Overstory Density Affects Field Performance of Underplanted Red Oak (*Quercus rubra* L.) in Ontario

Daniel C. Dey *and* **William C. Parker,** *Ontario Forest Research Institute, P.O. Box 969, 1235 Queen Street East, Sault Ste. Marie, Ontario, Canada, P6A 5N5.*

ABSTRACT. *Red oak seedlings were underplanted in a closed-canopy mature northern hardwood stand and an adjacent shelterwood in central Ontario. Overstory density effects on seedling survival and growth were assessed 2 yr after planting. After 2 yr, seedling survival was 90% in the uncut stand and over 99% in the shelterwood. Seedlings in the uncut stand experienced negligible or negative annual increments in stem diameter and height. Seedlings in the shelterwood were about 2 mm larger in diameter and nearly twice as tall as those in the uncut stand after 2 yr. Second-year stem diameter and height distributions of planted oak were significantly different in the shelterwood and the uncut stand. Root volume, area, and dry mass were substantially larger for seedlings grown in the shelterwood than those in the uncut stand. Loss of vigor, growth declines, and increased mortality of planted oak were largely a result of extremely low understory light levels in the uncut stand. Results of this study suggest that red oak underplanted in an uncut stand 2 or more years before a shelterwood harvest will be at a competitive disadvantage once they are released. Establishment and performance of underplanted red oak is promoted by shelterwoods that provide adequate light at the forest floor and should exhibit a strong positive growth response following final overstory removal. North. J. Appl. For. 14(3):120–125.*

The artificial regeneration of red oak (*Quercus rubra* L.) by underplanting in shelterwoods has been widely tested throughout eastern North America (Johnson et al. 1986, Lorimer et al. 1994, Gordon et al. 1995). Planting oak has been used to establish seedlings where advance reproduction is absent, when there is a lack of acorn-producing oaks, and to supplement natural reproduction when it occurs at low densities. The most common shelterwood prescription involves underplanting red oak the spring after harvest. However, foresters may encounter a scheduling problem in coordinating harvest and planting operations. The timing of silvicultural operations may be further complicated when vegetation management by herbicide application or understory burns are prescribed for the regeneration of red oak. Underplanting red oak several years before harvesting may relieve some of these scheduling conflicts.

There have been few studies that consider the effects of underplanting red oak in uncut stands before the shelterwood harvest on seedling field performance. In Virginia, Tworkoski et al. (1986) underplanted red oak in an oak-mixed hardwood stand 2 to 3 yr before harvesting by clearcut or shelterwood. Three years after harvest they observed that the underplanted red oak were competitive with other vegetation, survival was high, and postharvest seedling height growth increased with harvest intensity. More research is needed to further test the viability of preharvest planting of red oak, especially in relation to specific red oak ecosystems.

The objective of this study was to examine the effects of overstory density on survival and growth of red oak underplanted in a mature, closed-canopy and a shelterwood stand dominated by northern hardwoods in central Ontario. The feasibility of planting red oak several years before a harvest was evaluated through examination of 2 yr growth trends in underplanted oaks in response to overstory density.

Methods

This study was conducted in an undisturbed mature hardwood stand and in an adjacent shelterwood cut in McClintock Township, approximately 10 km north of Dorset, Ontario. The shelterwood stand was harvested

NOTE: We are thankful for the assistance of forester Dave Deugo, Bracebridge Area, Ontario Ministry of Natural Resources in the establishment of this study and the technical support provided by Blake Laporte, Garry Radey, Brian Bjorkquist, and Steve Watson.

during the winter of 1992–1993. Both study stands were 0.5–1.0 ha in area. Percent crown cover and basal area of the uncut and shelterwood overstories were determined in the summer of 1993. Six variable radius plots were established in the uncut area and ten in the shelterwood using a 2 m factor prism. A spherical densiometer (Lemmon 1956) was used to measure percent crown cover, based on the average of four readings at each plot center, each reading taken in a cardinal direction. Basal area averaged 8.2 ± 3.8 m^2/ha in the shelterwood and 21.0 ± 6.0 m^2/ha in the uncut stand. Percent crown cover was 66.3 ± 11.5% in the shelterwood and 94.0 ± 5.2% in the uncut stand.

Sugar maple and yellow birch dominated the uncut stand, comprising 78.5% and 17.3% of the basal area, respectively. The shelterwood harvest created a moderately dense residual overstory canopy and removed the taller understory woody vegetation. In the shelterwood, sugar maple accounted for 68.5% of the residual basal area. The remaining shelterwood overstory included white ash, red oak, American basswood, eastern hemlock and yellow birch.

Bareroot (1+0, undercut) red oak planting stock was obtained from the Ministry of Natural Resources nursery at Orono, Ontario, in the spring of 1993. Stem diameter, shoot length, and the number of first-order lateral roots ≥ 1 mm in diameter (FOLR) were recorded for approximately 950 seedlings. Stem diameter was measured 2.5 cm above the root collar. Shoot length was measured from the root collar to the base of the most apical live bud. After morphological assessment, seedlings were planted in the shelterwood (n = 438) and uncut (n = 464) stands. In the fall of 1993 and 1994, stem height and diameter of each planted seedling were measured. Stem diameter was averaged from two perpendicular measurements taken 2.5 cm above the ground. Seedling height was measured along a perpendicular line that was projected from the ground to the most apical live bud.

During early May 1995, 2 growing seasons after planting, 19 seedlings from the shelterwood and 25 from the uncut stand were randomly located and carefully lifted from the ground to recover as much of the root system as possible. Tap

Table 1. Initial morphological characteristics of red oak bareroot stock (1+0, undercut) underplanted in a shelterwood (Cut) (*n* = 438) and undisturbed mature (Uncut) (*n* = 464) hardwood forest. Values are presented as mean ± standard error.

Seedling characteristic	Uncut	Cut
Stem diameter (mm)	6.22 ± 1.07	6.12 ± 1.14
Shoot length (cm)	18.38 ± 4.54	17.67 ± 5.05
Number of FOLR	12.0 ± 5.7	10.4 ± 5.5

root length, stem diameter, number of FOLR, root volume, root area, and dry mass of the tap root and lateral roots were measured on the excavated seedlings. Tap root length was measured from the root collar to the base of callous tissue that resulted from undercutting seedlings in the nursery. Volume of the entire root system below the root collar was determined by water displacement. The projected area of the entire root system was measured using a rhizometer (LTS Technology Devices, Thunder Bay, Ontario). Dry mass of both the tap root and lateral roots were measured after drying the plant tissue for 48 hr at 65°C.

Pre- and post-planting differences in the frequency distributions of stem diameter, shoot length (i.e., height), and FOLR between the two overstory treatments were analyzed using the chi-square test. Size distributions were considered significantly different when the test statistic exceeded the $1-\alpha$ quantile of a chi-square, where $\alpha = 0.05$ (Conover 1980).

Results

Red oak seedlings planted in the uncut and shelterwood stands did not differ in initial morphology (Table 1). Initial root collar diameter averaged 6.17 mm and average height was about 18 cm for seedlings planted in both the shelterwood and uncut stands. Frequency distributions of both initial seedling stem diameter and height were not significantly different between the two overstory treatments (Figure 1a,b). Although initial mean number of FOLR of seedlings planted in both stands did not differ substantially, the distribution of seedlings among FOLR classes (Figure 1c) was significantly different ($P \geq 0.05$) between the two overstory treatments. Seedlings in the uncut stand generally had more FOLR at the time of planting than those in the shelterwood (Figure 1c).

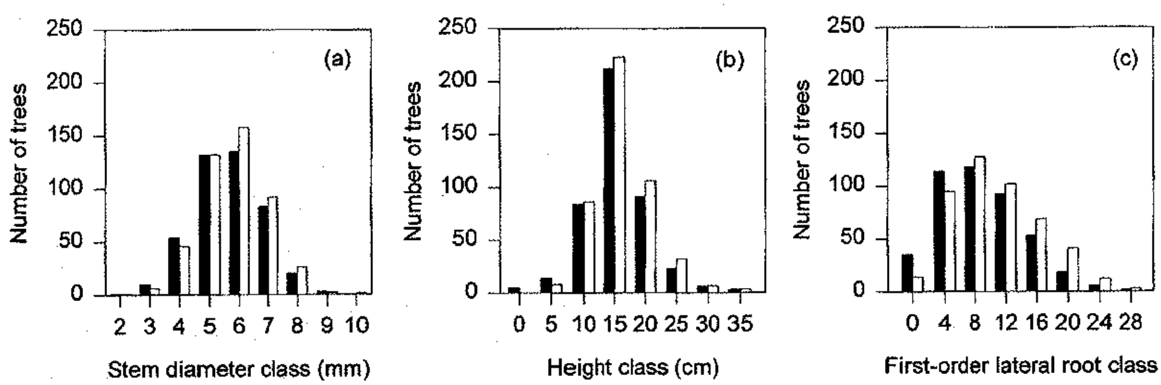

Figure 1. Frequency distributions of (a) stem diameter, (b) shoot height, and (c) number of FOLR of red oak nursery stock used for underplanting an Ontario shelterwood (black bar) and a closed-canopy mature northern hardwood forest (white bar). Stem diameter and height distributions were statistically similar between the shelterwood and uncut treatments, whereas FOLR distributions were significantly different based on chi-square analyses (∝ = 0.05).

The shelterwood harvest removed the tall woody understory and retained a light to moderately dense overstory canopy. As a result, oak seedlings were relatively free of overtopping vegetation during the first growing season in the shelterwood. In contrast, the dense understory of shade-tolerant advance reproduction and closed canopy of the uncut stand resulted in low light levels at the forest floor. Despite the difference in light environment between the two overstory treatments, survival of planted oaks in the shelterwood and uncut stand was high after the first growing season, averaging 99.6%. However, by the end of the second growing season, mortality of oak seedlings in the uncut stand increased to 10.7%, whereas it remained at less than 1% in the shelterwood.

After one growing season, stem diameter averaged 4.9 mm for seedlings planted in the shelterwood and 3.8 mm for those in the uncut stand. At the end of the second year, mean stem diameter further increased to 5.9 mm for seedlings in the shelterwood, but remained unchanged in the uncut stand. Approximately 52% of the seedlings in the uncut stand exhibited negative changes (i.e., decreases) in diameter the second year as compared to only 16% in the shelterwood (Table 2). Reductions in stem diameter resulted when seedlings experienced shoot dieback since the last measurement, in which case the stem diameter of the dominant new sprout was measured. Of the seedlings in the shelterwood, 42% showed a positive diameter increment (≥ 1 mm) in the second growing season. Only 4% of the seedlings in the uncut stand had positive diameter increments during this same period. Both first- and second-year stem diameter distributions were significantly different between the oaks in the shelterwood and uncut areas (Figure 2).

Seedling heights averaged 25.8 ± 8.9 cm in the shelterwood and 22.0 ± 6.2 cm in the uncut area at the end of the first growing season. During the second year after planting, seedling height increased to 38.9 ± 15.0 cm in the shelterwood, but oaks in the uncut stand had negligible height growth increment (21.5 ± 7.7 cm). Only 2.4% of the seedlings growing in the low light conditions of the uncut stand showed a positive change in height the second year. Most of the seedlings (97.6%) in the uncut stand had negligible height growth or decreased total height due to shoot dieback and resprouting. Conversely, 54.9% of the seedlings in the shelterwood exhibited positive height growth, with several seedlings increasing in height by more than 40 cm (Table 2). First- and second-year height distributions were significantly different between

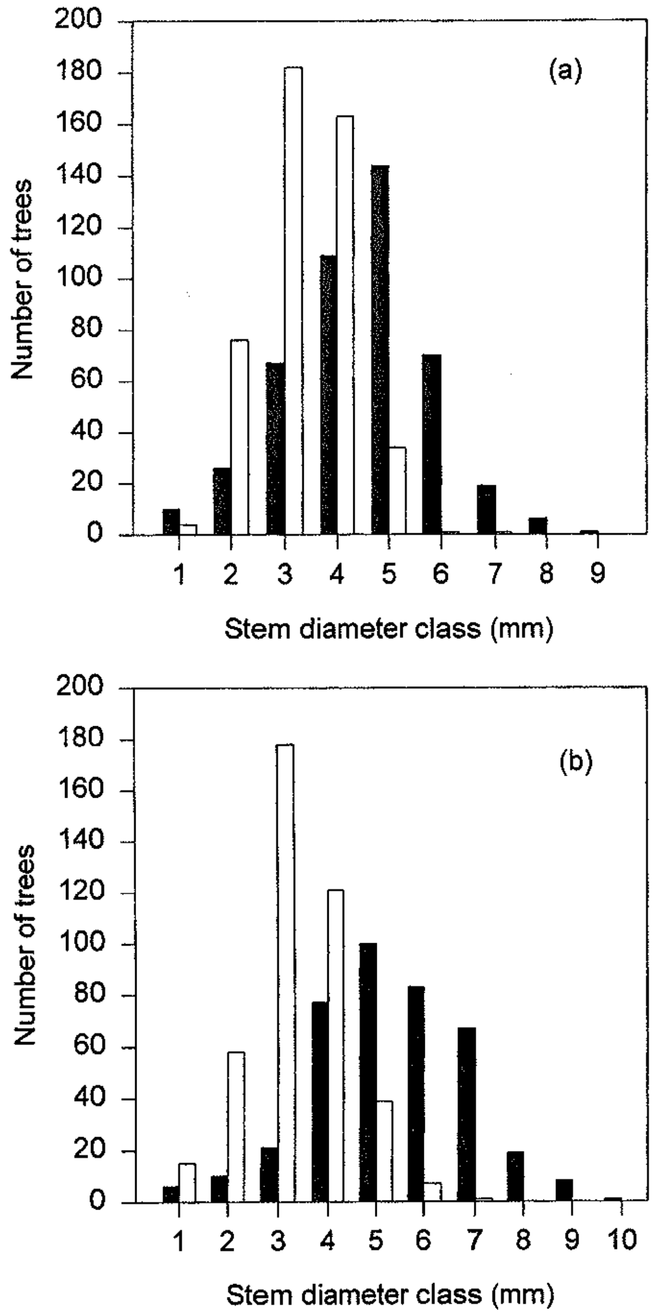

Figure 2. Stem diameter distributions of red oak seedlings grown under a shelterwood (black bar) and a closed-canopy hardwood stand (white bar) after (a) one and (b) two growing seasons. Both first- and second-year distributions were significantly different between the oaks in the shelterwood and uncut treatments based on chi-square analyses (α = 0.05).

Table 2. Frequency distribution of oak seedlings among classes of second-year (a) diameter and (b) height increment by overstory treatment (Cut = shelterwood, Uncut = closed-canopy forest). Negative increments resulted from the measurement of new sprouts that developed the second year following shoot dieback.

	Annual stem diameter increment						
	Negative	<1 mm	+1 mm	+2 mm	+3 mm	≥ +4 mm	Total
Cut	69	178	116	48	13	2	426
Uncut	240	204	17	2	0	0	463

	Annual stem height increment						
	Negative	<10 cm	+10 cm	+20 cm	+30 cm	≥+40 cm	Total
Cut	61	131	117	64	42	11	426
Uncut	276	176	8	3	0	0	463

the oaks in the shelterwood and uncut stand (Figure 3). Although we did not measure seedling crown development in the two overstory treatments, oaks in the shelterwood generally had more lateral branches and leaves, and supported higher total leaf area than seedlings in the heavily shaded uncut stand.

After 2 yr, seedlings grown in the shelterwood area had a larger average net increase in the number of FOLR than those in the uncut stand. Compared to initial lateral root counts, seedlings that were excavated from the shelterwood showed an average net increase of 2 FOLR, whereas oaks in the uncut stand had an average net loss of 1 FOLR (Table 3). The net change in the number of FOLR for individual oaks in the uncut stand ranged from a loss of 14 roots to a gain of 17 and in the shelterwood from a loss of 7 roots to a gain of 15. In the shelterwood, 68.4% of the excavated oaks had more FOLR than at the time of planting. Only 44% of the seedlings in the uncut stand exhibited an increase in number of FOLR after planting.

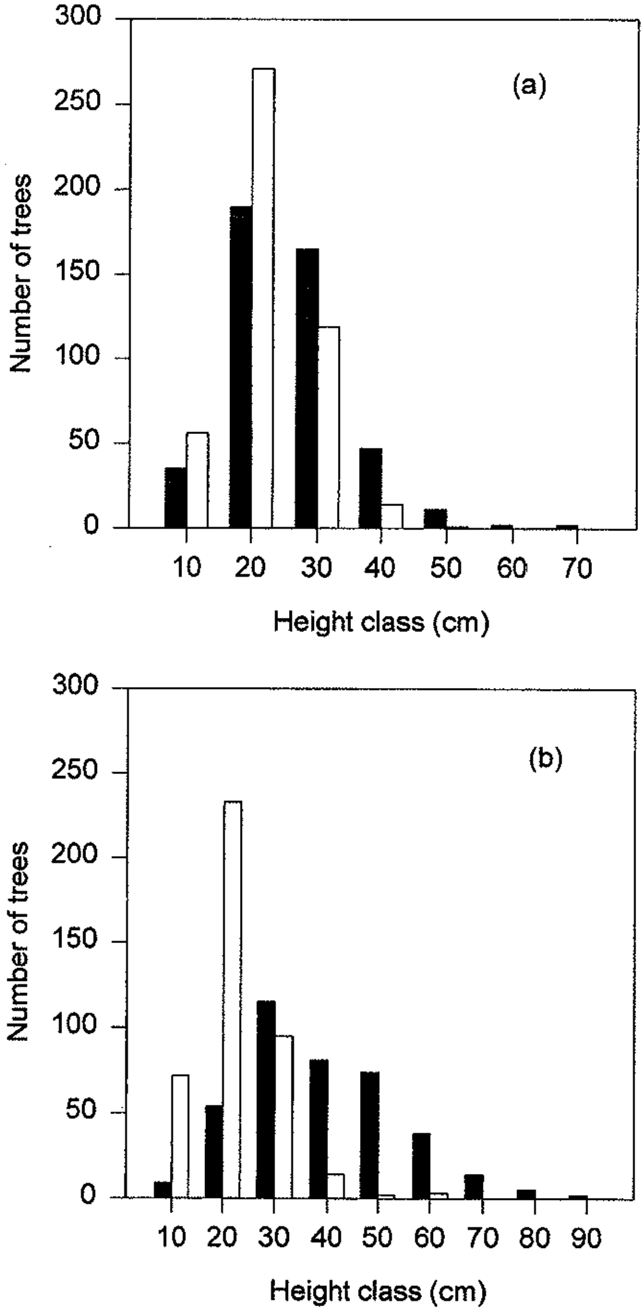

Figure 3. Height distributions of red oak seedlings grown under a shelterwood (black bar) and a closed-canopy hardwood stand (white bar) after (a) one and (b) two growing seasons. Both first- and second-year distributions were significantly different between the oaks in the shelterwood and uncut treatments based on chi-square analyses ($\alpha = 0.05$).

Two years after planting, the root systems of oak seedlings grown in the shelterwood were substantially larger than those of seedlings in the uncut stand (Table 3). Oak seedlings from the shelterwood had more than twice the root area and three times the root volume of seedlings grown under a closed-canopy. Tap root and lateral root dry mass in seedlings from the shelterwood were 4 and 13 times greater, respectively, than those of oaks from the uncut stand. Most of the root biomass of oaks in the uncut stand occurred in the tap root, and accounted for 86.6% of the total root dry mass.

Discussion

Light is the environmental factor most commonly limiting the growth of red oak reproduction (Abrams 1992). Light intensities as low as 1% of full sunlight are common in closed-canopy mature hardwood forests in central Ontario (Dey and Parker 1996). These low light levels are not sufficient for red oak seedlings to support competitive rates of net photosynthesis and maintain a positive carbon balance (Hanson et al. 1987). In the short term, heavy shading of underplanted seedlings leads to morphological adjustment in shoot and root biomass in response to the understory environment. This adjustment occurs through shoot and root dieback and the formation of a new shoot, and acts to establish some functional root-shoot balance in the field microenvironment. In the longer term, low light results in poor growth, low carbohydrate levels, and reduced sprouting potential, and increased seedling mortality.

Overstory density had a significant effect on field performance of underplanted red oak seedlings in this study. Nearly all of the planted red oak survived the first year after outplanting, even in the deep shade of the uncut stand. High early survival rates (e.g., > 85%) for planted red oak regardless of the overstory density have been observed by others (Teclaw and Isebrands 1991, McNeel et al. 1993, Lorimer et al. 1994). Over time, however, the survival of red oak seedlings underplanted in mature hardwood forests decreases substantially, with mortality ranging from 42% to > 70% (Gottschalk and Marquis 1982, Myers et al. 1989, Lorimer at al. 1994, Schuler and Miller 1995). In our study, the survival of red oak in the uncut stand decreased to 90% within 2 yr and will likely drop precipitously over the next few years. In contrast, survival of seedlings in the shelterwood should remain relatively high. Clearcutting or partial cutting that retained a residual overstory between 50% and 75% stocking or crown cover improved the survival of planted red oak for up to 7 yr, especially when the understory woody vegetation was also reduced (Gottschalk and Marquis 1982, Johnson 1984, Lorimer et al. 1994, Gordon et al. 1995, Schuler and Miller 1995).

Table 3. Root characteristics of excavated red oak seedlings at the time of planting and after two growing seasons in a shelterwood cut (n = 19) and an uncut stand (n = 25). Values are presented as mean ± standard error.

Root characteristic	Uncut		Shelterwood	
	Preplant	At year 2	Preplant	At year 2
Tap root length (cm)[a]		12.0 ± 1.9		12.1 ± 1.4
Number of FOLR	13.4 ± 5.5	12.4 ± 8.7	11.1 ± 5.9	13.3 ± 3.7
Root volume (cm^3)		8.0 ± 3.2		25.5 ± 15.8
Root area (cm^2)		29.8 ± 10.6		67.6 ± 26.0
Dry mass (g):				
Tap root		2.55 ± 1.06		8.81 ± 4.88
Lateral root		0.41 ± 0.29		5.28 ± 3.80
Total		2.96 ± 1.26		14.09 ± 8.28
% dry mass in tap root		86.6 ± 5.9		64.3 ± 7.7

[a] Tap root lengths are similar between stands because the seedlings were undercut in the nursery.

Red oak underplanted in the shelterwood and closed-canopy mature hardwood stand exhibited large differences in diameter and height increment. Oaks planted in the shelterwood were 55% larger in diameter and nearly twice as tall as those in the uncut stand after two growing seasons. Seedlings growing in heavy shade had no net diameter and height growth during the second year. Similar trends have been reported by others for red oak seedlings grown in closed-canopy stands (Teclaw and Isebrands 1991, Lorimer et al. 1994). Negative stem growth increments associated with frequent shoot dieback were common under the heavy shade of the uncut stand. As a result, a higher number of seedlings in larger diameter and height size classes were present in the shelterwood than the uncut stand 2 yr after planting.

Partial cutting, especially when in combination with control of the understory woody vegetation, has resulted in significantly increased height growth in red oak compared to growth in uncut hardwood stands (Gottschalk and Marquis 1982, Tworkoski et al. 1986, Myers et al. 1989, Teclaw and Isebrands 1991, Lorimer et al. 1994). In general, the larger the reduction in basal area and crown closure, the greater the increase in height growth in planted red oak (Johnson 1984, Tworkoski et al. 1986). Gottschalk (1985) found that red oak shoot growth was very low when seedlings were grown under 8% of full sunlight for 2 yr, but that shoot growth was similar for light treatments that provided 20% or more of full sunlight. Partial cutting hardwood stands so that more than 20% of full sunlight reaches the forest floor should provide light adequate to support near optimal shoot growth in red oak reproduction (Gottschalk 1985, 1994).

In a closely related companion study located near Foymount, Ontario, shelterwood harvesting increased light intensity from 1% of full sunlight in uncut stands to approximately 25% and 50% under canopies thinned to 70% and 50% crown cover, respectively (Dey and Parker 1996). The heavily shaded conditions in the uncut stands, with nearly 100% crown cover, reduced midday net photosynthesis of underplanted and naturally regenerated oak seedlings to less than 20% of the maximum rate. Light intensities under the two shelterwood treatments, however, were near or above that needed to maintain net photosynthesis close to its maximum. Because the shelterwood cutting treatments in these two studies were similar, the positive growth response exhibited in the present study probably resulted from light levels exceeding the 20% full sunlight required for optimal shoot growth.

It has been long recognized that a large root system is important for the successful regeneration of oak (Sander 1977). Survival and growth of planted red oak depends on a well-developed root system with large carbohydrate reserves, a balanced root-shoot ratio, and a well-branched root system (Farmer 1975, Johnson 1981, 1989, Crow and Isebrands 1986, Pope 1993). The initial number of FOLR has been related to outplanting performance, and survival and growth are significantly greater for seedlings with ≥10 FOLR than those with < 5 roots (Bardon and Countryman 1993, Teclaw and Isebrands 1993, Thompson and Schultz 1995). Nursery stock used in our study had ≥ 10 FOLR but only those underplanted in the shelterwood exhibited acceptable field performance. In the uncut stand, the oaks were unable to maintain the root system produced under nursery culture. More than half of the seedlings excavated after 2 yr in the uncut stand had fewer FOLR than at the time of planting, evidence of extensive root dieback. In contrast, after growing for 2 yr in a shelterwood, red oak seedlings were able to increase the number of FOLR, and the total volume, area, and dry mass of their root systems. This increase in root system size in the shelterwood stand most likely resulted from the improved understory light environment (Gottschalk 1985, 1987, Kolb and Steiner 1990).

Applications

Successful regeneration of red oak is dependent on the development of advance reproduction with large root systems, capable of rapid shoot growth or sprouting response to canopy disturbance. Underplanting large diameter red oak stock can be used effectively to augment advance reproduction and enhance the success of oak regeneration. However, the timing of underplanting relative to overstory thinning is critical for optimal development of the planted stock. Understory light levels prior to shelterwood cutting treatments must be sufficient to support the growth of physiologically vigorous root systems with large energy reserves needed to support competitive shoot response. Most researchers have used and recommend planting immediately following a shelterwood harvest that permits 20% or more of full sunlight to reach the forest floor. Delays in providing planted oak with adequate light by underplanting in closed-canopy mature hardwood stands results in loss of seedling vigor, decreased root and shoot growth, increased mortality, and a lower capacity for competitive response to overstory release.

Although survival of planted oak exhibited after 1 yr was high in the uncut stand in this study, significant declines in height and basal diameter growth occurred, which was unlike that observed in the adjacent shelterwood. Growth declines continued and mortality increased during the second year in the uncut stand. Given the observed decline in field performance of underplanted red oak seedlings in the uncut stand, we doubt that these seedlings will be able to respond to overstory release without substantial investment in competition control. On moderately to highly productive sites, similar to those in our study, we recommend that a shelterwood prescription such as that proposed by Johnson et al. (1986) be used to artificially regenerate oak. Their prescription for oak regeneration includes (1) controlling competition from woody vegetation with herbicides before planting, (2) creating a medium density shelterwood (55% to 65% stocking), (3) underplanting large diameter nursery stock and (4) removing the overstory three growing seasons after planting. In any event, planted oak should not remain under a closed-canopy overstory for more than 1 yr. More specific recommendations tailored to different ecosystems or types and sizes of nursery stock must await further research.

Literature Cited

Abrams, M.D. 1992. Fire and the development of oak forests. Bioscience 42:346–351.

Bardon, R.E., and D.W. Countryman. 1993. Survival and growth for the first-growing season of northern red oak (*Quercus rubra* L.) seedlings underplanted in mixed upland hardwood stands in south central Iowa. P. 195–209 *in* Proc. of 9th Central hardwood for. conf. USDA For. Serv. Gen. Tech. Rep. NC-161.

Conover, W.J. 1980. Practical nonparametric statistics. Ed. 2. Wiley, New York. 493 p.

Crow, T.R., and J.G. Isebrands. 1986. Oak regeneration—an update. P. 73–86 *in* Proc. of Integrated pest management symp. for northern forests.

Dey, D.C., and W.C. Parker. 1996. Regeneration of red oak (*Quercus rubra* L.) using shelterwood systems: Ecophysiology, silviculture and management recommendations. Ont. Min. Natur. Resour., Ont. For. Res. Inst. For. Res. Info. Pap. (in press).

Farmer, R.E., Jr. 1975. Dormancy and root regeneration of northern red oak. Can. J. For. Res. 5:176–185.

Gordon, A.M., J.A. Simpson, and P.A. Williams. 1995. Six-year response of red oak seedlings planted under a shelterwood in central Ontario. Can. J. For. Res. 25:603–613.

Gottschalk, K.W. 1985. Effects of shading on growth and development of northern red oak, black oak, black cherry, and red maple seedlings. I. Height, diameter, and root/shoot ratio. P. 189–195 *in* Proc. of 5th Central hardwood for. conf. Soc. Am. For. Publ. 85-05. Soc. Am. For., Bethesda, MD.

Gottschalk, K.W. 1987. Effects of shading on growth and development of northern red oak, black oak, black cherry, and red maple seedlings. II. Biomass partitioning and prediction. P. 99–110 *in* Proc. of 6th Central hardwood for. conf.

Gottschalk, K.W. 1994. Shade, leaf growth and crown development of *Quercus rubra*, *Quercus velutina*, *Prunus serotina* and *Acer rubrum* seedlings. Tree Physiol. 14:735–749.

Gottschalk, K.W., and D.A. Marquis. 1982. Survival and growth of planted red oak and white ash as affected by residual overstory density, stock size, and deer browsing. P. 125–140 *in* Proc. of 4th Central hardwood for. conf.

Hanson, P.J., J.G. Isebrands, and R.E. Dickson. 1987. Carbon budgets of *Quercus rubra* L. seedlings at selected stages of growth: influence of light. P. 269–276 *in* Proc. of 6th Central hardwood for. conf.

Johnson, P.S. 1981. Nursery stock requirements for oak planting in upland forests. P. 2–19 *in* Proc. of Northeastern area nurserymen's conf.

Johnson, P.S. 1984. Responses of planted northern red oak to three overstory treatments. Can. J. For. Res. 14:536–542.

Johnson, P.S. 1989. Growing hardwood nursery stock for planting on forest sites with special reference to northern red oak. P. 46–62 *in* Proc. of Northeastern area nurserymen's conf.

Johnson, P.S., C.D. Dale, K.R. Davidson, and J.R. Law. 1986. Planting northern red oak in the Missouri Ozarks: A prescription. North. J. Appl. For. 3:66–68.

Kolb, T.E., and K.C. Steiner. 1990. Growth and biomass partitioning response of northern red oak genotypes to shading and grass root competition. For. Sci. 36:293–303.

Lemmon, P.E. 1956. A spherical densiometer for estimating forest overstory density. For. Sci. 2:314–320.

Lorimer, C.G., J.W. Chapman, and W.D. Lambert. 1994. Tall understory vegetation as a factor in the poor development of oak seedlings beneath mature stands. J. Ecol. 82:227–237.

McNeel, C.A., D.M. Hix, and E.C. Townsend. 1993. Survival and growth of planted northern red oak in northern West Virginia. P. 222–228 *in* Proc. of 9th Central hardwood for. conf. USDA For. Serv. Gen. Tech. Rep. NC-161.

Myers, R.K., B.C. Fischer, and G.M. Wright. 1989. Survival and development of underplanted northern red oak seedlings: 6-year results. P. 150–155 *in* Proc. of 7th Central hardwood forest conf. USDA For. Serv. Gen. Tech. Rep. NC-132.

Pope, P.E. 1993. A historical perspective of planting and seeding oaks: Progress, problems, and status. P. 224–240 *in* Proc. Oak regeneration: Serious problems, practical solutions. USDA For. Serv. Gen. Tech. Rep. SE-84.

Sander, I.L. 1977. Manager's handbook for oaks in the North Central States. USDA For. Serv. Gen. Tech. Rep. NC-37. 35 p.

Schuler, T.M., and G.W. Miller. 1995. Shelterwood treatments fail to establish oak reproduction on mesic forest sites in West Virginia—10-year results. P. 375–387 *in* Proc. 10th Central hardwood forest conf. USDA For. Serv. Gen. Tech. Rep. NE-197.

Teclaw, R.M., and J.G. Isebrands. 1991. Artificial regeneration of northern red oak in the Lake States. P. 187–197 *in* Proc., Oak resource in the Upper Midwest: Implications for management. Univ. Minnesota, Minn. Ext. Serv. Publ. No. NR-BU-5663-S.

Teclaw, R.M., and J.G. Isebrands. 1993. Artificial regeneration of northern red oak in the Lake States with a light shelterwood: A departure from tradition. P. 185–194 *in* Proc. of 9th Central hardwood for. conf. USDA For. Serv. Gen. Tech. Rep. NC-161.

Thompson, J.R., and R.C. Schultz. 1995. Root system morphology of *Quercus rubra* L. planting stock and 3-year field performance in Iowa. New For. 9:225–236.

Tworkoski, T.J., D.W. Smith, and D.J. Parrish. 1986. Regeneration of red oak, white oak, and white pine by underplanting prior to canopy removal in the Virginia Piedmont. South. J. Appl. For. 10:206–210.