

Dominant Competitors

Eleven years after planting, the mean height of surviving planted trees averaged across all treatments was 3.1 m. Regardless of overstory density and weed control treatment, there were greater differences in height among dominant competitors than among planted trees (Figure 1). Within each density treatment, variability of planted tree heights and the difference between the heights of dominant competitor and planted trees decreased as intensity of weed control increased.

Five species were dominant competitors on 63% of the competition plots (where competition plots are the 3.14 m² plots centered on every fourth planted tree location): sassafras (*Sassafras albidum* Nutt.), blackgum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), black cherry (*Prunus serotina* Ehrh.), and flowering dogwood (*Cornus florida* L.) (Table 2). Four of these species—flowering dogwood, blackgum, sassafras, and red maple (Table 3)—also occurred as the most abundant competitor on 66% of the plots. Natural oak reproduction represented 6.1% of the dominant competitors and was the most abundant competitor on only 5.4% of the competition plots.

Although flowering dogwood was the most abundant competitor and ranked fifth in importance among dominant competitors by the eleventh year (Table 2), its dominance probability was relatively low (Figure 2a, Tables 4a and 4b). In addition, its dominance probability decreased with increasing intensity of weed control and decreased with increasing site index. Dominance probability of naturally occurring oak decreased with increasing site index (Figure 2b, Tables 4a and 4b). Probabilities were higher for lower shelterwood densities (40 or 60% stocking) than for the higher (80% stocking) density.
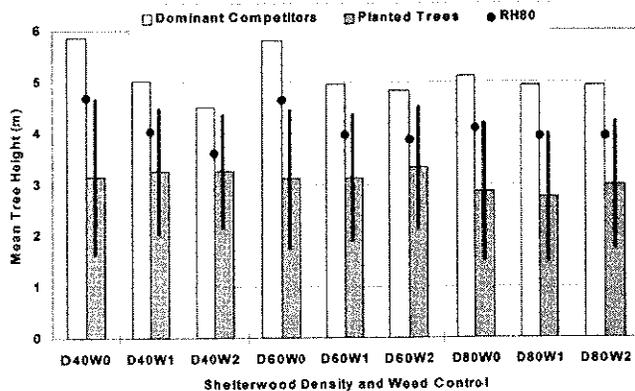
Figure 1. Mean eleventh-year heights of dominant competitors and surviving planted trees by preharvest overstory density (D) and weed control treatments (W) (see Table 1 for designed variable descriptions). Vertical lines within bars are standard deviations of mean planted tree heights. RH80 represents 80% of the mean height of dominant competitors and was used as the criterion for defining planted tree success.

Mean heights of dominant competitors increased with increasing site index, and differences among site indices increased with time (Figure 3, Tables 4a and 4b). The tallest competitor trees occurred on plots with no weed control (W0). Mean heights decreased as intensity of weed control increased from W0 to W1 to W2.

Dominance Probabilities—The Competitive Capacity of Planted Trees

Eleventh year dominance probabilities for planted trees varied with initial seedling caliper, site index, shelterwood stocking level, weed control, and seedling clipping. Greatest dominance probabilities existed on sites with the lowest site index (18 m) that received the 40 or 60% stocking shelterwood

treatment, for trees with the largest initial seedling caliper (22 mm), that had been top-clipped and planted in plots that had received two weed control treatments. The lowest probability of becoming a dominant tree existed on sites with the highest site index (24 m) that received the 80% stocking shelterwood treatment, for trees with the smallest initial seedling caliper (4 to 12 mm), and that were unclipped seedlings that were planted in plots that had received no weed control (Figure 4, Tables 4a and 4b).

Three of the designed study variables (Table 1) were not part of the model. These variables were seed source, time of lifting, and time of clipping. They were not significant predictors of dominance (P values > 0.05). Although time of clipping was not a significant predictor, whether a seedling was clipped or not clipped was significant.

The response surfaces in Figure 5 illustrate how dominance probability increases with years since planting. This increase in dominance probability over time is due to a continuing decrease in the difference between height of dominant competitors and the planted trees occurring at a more rapid rate than mortality of planted trees. Planted trees with the largest initial caliper consistently have the greatest capacity to compete over time.

Survival Probabilities of Planted Trees

Survival of all planted oaks was 91% in year 6, 86% in year 8, and 70% in year 11. Most of the trees that died during this period had an initial seedling caliper of ≤12 mm. In years 6, 8, and 11, trees with initial seedling calipers of ≤12 mm accounted for 67, 73, and 73% of planted northern red oak mortality, respectively.

Independent variables that changed with eleventh year survival probabilities of planted northern red oak paralleled

Table 2. Percent of competition plots* in which a given species occurred as the dominant competitor (relative to planted trees) in 1997 (11 yr after planting, 8 yr after shelterwood overstory removal). Weed control treatments W0, W1, and W2 are defined in Table 1.

Species	Stocking[†] = 40%			Stocking = 60%			Stocking = 80%			Totals
	W0	W1	W2	W0	W1	W2	W0	W1	W2	
Sassafras (*Sassafras albidum* Nutt.)	2	1	3	2	0	2	2	1	3	16.6
Blackgum (*Nyssa sylvatica* Marsh.)	1	2	1	2	2	2	2	2	2	15.3
Red maple (*Acer rubrum* L.)	1	1	2	1	3	1	2	1	1	12.5
Black cherry (*Prunus serotina* Ehrh.)	1	2	1	1	1	1	1	2	1	10.8
Flowering dogwood (*Cornus florida* L.)	1	1	0	1	1	0	1	2	0	7.8
Carolina buckthorn (*Rhamnus caroliniana* Walt.)	1	1	1	0	0	0	1	2	0	6.5
Oaks[††] (*Quercus* spp.)	0	1	1	0	1	1	1	0	0	6.1
Hickories (*Carya* spp.)	1	1	1	0	0	0	1	0	0	4.7
Eastern hophornbeam (*Ostrya virginiana* Mill.)	0	0	0	0	1	2	0	0	0	3.7
Sumac (*Rhus* spp.)	1	0	1	0	0	0	0	0	0	2.8
Sugar maple (*Acer saccharum* Marsh.)	0	0	0	0	0	0	0	0	1	2.2
Paw paw (*Asimina triloba* [L.] Dun.)	1	0	0	1	0	0	0	0	0	2.0
White ash (*Fraxinus americana* L.)	0	0	0	0	0	0	0	0	0	1.9
Other[§]	0	1	1	1	1	1	1	0	1	7.0
Totals	11.6	11.6	11.4	9.3	11.7	11.7	11.7	11.7	9.3	100.0

* Based on 1,027 plots, 3.14-m² in size, centered on every fourth planted tree.
† Represents percent stocking in the shelterwood phase.
†† Includes white oak (*Quercus alba* L.), northern red oak (*Quercus rubra* L.), and black oak (*Quercus velutina* Lam.).
§ Species that represent < 1.5% of the total and include: witch-hazel (*Hamamelis virginiana* L.), American elm (*Ulmus americana* L.), American beech (*Fagus grandifolia* Ehrh.), black locust (*Robinia pseudoacacia* L.), serviceberry (*Amelanchier spp.*), wild plum (*Prunus americana* Marsh.), redbud (*Cercis canadensis* L.), hackberry (*Celtis occidentalis* L.), mulberry (*Morus spp* L.), cucumber tree (*Magnolia acuminata* L.), Ozark chinkapin (*Castanea ozarkensis* Ashe), black walnut (*Juglans nigra* L.), umbrella magnolia (*Magnolia tripetala* L.), eastern redcedar (*Juniperus virginiana* L.), and devil's walkingstick (*Aralia spinosa* L.).

Table 3. Percent of competition plots* in which a given species occurred as the most abundant competitor in 1997 (11 yr after planting, 8 yr after shelterwood overstory removal)

Species	Stocking‡ = 40%			Stocking = 60%			Stocking = 80%			Totals
	W0	W1	W2	W0	W1	W2	W0	W1	W2	
Flowering dogwood	3	4	2	2	3	1	4	4	1	23.2
Blackgum	1	1	1	3	2	3	3	2	3	19.7
Sassafras	2	0	3	1	0	2	1	1	3	12.7
Red maple	2	1	1	1	2	1	1	1	1	10.7
Oaks††	0	1	1	0	1	1	1	0	0	5.4
Black cherry	1	1	0	0	0	1	0	1	0	4.4
Hickories	0	1	1	0	0	0	0	1	0	3.4
Sumac	0	0	1	0	0	1	0	0	0	3.4
Carolina buckthorn	0	1	0	0	0	0	0	1	0	3.1
Eastern hophornbeam	0	0	0	0	0	1	0	0	0	2.8
Sugar maple	0	0	0	0	0	0	0	1	1	2.1
Paw paw	1	0	0	1	0	0	0	0	0	2.1
White ash	0	0	0	1	0	0	0	0	0	2.0
Witch hazel	0	0	0	0	0	0	0	0	0	1.6
Other§	0	1	1	0	1	0	0	0	0	3.4
										100.0

* Based on 1,027 plots, 3.14 m² in size, centered on every fourth planted tree.
† Represents percent stocking in the shelterwood phase.
†† Includes white oak, northern red oak, and black oaks.
§ Species that represent <1.5% of the total and include: American elm, American beech, black locust, serviceberry, wild plum, redbud, mulberry, eastern redcedar, and tree huckleberry (*Vaccinium arboreum* Marsh.).

those of the dominance probabilities mentioned above. Using the Mann-Whitney rank sum test for the eleventh year after planting, we found no statistical difference between no weed control (W0) and one weed control (W1) (*P* value = 0.091). With this in mind, we illustrate the survival probabilities for W0 and W2 only (Figure 6, Tables 4a and 4b). In relation to the independent variables, both the highest and lowest survival probabilities paralleled that of the highest and lowest dominance probabilities as described above. However, differences between probabilities with respect to predictors (e.g., between weed control treatments, between site indices, etc.) were much smaller. Survival probabilities decreased

Table 4a. Models and model parameter estimates.

Model number	Figure number	Model*	Parameter† estimates††								
			W0	W1	W2	D40	D60	D80	C0	C1	C2
1	2-a	$P_{fd} = (1/(1 + \exp(-(-1.0615 - W - 0.0563 \times (SI/10)^4))))^\S$	0	0	−0.9967						
2	2-b	$P_{oak} = 1/(1 + \exp(-(-10.8661 + 176 \times (1/SI) - 0.0388 \times SI \times D)))^{\|}$				0	0	1			
3	3	$CH_m = -0.565 + (0.0268 \times SI \times YSP) + W^{\#}$	0	−0.666	−0.942						
4	4 & 5	$P_d = 1/(1 + \exp(-(-1.133 + D + W + C - (1.192 \times SI \times (1/ICAL)) + (0.133 \times YSP))))^{**}$	0	0.628	1.335	0	0	−0.728	0	0.206	0.206
5	6	$Ps = 1/(1 + \exp(-(5.033 + D + W + C - (0.332 \times SI \times (1/ICAL)) - (0.318 \times YSP))))^{@}$	0	−0.182	0.495	0	0	−0.468	0	0.141	0.141

* Models 1, 2, 4, and 5 are logistic regression models. Model 3 is a multiple linear regression.
† Parameters are defined in Table 1.
†† See Table 4b for associated *P* values, *n*, and linear regression statistics.
§ P_{fd} = the probability of flowering dogwood being a dominant competitor. *SI* = red oak site index (m) (Graney and Bower 1971).
‖ P_{oak} = the probability of natural oak being a dominant competitor.
\# CH_m = mean height of dominant competitor in m. *YSP* = years since planting oak. The *RH80* value used to determine success of each planted tree in model was calculated as *RH80* = CH_m * 0.80.
** P_d = the probability of planted oak equaling or exceeding 80% of the mean height of dominant competitors 11 yr after planting (8 yr after shelterwood removal). *ICAL* is the initial caliper (mm) of the seedling at time of planting.
@ *Ps* = the probability of planted oak surviving 11 yr after planting (8 yr after shelterwood removal).

Table 4b. Hosmer-Lemeshow goodness-of-fit *P* values, logistic regression predictor *P* values and multiple linear regression values.

Model number	Goodness of fit* (*P* value)	Predictor *P* values†							Multiple linear regression		*N*
		W	*SI*	*SI * D*	*SI* × (*1/ICAL*)	*D*	*C*	*YSP*	R^2	*SE*	
1	0.68	0.0014	0.0476								1,027
2	0.17		0.0001	0.0137							1,027
3	NA								0.85	0.524	129
4	0.738	<0.001			<0.001	<0.001	<0.001	<0.001			12,384
5	0.432	0.001			<0.001	<0.001	<0.001	<0.001			12,384

* Goodness of fit. Based on the Hosmer-Lemeshow goodness-of-fit statistic, differences between estimated probabilities and observed responses are not significant. Small *P* values designate a poor fit of the equation to the data while large values (>0.05) indicate a good fit.
† Based on the chi-square distribution with one degree of freedom. *SI* is site index in meters, *YSP* is years since planting, other predictor codes are defined in Table 1.

A

B
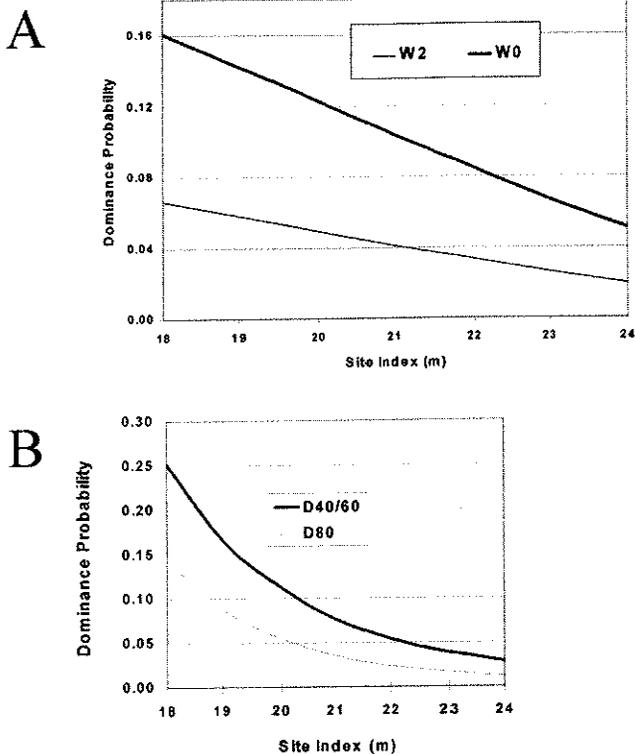
Figure 2. (a) Probability of flowering dogwood as a dominant competitor in 1997 (11 yr after planting and 8 yr after shelterwood removal) in relation to site index (m) and weed control treatments (W0 = average of no control and once-treated; W2 = twice treated). Based on logistic regression model number 1 (Tables 4a and 4b). (b) Probability of occurrence of natural oak reproduction (all species) as a dominant competitor to planted oaks in 1997 (11 yr after shelterwood harvest/planting and 8 yr after shelterwood removal) in relation to red oak site index (m) and shelterwood density (in stocking percent); D40/60 = 40 or 60% stocking; D80 = 80% stocking. Based on logistic regression model number 2 (Tables 4a and 4b).


Figure 3. Mean heights of dominant competitors in relation to years since initial shelterwood harvest/oak planting, site index and weed control (W) treatments (W0 = no weed control; W1 = once treated; W2 = twice treated). Based on linear regression model number 3 (Tables 4a and 4b).

over time (Figure 6, Tables 4a and 4b). Survival was lowest for seedlings of small initial caliper, given no weed control, and where site index was highest.

As with dominance probabilities, three of the designed study variables (Table 1) did not significantly contribute to the model. Seed source, time of lifting, and time of clipping were not significant predictors of survival (P values > 0.05).

Discussion

Simultaneous measurement of planted trees and competition over time and the rating of each individual planted tree to its most serious competitor tells us that, although there are many factors that affect planted tree success, the joint effects of these factors can be expressed as a single quantitative value. These dominance probabilities estimated from logistic regression are a measure of the competitive capacity of planted trees. Moreover, dominance probabilities and their reciprocals integrate planting environment, seedling quality, survival and growth into a single silviculturally and ecologically useful expression. This compels us to take a more holistic view of what underplanting in heterogeneous forest environments is all

about: being able to predict the outcome of the competitive struggle between planted trees and other vegetation.

The concept of competitive capacity and the use of logistic regression to compute dominance probabilities can be extended to other ecosystems and regions and can be used for predicting the future dominance potential of natural as well as artificial reproduction. Competitive capacity varies by ecosystem, along environmental gradients, with site productivity, with different suites of competitors, with variation in natural disturbance regimes or silvicultural systems, and by species of interest.

Oak Ecosystems of the Boston Mountains

In oak ecosystems of the Boston Mountains, the predominant nonoak species grow rapidly and can occupy a substantial portion of the growing space for 2 or 3 decades after shelterwood removal. Species such as flowering dogwood, sassafras, and eastern hophornbeam (*Ostrya virginiana* Mill.) influence oak dominance probabilities because of their rapid early growth and high stocking during the regeneration period. These species lose their competitive advantage in older stands because of their high mortality rates in developing stands or their limited height development potential. However, they are able to persist from one generation to the next as advance reproduction, ready to dominate growing space made available by the next stand replacement disturbance. Though their dominance is relatively short-lived, they can influence oak dominance probabilities in the long term by limiting oak development and survival in the regeneration period.

After 8 yr, the most abundant and frequently occurring dominant competitor was flowering dogwood, representing 27.7% and 20.1% of trees, respectively. However, by the eleventh year, dogwood ranked fifth as a dominant competitor at 7.8% (Tables 2 and 3). As the stands develop, this small-stature tree will be increasingly relegated to the subcanopy. Flowering dogwood is a persistent understory tree in these forests due to its tolerance to shade. For instance, its maximum capacity for photosynthesis occurs at about one-third of
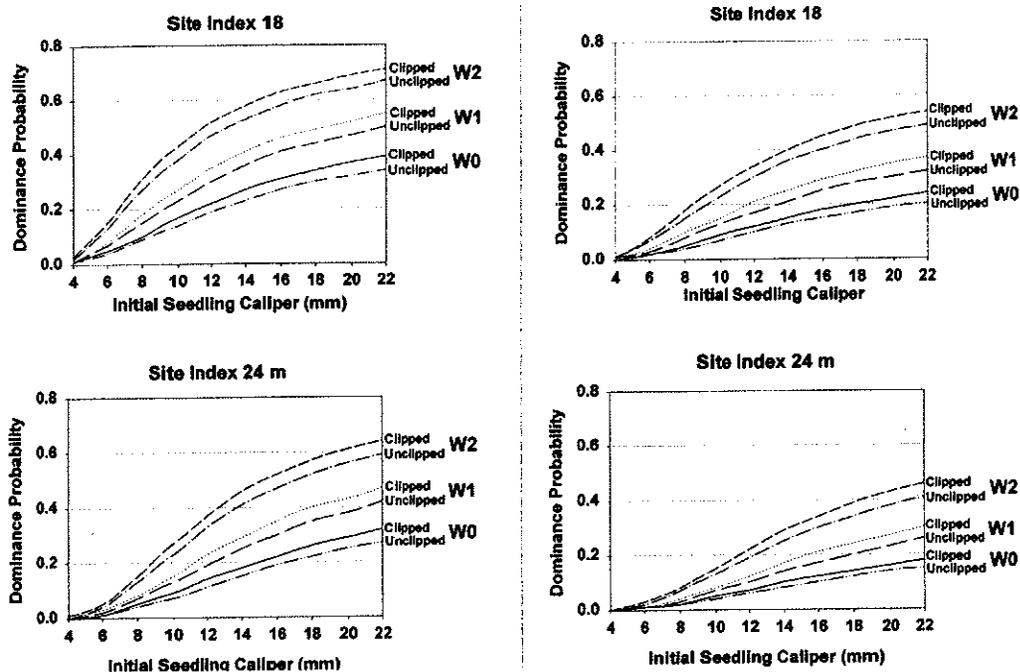
Figure 4. Eleventh-year dominance probabilities for planted northern red oaks in relation to initial seedling caliper, clipping, site index and weed control treatment. Based on logistic regression model number 4 (Tables 4a and 4b).

full sunlight (Vimmerstedt 1965). Although its dominance probability will continue to decrease as the main canopy develops, it is likely to persist throughout the life of the forest.

Other important species such as sassafras, eastern hophornbeam, and Carolina buckthorn (*Rhamnus caroliniana* Walt.) also tend to rapidly drop out of the developing main canopy due to high mortality or limited stature. Black cherry, with its rapid early height growth, does not have the resilience to withstand the frequent, periodic ice storms and summer droughts of the Boston Mountains. These ice storms result in broken tops in black cherry trees, which usually do not recover their height advantage. On site indices < 23 m, black cherry trees that do not succumb to ice storms lose vigor and often die by age 20 or 30 yr. The dynamics of black cherry competition in the Boston Mountains is a stark contrast to the dominance potential and competitive capacity of black cherry in the Allegheny Plateau Region (Marquis 1990).

The dominance probabilities of naturally occurring oak (Figure 2b) (i.e., reproduction that became established after the weed control treatment was applied or that was already established and survived the treatment) are relatively low. Natural oak reproduction dominance probabilities increase by a factor of approximately 0.10 where shelterwood density is low (40% or 60%) and oak site index is low (18 to 19 m). In oak ecosystems of similar productivity (site index 18 m at age 50), Schlesinger et al. (1993) found that reducing overstory density to 40% stocking by shelterwood harvesting significantly increased the abundance of large oak saplings, of natural regeneration origin, 10 yr after the removal of the shelterwood in the Missouri Ozarks. In the southern Appalachians (Loftis 1990), southwestern Wisconsin (Johnson et al. 1989), and Boston Mountains (Graney and Rogerson 1985),

the long-term competitiveness of natural northern red oak reproduction was increased through combinations of harvesting from below to create a shelterwood with control of competing woody vegetation and stump sprouts. In the Missouri Ozarks, Larsen et al. (1997) evaluated the regeneration potential of oak species in forests harvested by the selection regeneration method for over 40 yr and found that the probability of abundant large oak reproduction increased when overstory density was maintained at relatively low stocking (e.g., 58%).

Operational methods of treating competing woody vegetation can be designed so that the naturally occurring oak advanced reproductions are not subjected to herbicide treatment, as occurred in our study. This would allow more of the oaks to persist and thereby increase their likelihood of attaining dominance. In this study, however, shelterwoods without any weed control (W0) had fewer naturally occurring oaks because surrounding competitors also were not treated. For instance, of all the competition plots, only 1.5%, 2.7%, and 1.9% of the no weed control (W0), one weed control (W1), and two weed controls (W2) respectively contained naturally occurring oak as a dominant competitor. The lower percentage in the W0 treatment is likely due to greater competition. Even though naturally occurring oaks had been treated with herbicide in W1 and W2, they still were more frequently the dominant competitor. This is likely due to increased light availability, allowing new oaks to become established and surviving oaks to thrive. In mature forests of southwestern Wisconsin, Lorimer et al. (1994) found that controlling tall (1.5 m in height) woody vegetation with herbicides increased the abundance of natural reproduction of northern red oak over that observed in undisturbed stands, and this difference

40 and 60% Stocking
Clipped Seedlings

Site Index 18 m

Site Index 24 m

80% Stocking
Clipped Seedlings
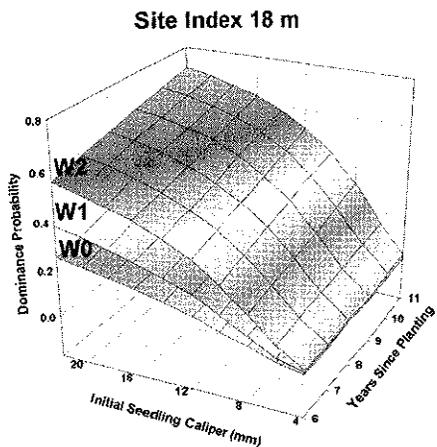
Site Index 18 m
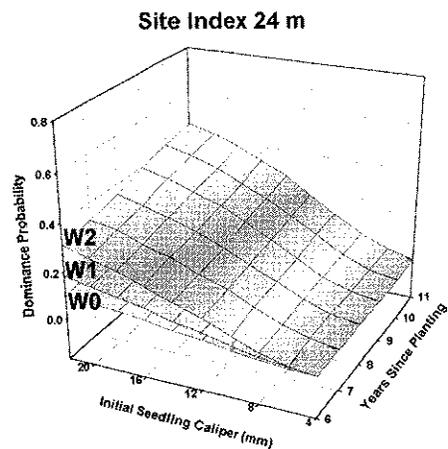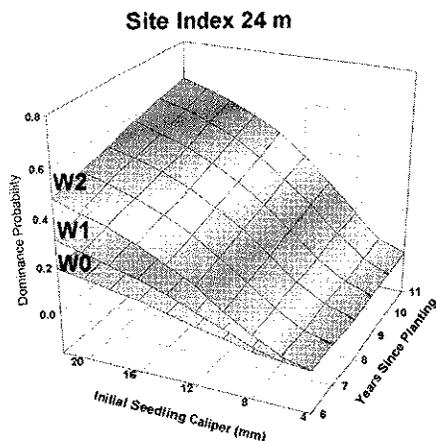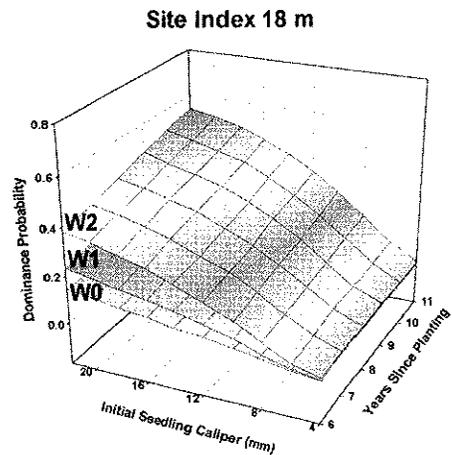
Site Index 24 m

Figure 5. Estimated dominance probabilities for planted northern red oaks in relation to initial seedling caliper, clipping, site index, years since planting, and weed control treatment. Based on logistic regression model number 4 (Tables 4a and 4b).

was more pronounced as site productivity increased. Control of understory competing woody vegetation and stump sprouts of undesirable species has also improved the competitiveness of natural northern red oak reproduction on sites of good to high productivity (site index 18 to 29 m) in the Missouri Ozarks, the Driftless Area of Wisconsin, and the southern Appalachians (Johnson et al. 1989, Loftis 1990, Schlesinger et al. 1993).

Competitive Capacity of Planted Oaks

In the Boston Mountains of Arkansas, competitive capacity, as estimated by dominance probability, for planted northern red oak seedlings was highest when shelterwood overstory stocking level was low (40% to 60% stocking), understory woody competition was treated twice, site quality was relatively low (18 m), and initial seedling caliper was large (≥ 12 mm). Planted oaks had higher dominance probabilities in the 40 and 60% stocking treatments than the 80% stocking treatments (Figures 4 and 5). Differences between the 80% stocking treatment and the two lower stocking treatments are likely due to differences

in understory light levels. In a study by Dey and Parker (1997b), northern red oak seedlings planted in a shelterwood were taller, larger in diameter, and had greater root volume, area, and dry mass than seedlings planted in an uncut, mature northern hardwood stand. They attributed the increase in growth and competitiveness to dramatic increases in light in the shelterwood over the extremely low light levels (i.e., 1% of full sunlight) in the uncut stand. Loftis (1990) found that reducing initial basal area by 20 to 40% benefited growth and survival of northern red oak seedlings in the southern Appalachians. In the Missouri Ozarks, Larsen et al. (1997), Schlesinger et al. (1993) and Johnson (1984) observed that oak advance reproduction and underplanted northern red oak seedlings had improved growth and were more competitive when overstory density was reduced by harvesting to 40 to 60% stocking. Similar benefits of reduced overstory stocking to oak regeneration success have been noted in southwestern Wisconsin (Johnson et al. 1989). However, shelterwood harvesting alone has not always resulted in successful oak regeneration. Johnson et al. (1986), Loftis

Clipped Seedlings

Site Index 18 m

Unclipped Seedlings

Site Index 18 m


Site Index 24 m
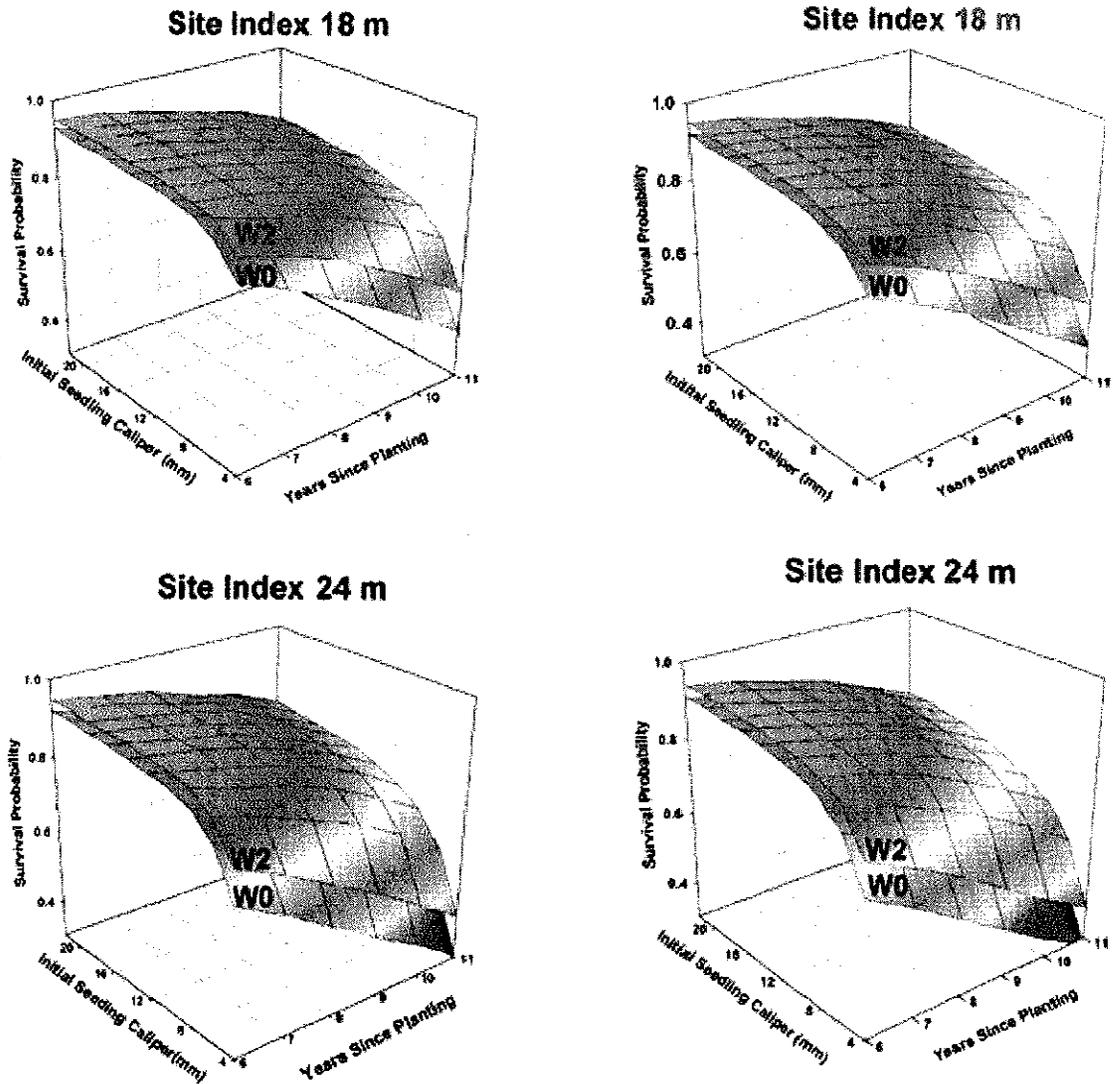
Site Index 24 m

Figure 6. Estimated survival probabilities for planted northern red oaks with preharvest overstory densities of 40 and 60% stocking in relation to initial seedling caliper, clipping, site index and weed control treatment. Based on logistic regression model number 5 (Tables 4a and 4b).

(1990), Schlesinger et al. (1993), and Lorimer et al. (1994) emphasize the need to control competing woody vegetation in conjunction with harvesting to reduce overstory density and that the level of overstory reduction should be reduced with increases in site quality.

Two weed control treatments of competing understory woody vegetation and initial control of stump sprouts significantly improved the dominance probability of planted northern red oak (Figures 4 and 5). One weed control treatment at the time of shelterwood creation was significantly better than no weed control treatment. Weed control, in conjunction with overstory stocking reductions, has been shown to increase the survival and growth of planted northern red oak and natural oak advance reproduction in a variety of oak ecosystems from the southern Appalachians to the Missouri Ozarks and the southern Lake States (Johnson et al. 1989, Loftis 1990, Schlesinger et al. 1993). Weed control of woody competi-

tors has been especially important to oak regeneration success on higher quality sites. Control of taller (>1.5 m) understory woody vegetation in mature, undisturbed forests in southwestern Wisconsin provided some benefit to northern red oak advance reproduction, but growth gains were modest in the absence of any reduction in overstory density (Lorimer et al. 1994).

Site quality was significantly and negatively related to dominance probability for planted northern red oak reproduction (Figures 4 and 5). Although competition is more intense on higher quality sites, over time height differences between planted oaks and dominant competitors changed in favor of the planted oaks. In the Boston Mountains, site quality changes abruptly across the bench-and-bluff topography (Graney 1977). A distance of 40 m may encompass site index differences of more than 3 m as the topography changes from concave inner benches to convex outer benches. Dominance probabilities vary accord-

ingly with the outer benches more likely to produce a dominant tree. Not only does increasing site index reduce survival probabilities for small caliper trees (Figure 6), it also reduces dominance probabilities over a wide range of initial seedling calipers (Figure 4). Holding relatively higher overstory stocking on higher quality sites has been recommended to control the release of oak competitors while attempting to increase light levels at the forest floor for oak advance reproduction (Loftis 1990, Schlesinger et al. 1993). However, in our study, the 80% stocking treatment resulted in decreased survival and growth of planted trees relative to the 40% to 60% stocking treatment. The 80% stocking treatment would probably have benefited from a third weed control treatment. Differences between these studies stress the importance of analyzing competitive capacity in other ecosystems to account for differences in relative competitor relationships, species, environmental conditions, silvicultural practices, planting stock, genetics, productivity, and local climatic influences. For instance, the Loftis study recommended higher stocking on higher site index sites mainly to control yellow-poplar. However, yellow-poplar was not a competitor in our study or in the Boston Mountains in general.

Dominance probabilities of planted northern red oak increased significantly with increasing initial stem basal caliper in both the good and high site quality stands (Figures 4 and 5). Similarly, planting large diameter oak seedlings has resulted in higher success rates in Missouri and Indiana (Johnson 1984, Johnson et al. 1986, Kazmarek and Pope 1993, Weigel and Johnson 1998a, Weigel and Johnson 1998b, Weigel and Johnson 2000). Increasing competitive capacity with increasing shoot diameter is likely related to root morphology and seedling quality. In a comparison of shoot diameter, number of first-order lateral roots, and shoot length, Dey and Parker (1997a) found shoot diameter to be a good integrator of root system characteristics and the best predictor of seedling field performance of northern red oak underplanted in a shelterwood. They found that basal stem caliper was significantly correlated with root volume, area, and biomass. Consequently, planting larger seedlings is often recommended especially for species such as the oaks (Johnson et al. 1986, Schultz and Thompson 1997, Kormanik et al. 1998). Planting oaks with large stem caliper and well developed root systems takes advantage of oak's regeneration strategy that involves development of large energy reserves in the roots to support rapid shoot growth following release from competing vegetation and overstory shade. The current management problem is that the caliper of conventional nursery grown bareroot oak seedlings is highly variable and often smaller than minimum diameters recommended by, for example, Johnson et al. (1986) for planting in shelterwoods or clearcuts.

Shoot clipping increased dominance probabilities in planted northern red oak, regardless of overstory stocking or weed control treatments (Figure 4). Previous studies have demonstrated that shoot clipping nursery stock improves survival and height growth. In a study conducted in Missouri,

Sander (1983) found better survival for clipped (91–96% survival) than unclipped seedlings (63 to 71% survival) 5 yr after planting. Zaczek et al. (1997) examined northern red oak outplanted in a clearcut and found that 2-0 stock, undercut in the nursery and shoot-clipped at planting, performed best, with a mean height of 3 m and 100% survival after 6 yr. Johnson (1984) found that shoot-clipping significantly improved the performance of northern red oak in Missouri Ozark clearcuts and shelterwoods. However, other researchers have not found clear positive effects from shoot clipping including Russell (1971, 1973, 1979), Gordon et al. (1993) and Crunkilton et al. (1989).

The designed study variables: time of shoot clipping, time of lifting, and seed source did not significantly contribute to our models and therefore were not included in them. Past research and/or recommendations indicated that these variables could have significant impact on growth and survival. For instance, Johnson et al. (1984, 1986), Johnson (1984, 1988, 1990), and Zaczek et al. (1993) proposed that shoot-clipping be done near the day of planting so that transport of growth regulators from shoot to roots is given ample opportunity to occur. Time of lifting was included in our study because of the advantages that spring-lifted trees are purported to have. Pope (1993) noted that spring-lifted trees are often in better physiological condition than fall-lifted trees. Also, the fact that seed source was not a significant variable in our models is probably a result of the close proximity of our four local seed sources.

Recommendations

Calculation of dominance probabilities for planted oak reproduction has practical applications in determining the planting densities needed to achieve a target stocking at some specified future date. In this study, 32% of the planted northern red oak had an initial caliper of ≥ 12 mm with a mean caliper of that subpopulation of 14 mm. For D40/W2 field treatments on a site index of 18 m, the predicted dominance probability for a 14 mm clipped seedling at year 11 is 0.58. If seedlings of that average diameter were planted and the goal was to obtain 250 competitively successful seedlings per ha 11 yr after planting, 428 seedlings per ha [i.e., (1/0.58)*250] would need to be planted. For the same seedlings on site indices 21 and 24 m, dominance probabilities of 0.52 and 0.46 indicate that 480 and 547 seedlings per ha should be planted, respectively. However, if seedlings had an average diameter of 6 mm for the D40/W2 field treatments on a site index of 18 m, the predicted dominance probability for a clipped seedling at year 11 is 0.15, and 1,625 seedlings would need to be planted to produce 250 dominant seedlings. For a 6 mm seedling under the same conditions, changing site index to 24 m would result in a dominance probability of 0.05 and the need to plant 4,780 seedlings to produce the same results. Therefore, initial seedling size and site quality will have a significant effect on planting costs when costs are expressed as dollars per competitively successful tree. Even though large seedlings are more expensive to grow in the nursery and outplant, the cost per competitively successful planted tree decreases as initial seedling size increases. This

results from a rapid rate of increase in dominance probabilities with increasing seedling caliper, which outweighs the rate of increasing cost associated with increasing seedling size. Therefore, a cost analysis of planting options should be an integral part of an overall regeneration strategy.

The high cost of establishing successful oak plantings may dictate limiting plantings to designated portions of stands. Accordingly, plantings could cover a single contiguous area of several hectares or be dispersed across several patches or groups, each comprising a fraction of a hectare. The latter method could be used in conjunction with the group selection method (Murphy et al. 1993). In principle, this approach would combine the objectives of shelterwood and group selection methods into a silvicultural variant called the group shelterwood method (Smith et al. 1997, p. 408). In applying the method to oak planting, we propose that only a portion of group openings created in any one harvest cycle be planted. Regardless of the silvicultural system used, concentrating planting within designated areas (contiguous or dispersed) minimizes herbicide or other site preparation costs associated with planting.

Conclusions

This competition-centered approach to evaluate regeneration potential integrates environmental influences and competition relationships with survival and growth of desired reproduction into a single silviculturally and ecologically useful expression, i.e., competitive capacity. We interpreted dominance probability as a measure of the competitive capacity of an individual seedling. This value is the seedling's likelihood of attaining dominance in a specified environment at a specified future time. This concept may be useful in determining planting strategies to meet forest planning objectives. Overall, it allows us to take a more holistic view of what underplanting is all about: the ability to predict the outcome of the competitive struggle between planted trees and natural vegetation.

Through the use of logistic regression, we examined the struggle between planted seedlings and their competitors, and evaluated the importance of seedling size, site quality and intensity of weed control to seedling success in order to develop planting recommendations that could help breathe new life into these forests. When planting northern red oaks in the Boston Mountains one can maximize the likelihood of their attaining dominance or codominance 11 yr after planting (8 yr after overstory removal) by: (1) planting large (e.g. > 12 mm caliper), shoot-clipped seedlings, (2) planting under shelterwoods thinned to 40 to 60% stocking, and (3) controlling competing woody vegetation, including stump sprouts during early establishment similar to methods applied in this study. Weed control treatments become more important on high site index/quality sites.

Results from the present study indicate that the performance of planted oaks (i.e., their competitive capacity) relative to the developing competition is partially dependent on site quality. At low site indices, potentially long-lived competitors such as maples, white ash (*Fraxinus Americana* L.), and black cherry often occur during the early stand

development stage. However, they are less likely to persist there than the comparatively drought-tolerant oak. On higher quality sites, the dominance probability of these competitors increases, i.e., they have a higher competitive capacity, which causes subsequent decreases in the dominance of oak, unless weed control is applied.

In this study, natural oak reproduction rarely occurred as dominant trees 8 yr after shelterwood removal, especially on higher quality sites. However, many forests in the east are now managed using single tree selection, which provides less growing space and light at the forest floor than is provided in a shelterwood environment. This suggests that, under stand conditions now characteristic of the region, widespread failures in natural oak regeneration are likely occurring.

Loss of oak dominance in this and ecologically similar regions may largely be related to the exclusion of fire that previously acted to reduce competition and favor oak species. Oak planting by methods similar to those used in this study may provide a viable silvicultural alternative for maintaining oaks on at least some sites where they are threatened by successional displacement in the absence of fire. Managers that currently use prescribed fire in similar forests may be able to eliminate the cost and necessity of herbicide application by using several periodic fires to reduce competing vegetation in conjunction with shelterwood harvesting, weeding, or thinning.

Despite uncertainties in future stand development, eleventh year dominance probabilities provide a measure of planting success during the early stem exclusion phase that we term "competitive capacity." Current results confirm that overall survival is high. For initially large seedlings planted under shelterwoods at 40 to 60% stocking and given adequate weed control, a substantial proportion of planted trees can be expected to occupy crown positions favorable to their long-term survival and growth. Dominance probabilities are quite useful in estimating planting densities needed to achieve a target stocking by species as they vary by the combination of environmental conditions, silvicultural systems and planting stock characteristics, which are set by the manager.

Regardless of species or reproductive origin, the concept of competitive capacity can be used to assess regeneration success in any region by determining dominance probabilities based on comparisons of the reproduction and its competition, environmental factors such as site productivity, morphological characteristics of the desired reproduction (i.e., height and stem diameter), measures of stand structure and stocking. They can be derived for specific silvicultural practices and systems and for given ecosystems. The specific dominance probabilities developed in this study should be used with caution outside of the Boston Mountains and if the silvicultural practices differ from those applied here. Similar trends in dominance probabilities with changing site quality, overstory stocking, and size of planting stock have been observed in other oak-dominated ecosystems throughout the east. However, oak ecosystems within the range of such competitors as yellow-poplar (*Liriodendron tulipifera* L.) have significantly different competitive relationships that

drastically alter the competitive capacity of oak from that which we observed in the Boston Mountains. Our methods can be used to develop ecosystem-specific measures of competitive capacity and dominance probabilities through controlled studies such as ours.

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