Shelterwood-Planted Northern Red Oaks: Integrated Costs and Options

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ABSTRACT

Tree biology, environmental site conditions, relative monetary costs, management options, and the competitive struggle between planted trees and other vegetation were integrated when underplanting northern red oak (*Quercus rubra* L.) seedlings in Boston Mountain shelterwoods. This approach provides insight into the collective costs (biological, environmental, and monetary) associated with artificial regeneration. This analysis is partly based on previous research that determined the competitive capacity of more than 4,000 seedlings planted under shelterwood overstories. Using these probabilities in our simple accounting of cost, the cost of obtaining one competitively successful tree was calculated under various combinations of environmental variables, silvicultural treatments and seedling sizes. A successful tree was defined as one predicted to survive and attain dominance or codominance 11 years after planting. The cost of trees that were not likely to survive or reach a dominant or codominant position was added to the cost of obtaining a successful tree. In this way, the cost of the competitive struggle between planted trees and other vegetation is integrated into the monetary cost per successful tree. Results provide a practical tool for evaluating various planting options in relation to both associated costs and the expected biological success of alternative planting prescriptions.

Keywords: underplanting, oak, planting, trees, artificial regeneration

In the Central Hardwood Region (Merritt 1980, p. 108), oaks (*Quercus* spp.) flourished for thousands of years as dominant, keystone species (Spetich et al. 2002, Fralish 2004). However, on medium- to high-quality sites in the eastern United States today, successful natural oak regeneration often fails (Jackson and Buckley 2004, Spetich 2004) because of successional displacement of oaks by other species (McGee 1986, Shotola et al. 1992, Dodge 1997). From a practical standpoint, oak reproduction fails to attain dominance under current disturbance regimes that favor more shade-tolerant species or species with faster juvenile height growth. This has produced oak-dominated forests with insufficient natural oak regeneration potential and recruitment into the overstory to sustain current levels of oak stocking. The factor most often cited as the likely cause of this species shift is the absence of fire during the past century (Parker and Ruffner 2004, Spetich 2004, Dey and Hartman 2005).

Where natural oak regeneration potential to sustain current levels of oak stocking is lacking, effective management methods are needed to sustain oak stocking in future forests by promoting successful oak regeneration in an affordable manner (Johnson et al. 2002). Where sustaining or restoring oak is the goal, artificial regeneration by planting may be required (Dey et al. 2008). However, on medium- to high-quality sites, planting costs can be high and obtaining successful oak regeneration can be difficult because of intense competition from other species. Although regenerating by underplanting shelterwoods has been reported (Dey and Parker 1997, Spetich et al. 2002, Oswalt et al. 2004), these studies have not integrated the costs of planting and other treatments with regeneration success. Because managers need methods that are cost-effective, information is needed on comparative costs of alternative silvicultural treatments.

In this study, the relative costs of alternatives for planting oaks are evaluated by integrating differences in seedling size, competing vegetation, silvicultural treatment, and site quality with the competitive success of oak seedlings. Few studies have evaluated the costs of planting northern red oak (*Quercus rubra* L.) under a shelterwood (e.g., Weigel and Johnson 1998, Weigel and Johnson 2000). Only one study (Johnson 1992) has examined the relative costs of planting by incorporating competitive success and competition control costs. In his "provisional assessment," based on preliminary and extrapolated data, Johnson (1992) suggested that in Missouri forests, costs may be lower when planting large-caliper seedlings without herbicide treatment than when planting smaller seedlings and applying herbicide. The projected result was an equally successful planting at lower cost using large seedlings and omitting the expense of herbicide.

This article applies simple accounting of seedling biology, environmental site conditions, and planting costs. It evaluates related trade-offs by determining the relative costs of planting northern red oaks under shelterwoods. This was determined by integrating seedling size, various silvicultural and seedling treatments and their costs, competitive success, growth, future predicted mortality, silvicultural options, and planting environment through the use of the relations quantified by Spetich et al. (2002). We explain how and why we integrate planting costs with the predicted competitive success of planted seedlings.

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Rather than evaluate only planting costs, we estimate the cost of producing a successful seedling (i.e., one that is likely to attain a dominant or codominant crown position by stand age 11). This provides a more realistic cost estimate, since the objective is to obtain a given number of competitively successful trees. Thus, the cost of trees that are likely to die or not attain a competitively successful crown position (dominant or codominant) is added to the cost per successful seeding. This provides a more inclusive approach to accounting for costs by integrating the outcome of the competitive struggle between planted trees and other vegetation, the relative cost of the various underplanting treatments, and effects that environmental site quality have on planted tree success.

The Underplanting Study: Sites

The study was located in the Boston Mountains of Arkansas, in the southern lobe of the Central Hardwood Region (Merritt 1980). The Boston Mountains are the highest and most southern member of the Ozark Plateau physiographic province. They form a band 30–40 miles wide and 200 miles long from north central Arkansas westward into eastern Oklahoma. Elevations range from about 900 ft in the valley bottoms to 2,500 ft at the highest point. The plateau is sharply dissected. Most ridges are flat to gently rolling and are generally less than 0.5 mile wide. Mountainsides consist of alternating steep simple slopes and gently sloping benches. Site index for red oaks (northern red and black oaks [*Quercus velutina* Lam.]) on study sites ranged from 60 to 79 ft at 50 years (where site index is a measure of site quality).

Soils on mountaintops and slopes are usually of shallow to medium depth and are represented by medium-textured members of the Hartsells, Linker, and Enders series (Typic Hapludults). They are derived from sandstone or shale residuum, and their productivity ranges from medium to low. In contrast, soils on mountain benches are deep, well-drained members of the Nella and Leesburg series (Typic Paleudults). They developed from sandstone and shale colluvium, and their productivity is medium to high. Rocks in the area are alternating horizontal beds of Pennsylvanian shales and sandstones. Annual precipitation averages 46–48 in., and March, April, and May are the wettest months. Extended summer dry periods are common, and autumn is usually dry. The frost-free period is normally 180–200 days long.

Methods

Stand Characteristics

The shelterwood method was applied to create residual stocking of 40, 60, or 80% (Gingrich 1967). Initial overstory characteristics of stands before shelterwood creation averaged 443 trees/ac, 119 ft^2/ac of basal area, 93% stand stocking (Gingrich 1967), and 7.1 in. quadratic mean stand diameter (i.e., the diameter of the tree of average basal area). After shelterwood creation, number of trees/ac averaged 68, 114, and 229; mean basal area was 57, 85, and 105 ft^2/ac; and quadratic mean dbh was 12.6, 11.9, and 9.5 in. for the 40, 60, and 80% stocking treatments, respectively. Oaks were dominant before and after the shelterwoods were created, with removals largely composed of nonoaks in inferior crown classes.

Competition Control Treatments

Woody competition control treatments were applied to woody stems ≤1.5 in. dbh using the cut stem method. There were three levels of woody competition control (Table 1): (1) a control in which stems ≤1.5 in. dbh were not treated, but stems >1.5 in. dbh that were cut with the overstory were treated with Roundup; (2) one herbicide treatment was applied the winter before spring planting (this treatment also included a mechanical weeding in which trees ≥1 ft tall and ≤1.5 in. dbh were cut the winter before overstory removal); and (3) two herbicide treatments. In both level 2 and level 3, the first herbicide application (Tordon 101R or Roundup) was applied to stumps of cut overstory trees, to cut stems ≥1.5 in. dbh, and to cut stems of understory trees ≥1 ft tall the winter prior to planting. In level 3, the second herbicide application (Garlon-4) was applied the winter before overstory removal to cut stems of trees ≥1 ft tall and ≤1.5 in. dbh.

Table 1. Treatments and the dates that they occurred.

Date	Treatment
Fall 1986	Shelterwood creation
December 1986 to January 1987	Stumps of overstory trees cut during shelterwood creation were treated with an herbicide.
(No date)	Woody competition control treatment, level 1: A control in which stems ≤1.5 in. dbh were not treated.
	Woody competition control treatment, level 2:
March 1987	One herbicide treatment (Tordon 101R or Roundup) was applied to cut stems of trees ≥1 ft tall and ≤1.5 in. dbh prior to tree planting
March 1989	This treatment also included a mechanical weeding in which trees ≥1 ft tall and ≤1.5 in. dbh were cut the winter before overstory removal
March 30 to April 9, 1987	Tree planting on study sites
	Woody competition control treatment, level 3 (two-herbicide treatments):
March 1987	The first herbicide application (Tordon 101R or Roundup) was applied to cut stems of trees ≥1 ft tall and ≤1.5 in. dbh prior to tree planting
March 1989	The second herbicide application (Garlon-4) was applied to cut stems of trees ≥1 ft tall and ≤1.5 in. dbh
Winter (1989–1990)	Shelterwood harvest, all overstory trees harvested.

Note on woody competition control: In all three cases of no control, control once, and control twice, competing stems >1.5 in. dbh were cut with the overstory and treated with herbicide.

Acorn Collection, Nursery Production, and Outplanting

Acorns were collected from four local forest stands in the Ozark National Forest. Seedlings were grown in the nursery for two years prior to lifting. At the time of outplanting, each seedling was identified with a unique tagged number. A total of 4,320 2-0 northern red oak seedlings, all of which were undercut the first year in the nursery, were outplanted by hand under shelterwoods in early April 1987 at a 7.9 × 7.9-ft spacing in a split-split plot experimental design with five replicates. Each replicate was at least 7.6 ac in size. There were 45 (0.84-ac) main plots, with 9 main plots per replicate. The later loss of two main plots resulted in 4,128 available seedlings for study.

There were three levels of shoot top clipping: (1) shoots not clipped, (2) shoots clipped 8 in. above their rootcollar in fall before planting, and (3) shoots clipped 8 in. above the rootcollar in the spring before planting. Prior analyses showed there was no statistical difference between the two shoot-clipping treatments (levels 2 and 3), so these treatments were combined. This resulted in two levels of shoot clipping: not clipped (control) and top clipped.

Initial basal stem diameter (caliper) of each planted oak seedling was measured 0.8 in. above the rootcollar to 0.004 in. Initial caliper of 2-0 northern red oak seedlings averaged 0.43 in. and ranged from 0.16 to 0.89 in.

Planted trees and competition were measured after the 1st, 3rd, 4th, 6th, 8th, and 11th growing seasons. The height of the dominant woody competitor was measured on a 33.8-ft^2 plot centered at every fourth planted tree location, resulting in 1,024 competition plots. The dominant competitor species, most abundant competitor species, and density of all tree reproduction ≥1 ft tall also were recorded for each competition plot. Details are described in Spetich et al. (2002).

Shelterwoods

Trees were felled by chainsaw in the fall of 1986 to create shelterwoods. Stumps of cut trees were sprayed with herbicide during December 1986 and January 1987 on all plots (see Spetich et al. 2002 for details). In March 1987, the first herbicide treatment was applied. At that time, woody stems ≥1 ft tall were cut and treated. Naturally occurring oaks were treated as any other competitor during the level 1, 2, or 3 weed control treatments listed above. Three growing seasons after planting the shelterwood trees were harvested. Stumps were treated with herbicide. Overstory shelterwood removal occurred during the winter of 1989–1990.

Predicting Success of Planted Trees

In our prior analysis, we used logistic regression to identify and assess significant environmental and silvicultural variables that affected planted tree success. This included initial seedling basal diameter, site quality, intensity of weed control, and shelterwood stocking percentage (Spetich et al. 2002). The logistic model allowed us to integrate the combined effects of these variables into a single model. This model not only predicts the likely success of a planted tree under specific conditions, but the reciprocal of the probability of success provides a practical tool for resource managers.

Integration of Biological, Environmental, and Monetary Costs

The reciprocal of the success probability integrates planting environment, seedling quality, survival, and growth into a single silviculturally and ecologically useful value, namely the number of planted trees needed to obtain one successful tree. This compels us to take a more holistic view of underplanting in heterogeneous forest environments by enabling prediction of the outcome of the competitive struggle between planted trees and other vegetation over an 11-year period. These reciprocals were used to determine the number of trees to plant to achieve a target future stocking of successful trees, where successful trees are defined as those that survive to become dominant or codominant 11 years after planting (i.e., 8 years after final shelterwood removal). These calculated values were then used to evaluate the various costs to develop both the most economical and successful planting option. Based on those results, this study outlines five steps for optimizing both the costs and biological efficacy of planting northern red oaks under shelterwoods.

Results and Discussion

Seedling Response

Overall, larger seedlings had higher survival rates than smaller seedlings. Survival was lowest (67% survival rate) in the 0.16–0.47-in. basal diameter (caliper) class. By the 11th year after planting, the highest survival rate, 79%, occurred in seedlings in the largest size class (0.67–0.87 in.).

Competitive crown position relative to surrounding vegetation is also important to seedling survival. Specifying the crown class of the largest competitor in proximity to a planted tree results in a competition-centered approach to tree-planting. Four species accounted for more than 50% of the dominant competitors: sassafras (*Sassafras albidum* Nutt.), blackgum (*Nyssa sylvatica* Marsh.), red maple (*Acer rubrum* L.), and black cherry (*Prunus serotina* Ehrh.), which occurred in 17, 15, 13, and 11% of the plots, respectively. The top four most abundant competitors were flowering dogwood (*Cornus florida* L.), blackgum, sassafras, and red maple representing 23, 20, 13, and 11% of competitors, respectively.

Logistic regression was used to evaluate the competitive success of planted trees and the variables important to their success. Based on Spetich et al. (2002), at year 11, the probability of planted tree success increased with increasing initial seedling stem caliper, decreasing site index, decreasing shelterwood stocking levels, increasing woody vegetation competition control, and shoot clipping. Variables that increased success probabilities the most were shelterwood stocking (lower stocking was better), woody vegetation competition control (greater control was better), and initial caliper of seedlings (bigger was better).

The reciprocals of success probabilities provide silviculturally useful estimates of the number of trees needed to obtain, on the average, one competitively successful tree for a specified treatment combination. We used these reciprocals as a practical tool to predict the number of seedlings to plant to obtain 100 competitively successful trees per acre at year 11 for various treatment options and to provide cost comparisons among the treatment options (Tables 2 and 3).

Cost Comparisons

Table 2 includes only the cost of seedlings and planting costs per successful tree. Because the relative cost of seedlings, planting, herbicide, and herbicide application are likely to change over time, we include two tables to provide a better understanding of how these costs can affect various treatment costs and planting decisions (Table 2 is without herbicide costs, and Table 3 includes herbicide costs).

By multiplying the reciprocals of success probabilities by the sum of seedling and planting costs, the cost per successful tree was calculated (Table 2). In Table 2 (without herbicide and application costs), the highest costs are incurred for the no competition control scenario because of the need to plant a greater number of trees to obtain one successful tree. The highest cost of $75 per successful tree is required for 0.24 in caliper seedlings without woody competition control on higher quality sites, i.e., 79-ft site index. The lowest cost, $1.35 per successful tree, is obtained when large-caliper seedlings (0.87 in.) are planted and given two competition control treatments on sites of lower quality (i.e., site index of 60 ft). Fewer trees of a given diameter and site index are needed as competition control increases (Table 2). That, however, does not come inexpensively, due to increasing treatment costs.

When the cost of herbicide and its application to competitors are included, relative costs change considerably (Table 3). For large-caliper seedlings planted on the lower quality sites, the lowest cost is incurred using the planting method with no woody competition control. Under this scenario, planting a larger number of seedlings is necessary. For example, for a seedling with a caliper of 0.87 in on site index 60 with no woody competition control, 256 seedlings are needed to obtain 100 successful trees 11 years later (Table 2). With

Table 2. Estimated cost of obtaining one competitively successful planted oak 11 years after planting in relation to initial seedling size and site index. Costs shown include only the cost of nursery stock and planting and are based on dominance probabilities for undercut and top-clipped 2-0 seedlings planted under shelterwoods thinned to 40–60% stocking. See Table 3 for inclusion of the cost of herbicide and its application.[a]

				Red oak site index at 50 yr					
				Number of trees to plant in order to obtain 100 successful trees in year 11			Cost per successful tree ($)[e]		
Seedling caliper (in.)[b]	Cost of one seedling[c]	Cost of planting one seedling[d]	Seedling + planting cost	60	69	79	60	69	79
	($)			(ft)					
No woody competition control									
0.24	0.20	0.55	0.75	2,000	3,333	10,000	15.00	25.00	75.00
0.39	0.30	0.55	0.85	588	833	1,111	5.00	7.08	9.44
0.51	0.40	0.60	1.00	400	500	625	4.00	5.00	6.25
0.63	0.50	0.60	1.10	323	385	455	3.55	4.23	5.00
0.75	0.60	0.65	1.25	278	323	370	3.47	4.03	4.63
0.87	0.70	0.65	1.35	256	286	313	3.46	3.86	4.22
Woody competition control once[f]									
0.24	0.20	0.55	0.75	1,250	2,000	3,333	9.38	15.00	25.00
0.39	0.30	0.55	0.85	370	476	667	3.15	4.05	5.67
0.51	0.40	0.60	1.00	263	313	385	2.63	3.13	3.85
0.63	0.50	0.60	1.10	217	250	286	2.39	2.75	3.14
0.75	0.60	0.65	1.25	196	217	238	2.45	2.72	2.98
0.87	0.70	0.65	1.35	182	196	213	2.45	2.65	2.87
Woody competition control twice									
0.24	0.20	0.55	0.75	667	1,111	2,000	5.00	8.33	15.00
0.39	0.30	0.55	0.85	233	286	370	1.98	2.43	3.15
0.51	0.40	0.60	1.00	182	204	238	1.82	2.04	2.38
0.63	0.50	0.60	1.10	159	172	192	1.75	1.90	2.12
0.75	0.60	0.65	1.25	147	159	169	1.84	1.98	2.12
0.87	0.70	0.65	1.35	141	147	156	1.90	1.99	2.11

[a] Woody competition control was applied to stems >1.5 in. dbh. In all three cases of no control, control once, and control twice, competing stems >1.5 in. dbh were cut with the overstory and treated with herbicide.
[b] Average seedling caliper (measured 0.8 in. above the root collar to 0.004 in.).
[c] Based on 2-year-old seedlings undercut the first growing season in the nursery. Costs are approximate and based on prices of nursery stock from state-owned nurseries in the Central Hardwood Region (Weigel and Johnson 2000). Larger size classes may not be available.
[d] Estimated from experimental plantings.
[e] Cost per successful tree = (Seedling + Planting cost) × (1/Success probability).
[f] Includes a mechanical weeding before shelterwood removal.

the same seedling size and on the same site index twice-treated with herbicide, only 141 seedlings need to be planted. However, because of the relatively higher cost of herbicide and its application, the end result of the no competition control option is a lower cost per successful tree 11 years later. For example, the cost per successful 0.87-in. seedling on site index 60 is $3.46 versus $9.11 when the two woody competition control treatments are applied (Table 3). The cost per successful tree also includes the cost of planting those trees that do not become successful because they are unable to survive or to stay ahead of the competition. This supports the assessment by Johnson (1992) that underplanted northern red oak seedlings can be successfully established by planting in a cost-effective way without treating woody competitors (as defined in this study) with herbicides. Under the scenarios evaluated in this study, the most cost-effective options omit herbicide treatments (applied to competitors >1 ft tall and ≤1.5 in dbh) and instead call for planting large seedlings in sufficient numbers to offset anticipated losses due to competing vegetation.

However, the above assessment does not completely eliminate the need for herbicide treatment. In this study, the stumps of harvested overstory trees and stems >1.5 in. dbh were treated with herbicide to prevent stump sprouting in all treatment scenarios. Because the stumps were treated in all of our treatments, these results may not be applicable where overstory stumps and stems >1.5 in. dbh are not treated.

A Management Scenario

Silviculturists typically have both budget and staff constraints that limit management options. Although it may be necessary for attaining a given management goal, artificial regeneration requires an investment of both money and labor. Thus, managers need to prioritize stands based on knowledge of oak regeneration ecology (Johnson et al. 2002) and related assessments of the necessity of artificial regeneration on a stand-by-stand basis. Once the decision has been made to plant oaks, the silviculturist must then decide how to do this most cost effectively.

Silviculturists have some control over the artificial regeneration process. For instance, they can control stock type and characteristics; frequency, type, and number of weed control treatments; the site to regenerate (low or high site quality); and planting density. Moreover, these decisions affect the cost of regeneration, as well as the success of meeting oak stocking goals.

To further compare relative costs, we present a scenario in which the silviculturist's objective is to obtain 100 competitively successful trees per acre at minimal cost 11 years after planting. To facilitate realizing maximum advantage of investments in site preparation or in planting alone, oaks should be planted at densities that reasonably ensure that future stocking goals are met. Estimated dominance probabilities can facilitate attaining those goals.

The maximum amount per acre that can be spent on herbicide and its application is listed in Table 4 by each seedling size, site

Table 3. Total estimated cost of obtaining one competitively successful planted oak 11 years after planting in relation to initial seedling size and site index. Costs shown include the cost of nursery stock, planting, herbicide, and herbicide application. These estimates are based on dominance probabilities for undercut and top-clipped 2-0 seedlings planted under shelterwoods thinned to 40–60% stocking.[a]

Seedling caliper (in.)[b]	Cost of one seedling[c]	Cost of planting one seedling[d]	Seedling + planting cost	Cost per successful tree, red oak site index[e]		
				60	69	79
	($)			(ft)		
No woody competition control						
0.24	0.20	0.55	0.75	15.00	25.00	75.00
0.39	0.30	0.55	0.85	5.00	7.08	9.44
0.51	0.40	0.60	1.00	4.00	5.00	6.25
0.63	0.50	0.60	1.10	3.55	4.23	5.00
0.75	0.60	0.65	1.25	3.47	4.03	4.63
0.87	0.70	0.65	1.35	3.46	3.86	4.22
Woody competition control once[f]						
0.24	0.20	0.55	0.75	15.18	20.81	30.81
0.39	0.30	0.55	0.85	8.95	9.85	11.47
0.51	0.40	0.60	1.00	8.44	8.93	9.65
0.63	0.50	0.60	1.10	8.20	8.56	8.95
0.75	0.60	0.65	1.25	8.26	8.52	8.78
0.87	0.70	0.65	1.35	8.26	8.45	8.68
Woody competition control twice						
0.24	0.20	0.55	0.75	12.21	15.54	22.21
0.39	0.30	0.55	0.85	9.19	9.64	10.36
0.51	0.40	0.60	1.00	9.03	9.25	9.59
0.63	0.50	0.60	1.10	8.96	9.11	9.33
0.75	0.60	0.65	1.25	9.05	9.19	9.33
0.87	0.70	0.65	1.35	9.11	9.20	9.32

[a] Woody competition control was applied to stems >1.5 in. dbh. In all three cases of no control, control once, and control twice, competing stems >1.5 in. dbh were cut with the overstory and treated with herbicide. This cost is not included here since it does not affect relative cost among treatments.
[b] Average seedling stem diameter (measured 0.8 in. above the root collar to 0.004 in.).
[c] Based on 2-year-old seedlings undercut the first growing season in the nursery. Costs are approximate and based on prices of nursery stock from state-owned nurseries in the Central Hardwood Region (Weigel and Johnson 2000). Larger size classes may not be available.
[d] Estimated from experimental plantings.
[e] Cost per successful tree = (Seedling + Planting cost) × (1/Success probability) + Cost of herbicide and its application. Herbicide and application costs are estimated at $360.50/ac based on Ozark National Forest costs.
[f] Includes a mechanical weeding before shelterwood removal. For this treatment, we added $220/ac to the cost formula in footnote *d*, above.

index, and competition control treatment. We define *maximum amount* as the amount that can be spent without exceeding the cost of using the no competition control method (i.e., by planting more seedlings). In the case of the one competition control treatment, this includes the cost of mechanical weeding of competing woody stems prior to shelterwood removal. If costs exceed these values, then it would be less costly to use the no competition control method and plant a larger number of trees than to apply herbicide.

Table 4. Maximum amount that can be spent on woody competition control of stems 1.5 in. dbh and less without exceeding the cost of using the no competition control method (i.e., planting more seedlings). Values are the dollar cost difference between the no woody competition control treatment and the respective competition control treatment below.[a]

Seedling caliper[c] (in.)	Maximum cost[b] per acre that can be incurred for herbicide and its application without exceeding the cost of planting without woody competition control		
	Site index 60 ft	Site index 69 ft	Site index 79 ft
	($)		
Woody competition control once[d]			
0.24	563	1,000	5,000
0.39	185	304	378
0.51	137	188	240
0.63	116	148	186
0.75	102	131	165
0.87	101	121	135
Woody competition control twice			
0.24	1,000	1,667	6,000
0.39	302	465	630
0.51	218	296	387
0.63	180	233	288
0.75	163	205	251
0.87	156	187	211

[a] Woody competition control was applied to stems >1.5 in. dbh. In all three cases of no control, control once, and control twice, competing stems >1.5 in. dbh were cut with the overstory and treated with herbicide.
[b] Assumes that the objective will be to obtain 100 successful trees per ac at year 11.
[c] Average seedling caliper (measured 0.8 in. above the root collar to 0.004 in.).
[d] Includes a mechanical weeding before shelterwood removal.

Spatial Scale Options: Concentrated versus Dispersed Planting

Although not considered in the cost analyses presented, the spatial distribution of planted trees within a stand (or larger area) can affect planting costs. For example, costs could be reduced by planting the same number of trees in a smaller area, resulting in reduced planting and weed control costs, other factors being equal.

Some obvious downsides to concentrated planting include the uneven stocking that might result and/or possible losses related to localized fire, windthrow, or insect or disease problems that could destroy all of the planted trees in one small area. Nevertheless, the resulting reduced costs might determine, in some situations, whether or not planting is at all feasible. If the objective of planting oaks is primarily for wildlife, then the spatial distribution of oaks across the landscape may be more important than it would for timber production alone. More generally, spatial scale is a cost issue that itself could be the focus of considerable analysis—especially with respect to herbicide costs.

Recommendations

To plant northern red oak seedlings under a shelterwood while optimizing costs and biological efficacy, we suggest the following steps:

1. Select upland sites within the site index range of 60–79 ft at 50 years for red oak.
2. Create a shelterwood to reduce overstory density to 40–60% stocking. Thinning from below concentrates removals on subcanopy trees, starting at 1.5 in. dbh and expanding to larger trees until the target residual stocking density is obtained. Treat cut surfaces of harvested (nonoak) competitors with an effective herbicide.
3. Before planting, cut all competing woody plants >1 ft tall and ≤1.5 in. dbh. No herbicide is needed to treat woody competitors in this step if large-caliper seedlings are planted in the next step.
4. Plant large-diameter (caliper), 2-year-old undercut seedlings with clipped tops that average at least 0.5 in. in diameter measured 0.8 in. above the rootcollar. These seedlings should be grown from a local seed source. Refer to Table 2 for the number of seedlings to plant.
5. Remove the shelterwood overwood three growing seasons after planting. Treat the cut surfaces of nonoak stumps with an effective herbicide to prevent sprouting.

To stretch dollars and increase the chances of meeting silvicultural objectives for restoring or sustaining oak stands, we suggest integrating planting with a stand's natural regeneration potential (Johnson et al. 2002). For instance, an inventory of natural reproduction should be made before planting so that underplanting can be used to supplement existing desirable natural reproduction and to provide adequate oak reproduction where it is inadequate. Where there is a greater number of potential stands to underplant than it is possible to plant, stands should be prioritized for planting on the basis of existing desirable natural reproduction, wildlife objectives, esthetics, and other important management objectives.

Conclusions

This study evaluated the combined biological effectiveness and cost effectiveness of various methods of underplanting northern red oak under shelterwoods. The results provide insight on how to integrate planting costs with biological efficacy of various planting methods. The silviculturist can use this information to make better oak regeneration decisions.

Literature Cited

Dey, D.C., D. Jacobs, K. McNabb, G. Miller, V. Baldwin, and G. Foster. 2008. Artificial regeneration of major oak (*Quercus*) species in the eastern United States: A review of the literature. *For. Sci.* 54:77–106.

Dey, D.C., and G. Hartman. 2005. Returning fire to Ozark Highland forest ecosystems: Effects on advance regeneration. *For. Ecol. Manag.* 217:37–53.

Dey, D.C., and W.C. Parker. 1997. Overstory density affects field performance of underplanted red oak (*Quercus rubra* L.) in Ontario. *North. J. Appl. For.* 14(3):120–125.

Dodge, S.L. 1997. Successional trends in a mixed oak forest on High Mountain, New Jersey. *J. Torrey Bot. Soc.* 124:312–317.

Fralish, J. 2004. The keystone role of oak and hickory in the central hardwood forest. P 78–87 in *Upland oak ecology symposium: History, current conditions, and sustainability*, Spetich, M.A. (ed.). Asheville, NC: US For. Serv. Gen. Tech. Rep. SRS–73. 311 p.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. *For. Sci.* 13:38–53.

Jackson, S.W., and D.S. Buckley. 2004. First-year effects of shelterwood cutting, wildlife thinning, and prescribed burning on oak regeneration and competitors in Tennessee oak-hickory forests. P. 231–237 in *Proc. of the 12th biennial southern silvicultural research conference*, Connor, K.F. (ed.). US For. Serv. Gen. Tech. Rep. SRS–71. 594 p.

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

Johnson, P.S. 1992. *Underplanting northern red oak in Missouri without herbicides*. US For. Serv. Gen. Tech. Rep. NC-152. 6 p.

McGee, C.E. 1986. Loss of *Quercus* spp. dominance in an undisturbed old-growth forest. *J. Elisha Mitchell Sci. Soc.* 102:10–15.

Merritt, C. 1980. The central region. P. 107–143 in *Regional silviculture of the United States*, 2nd ed., Barrett, J.W. (ed.). John Wiley and Sons, New York.

Oswalt, C.M., W.K. Clatterbuck, S.E. Schlarbaum, and A.E. Houston. 2004. Growth and development of outplanted high-quality northern red oak seedlings and the effects of competing herbaceous production within four overstory treatments: First-year results. P. 559–564 in *Proc. of the 12th biennial southern silvicultural research conference*, Connor, K.F. (ed.). US For. Serv. Gen. Tech. Rep. SRS-71.

Parker, G.R., and C.M. Ruffner. 2004. *Current and historical forest conditions and disturbance regimes in the Hoosier-Shawnee ecological assessment area.* US For. Serv. Gen. Tech. Rep. NC-244. 267 p.

Shotola, S.J., G.T. Weaver, P.A. Robertson, and W.C. Ashby. 1992. Sugar maple invasion of an old-growth oak–hickory forest in southwestern Illinois. *Am. Midl. Natur.* 127:125–138.

Spetich, M.A. 2004. Upland oak ecology symposium: A synthesis. P. 3–9 in *Upland oak ecology symposium: History, current conditions, and sustainability*, Spetich, M.A. (ed.). US For. Serv. Gen. Tech. Rep. SRS-73. 311 p.

Spetich, M.A., D.C. Dey., P.S. Johnson, and D.L. Graney. 2002. Competitive capacity of *Quercus rubra* L. planted in Arkansas' Boston Mountains. *For. Sci.* 48(3):504–517.

Weigel, D.R., and P.S. Johnson. 1998. *Planting northern red oak in the Ozark Highlands: A shelterwood prescription.* US For. Serv. Tech. Brief TB-NC-6. 8 p.

Weigel, D.R., and P.S. Johnson. 2000. *Planting red oak under oak/yellow-poplar shelterwoods: A provisional prescription.* US For. Serv. Gen. Tech. Rep. NC-210. 16 p.