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Maximizing Northern Red Oak (Quercus rubra) Seedling Growth to Sustain Oak-Dominated Ecosystems in East Tennessee

Brian Andrwe Barwatt
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To the Graduate Council:

I am submitting herewith a thesis written by Brian Andrwe Barwatt entitled "Maximizing Northern Red Oak (Quercus rubra) Seedling Growth to Sustain Oak-Dominated Ecosystems in East Tennessee." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

David S. Buckley, Major Professor

We have read this thesis and recommend its acceptance:

Wayne K. Clatterbuck, Arnold M. Saxton, Scott E. Schlarbaum

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Dr. Anne Mayhew
Vice Chancellor and Dean of
Graduate Studies

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A Thesis presented for the Master of Science Degree
The University of Tennessee, Knoxville

Brian Andrew Barwatt
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Abstract

The success of northern red oak *(Quercus rubra* L.*)* in the oak-hickory forest type and its growth and development into the overstory is of great concern due to the value of this species as a source of forest products and mast for wildlife. There is a general consensus that rapid oak seedling height growth occurs above certain threshold levels of light, soil moisture, and nutrients. If these specific levels and the relative importance of competition between northern red oak (NRO) seedlings and other individual plant species can be determined, then the implementation of more precise management practices that promote rapid NRO seedling height growth and more cost-efficient competition control treatments could be developed. The detection of genetic family differences among artificially regenerated NRO seedlings could also have future applications in advancing the competitive ability of NRO in the field.

This study had three objectives. The first objective was to identify light, soil moisture, and nutrient levels in the immediate vicinity of NRO seedlings that lead to rapid height growth. The second objective was to establish which plant species are the most important competitors limiting these resources and thus the height growth and survival of NRO seedlings. The third objective was to identify potential genetic family differences among the NRO seedlings used in this experiment.

This study was conducted on moderately productive sites in mature oak-hickory forests on the University of Tennessee Forestry Experiment Station at Oak Ridge in east Tennessee. A randomized complete block design was used, and the dependent variables were height growth and percent survival for all NRO seedlings. Six treatments were randomly assigned to equally sized plots within three blocks (10 hectares per block) during the summer of 2002. Blocking was based primarily on aspect, but also included stand structure, forest composition, and landscape position. In order of decreasing canopy cover, the treatments were: uncut (Control), 50% basal area retention (BAR), 25% BAR, 12.5% BAR, commercial clearcut (CCC), and silvicultural clearcut (SCC). Sixty premium artificially regenerated NRO seedlings from 18 different half-sibling families were then planted within each treatment in mid April of 2003.

Significant differences in mean percent full photosynthetically active radiation (PAR) existed between nearly all treatments. The Control treatments received the lowest percent full PAR level at 3.84 percent and the SCC received the most at 86.67 percent. The north facing block was significantly different from the south facing and ridge top blocks receiving almost 8 percent less PAR on average. Soil moisture levels were not significantly affected by treatments or blocks. Greater than normal precipitation levels during the 2003 growing season may have influenced soil moisture and seedling performance. Macronutrient levels were not significant in explaining NRO performance in this study.

Total height growth was noticeably greater (by more than 12 cm on average) in the Controls than all other treatments. Mortality was also highest in this treatment (10 percent) and most likely due to heavy shade. Very little mortality (<2 percent) occurred in all other treatments combined. Fireweed (*Erechtites hieracifolia* L.) and horseweed (*Erigeron canadensis* L.) were the most abundant herbaceous species overtopping the NRO seedlings. They occurred mainly in the 25% BAR, 12.5% BAR, CCC and SCC totaling 7, 5, 12, and 5 percent of the total cover respectively. Yellow-poplar

(Liriodendron tulipifera L.*)* and red maple *(Acer rubrum* L.*)* were the most abundant woody species in this study.

Ranging from 17 cm to 29 cm, mean height growth differed significantly between genetic families. No differences in survival were detected between families. However, three genetic families had 100 percent survival and the family with the greatest mortality had 9 percent mortality.

Multiple regression was conducted using the backward selection technique to determine the best model for predicting NRO seedling height growth in this study. The best model had nine independent variables for predicting NRO seedling growth with an R^2 of 36.37 percent. Initial seedling height after planting and percent full PAR were the most significant variables in the model. PAR and initial seedling height both had a negative relationship with first year height growth. Initial root collar diameter was also significant and had a positive relationship with first year height growth. Potential woody competitors such as redbud *(Cercis canadensis* L.*)* and blackgum *(Nyssa sylvatica* Marsh*)* also proved to be significant in predicting NRO seedling height growth. Both species had a positive relationship with seedling growth in the 51-150 cm size class.

Based on these first year results, greater height growth appears to be associated with less sunlight, although this seems to be the result of etiolation in the Controls. Yellow-poplar and red maple, which were the most abundant competitors in this study, do not appear to currently have any effect on NRO seedling height growth. Redbud and blackgum, on the other hand, seem to be possible indicators of good sites for NRO seedling height growth. Shorter seedlings with thicker root collar diameters exhibited more height growth than seedlings that were taller or had smaller root collar diameters.

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I. Literature Review

Oak History

Oak *(Quercus spp.* L.*)* forests first became widely distributed across the central U.S. about 9000 years ago after the widespread retreat of the boreal spruce-pine forest of the Pleistocene (Watts 1979, DeGraaf and Miller 1996). During pre-European settlement times, fire was an influential force in shaping the forest landscape of the central U.S. Most fire disturbances were anthropogenic as Native Americans burned woodlands to improve game habitat for hunting and to make traveling easier. Fire therefore, was probably the most dominant source of disturbance in oak forest types during pre-European settlement times (Lorimer 2001).

Rostlund (1957) believes that the oak and pine forests of today would probably be restricted to dry ridges, upper slopes, thin soils, and burned windfalls had not humans entered North America some 12,000 years ago. Historical evidence suggests that existing oak stands on mesic sites developed after those sites were subjected to fire and/or other disturbances that removed the understory and sub-canopy trees (Lorimer 1992). Fires favored oaks by excluding fire sensitive species that are more competitive than oak in the absence of fire (Abrams 1992). Frequent fires resulting from Native American activities most likely allowed the oaks to expand onto mesic landforms. Post-settlement fire frequency in oak-hickory stands ranged from 7-30 years within the first 150 years following European settlement. It is believed that pre-European settlement fire frequencies were similar (Dey and Guyette 2000).

Thousands of years ago, the first European farmers considered oaks to be the enemy. Oaks were to be girdled and burned to make way for crops and a better life (Clark 1992). However, the French had mandated practices to establish oak seedlings in order to improve wood supplies by the 13th century (Thirgood 1971). Few references concerning oak regeneration problems appear in American forest literature until after the 1930's (Clark 1992). According to Clark (1992), this lack of concern was due to the facts that: (1) agricultural development was more important than forestry, (2) oaks were still plentiful, (3) protection and reestablishment were the primary early forestry concerns, and (4) burning and overcutting favored oak. Many present oak stands became established following strong efforts to convert forests into agricultural land through grazing or logging with no plans for reforestation. In fact, the physiologic and genetic characteristics that make oak difficult to establish have also sustained it through centuries of heavy forest disturbance (Clark 1992). Carvell and Tryon (1961) found that the greater the past disturbance from fire, logging, and grazing, the greater the abundance of oak.

The earliest concern for oak regeneration in the U.S. dates back to the 1800's. Possibly the first government sponsored forest research in the U.S. involved live oak *(Quercus virginiana* Mill.*)*. It was planted on public land in Florida to increase supplies of oak timber for shipbuilding (Hough 1878). By the 20th century, the chestnut blight disease caused by the fungus *(Cryphonectria parisitca)*, and the loss of the American chestnut *(Castanea dentata* (Marsh.) Borkh.*)*, created gaps in the forest that are believed to have been filled with oak (Clark 1992, Hardin et al. 2001). However, Kellison (1992) believes that a possible cause for the demise of species such as northern red oak *(Quercus* *rubra* L.*)* was ironically the loss of the American chestnut. His hypothesis is that northern red oak (NRO) has suffered at the expense of red maple *(Acer rubrum* L.*)* and more particularly, yellow-poplar *(Liriodendron tulipifera* L.*)*, which occurred more frequently after the demise of American chestnut. Gypsy moths and browsing by over abundant deer are other types of disturbances that are believed to be factors in converting oak stands in the eastern U.S. into red maple and other species of lower value. Deer can browse younger trees, preventing them from escaping the sapling stage, and gypsy moths can defoliate trees of all ages (Clark 1992, Buckley et al. 1998).

Importance of Northern Red Oak

Oaks are the largest tree genus in the U.S. and the most important hardwood genus. There are 25 oak species in the eastern U.S. and six in the western U.S. Oaks are known for their strength, durability, and also beauty as majestic oaks are highly sought after for lawn and shade trees (Smith 1992). The success of NRO is of particular concern due to its many uses. It is both a valuable source of forest products and an important mast species for wildlife. High quality wood and rapid diameter growth make NRO one of the most desirable sawtimber species (Loftis 1992b). NRO is best known for its use in solid oak furniture, but it is also used for veneer, cabinets, paneling, flooring, caskets, pulpwood, railroad ties, fence posts, and firewood (Ontario DLF 1953, Millers et al. 1989). NRO acorns are an important food source to certain mammals such as the black bear, eastern chipmunk, gray squirrel, white-tailed deer and to birds such as the blue jay, bobwhite, quail, ruffed grouse, and turkey (Van Dersal 1940, Sork et al. 1983, Briggs and Smith 1989).

In the Lake States, the value of NRO has been increasing six to eight percent per year above inflation since the 1970's (North Central Experiment Station 1991). Grade 1, 16 foot NRO logs increased from $161 per thousand board feet (mbf) to $648 per mbf from 1978-1988. Export of NRO logs also increased from 16,500 mbf to 54,400 mbf during these same years (Kellison 1992). Increased prices for oak timber suggests that accelerated harvesting is adding to ecological changes. This tremendous value makes NRO management a high priority (Clark 1992).

Northern Red Oak Ecology

Oaks tend to establish and persist on drier sites where stands are usually more open. The development of competing species is restricted on these sites due to limited belowground resources such as water (Carvell 1979). Kolb et al. (1990b) examined the influence of light, soil moisture, and nutrients on the growth of NRO and concluded that NRO is better adapted to moderately low resource levels, particularly low soil moisture. NRO seems to have a "stress tolerant" strategy as described by Grime (1979). This conservative growth strategy supports the development of a large root system, and shoot growth remains slow until the root system develops (Sander 1972, Dickson 1991). The success of a NRO seedling and its root system depends as much on soil moisture as sunlight. Although NRO is a stress tolerant species, its root regeneration and root growth is very sensitive to soil moisture, which could determine the success or failure of a seedling (Larson and Whitmore 1970, Larson 1980).

The probability of a seedling's survival is related to its competitive environment. The competitive environment is defined as the composition and structure of vegetation immediately proximal to a plant (Pickett and Bazzaz 1978). NRO is classified as a shade intermediate species and thus reaches its maximum rate of net photosynthesis at intermediate light intensities. Therefore, NRO regeneration will not necessarily be acceptable even if released by clearcutting because it will have to compete with species that are better adapted to open sunlight (Beck 1970, Sander and Clark 1971, Sander 1972, Janzen and Hodges 1987, Loftis 1990). Under low light intensity levels, oak survival can also be inhibited. Surprisingly, a continuous sub-canopy or multi-storied layer of tolerant vegetation below the main canopy inhibits NRO seedling growth more than a dense main canopy layer (Janzen and Hodges 1985, Hodges 1987, Janzen and Hodges 1987, Kolb et al. 1990b, Pubanz and Lorimer 1992).

The effect of herbaceous vegetation on oak survival is not well understood. This establishment of herbaceous vegetation depends on many factors such as light, moisture, and nutrients. Regeneration of desirable timber species such as NRO is frequently hindered by competing herbaceous vegetation. Many ferns and grasses benefit from disturbances in site conditions created by overstory removal (Bowersox 1992).

Photosynthetically active radiation (PAR), which measures the amount of light available for photosynthesis in a forest stand, is critical to understanding the performance of tree species and effects of competition. PAR measurements have shown strong relationships with canopy cover and basal area (Buckley et al. 1999). Hanson (1986) found that the level of PAR needed for a positive carbon balance was about 30 micromols per meter squared per second ($u$mol m^{-2} s^{-1}) for NRO in the first growth flush. Light levels in dense hardwood stands are often below this level. Carbohydrate reserves used in respiration thus exceed that produced by photosynthesis, leading to seedling death (Hanson 1986, Crow 1988, Pubanz and Lorimer 1992).

Oak-Hickory Forest Type

The upland oak-hickory forest type occupies nearly 50 million hectares (123.5 million acres) within the Central Hardwood Forest Region (Miller and Lamb 1985). This forest type occurs across eight states in the eastern U.S. from the Ozark Highlands of Missouri to the Coastal Plain of the southeast (Lorimer 2001). Associated oak-hickory tree species include maples *(Acer spp.* L.*)*, blackgum *(Nyssa sylvatica* Marsh.*)*, beech *(Fagus grandifolia* Ehrh.*)*, dogwood *(Cornus florida* L.*)*, sourwood *(Oxydendrum arboreum* (L.) DC.*)* and yellow-poplar. If left undisturbed, succession within the oak-hickory forest type tends to lead towards a greater abundance of shade tolerant species. If the overstory is removed and seed sources are available, shade intolerant species will become a major component of the stand (Sander and Clark 1971, McGee 1975).

Of the 31 oak species in the U.S., 20 are considered to be upland species and 11 are considered to be bottomland species. Upland oaks are a major component of eastern deciduous forests and currently dominate stands of the oak-hickory forest type (Smith 1992). Oaks regenerate well after clearcutting on low quality xeric sites (Loftis 1992b). Ecosystems of oak, primarily NRO, black oak *(Quercus velutina* Lam.*)*, and white oak

(Quercus alba L.*)* dominate forests of the Boston Mountains in Arkansas where site indices are approximately 80 feet at a base year of 50 (Graney 1983). However, regeneration is more typically a problem on high quality sites because large advance reproduction is seldom present (Loftis 1992b). In general, moist sites are harder to regenerate with oak than dry sites (Carvell and Tryon 1961).

In the Central Hardwood Region, oak regeneration has become a serious problem (Clark 1992). Lorimer (2001) suggests that on mesic sites, oak forests are not compositionally stable under the current climate and disturbance regime. Crow (1988) refers to the present abundance of oak in eastern forests as "an artifact of disturbance regimes that are no longer common." Kellison (1992) believes that efforts to have oaks replace themselves on upland mesic sites are unnatural.

NRO in particular performs poorly in competition with species such as yellow-poplar and shade tolerant sub-canopy species such as red maple and beech on high quality sites after clearcutting. Large advanced reproduction for NRO will not occur without some type of disturbance prior to harvest (Loftis 1992b). Following clearcuts on high quality sites, greater supplies of light, water, materials, and space cannot be utilized by many oaks since they have a more conservative growth strategy than shade intolerant species such as yellow-poplar. Oaks are not as flexible to rapidly changing environments as some of their associated species (Loftis 1992c).

Important Oak Competitor: Yellow-poplar

Shade intolerant species such as yellow poplar can become a major component of the oak-hickory forest type on mesic sites if the overstory is removed and they have a seed source available (Sander and Clark 1971, McGee 1975). The natural range of yellow-poplar encompasses nearly the entire eastern United States. It ranges from southern New England, west through southern Ontario and Michigan, south to Louisiana and east through north-central Florida (Beck and Della-Bianca 1981). Yellow-poplar is site sensitive and intolerant of shade, as it grows poorly under full canopy closure.

However, first year growth of yellow-poplar on good sites with adequate sunlight, especially from stump sprouts, can be so rapid that competitors have little or no chance to out compete this species. Heights of 37 meters (120 feet tall) and 46 centimeters (cm) to 61 cm (18 to 24 inches) in diameter at breast height (dbh) at age 50 are normal on the best sites (Hardin et al. 2001). Twenty years after clearcutting a mixed hardwood stand near Asheville, North Carolina, Beck and Hooper (1986) found that yellow-poplar composed 44 percent of the stand's basal area and 80 percent of all stems were greater than eight inches in dbh. Oaks comprised less than four percent of the stand's basal area, and NRO comprised less than one percent.

Yellow-poplar is a pioneer on disturbed sites and can also persist in climax stands (Hardin et al. 2001). It is a prolific seeder and large crops are produced annually. A study in North Carolina discovered that over 300,000 seeds per acre is not uncommon (Carvell and Korstian 1955). Yellow-poplar outgrows oaks on high quality sites after clearcutting, particularly NRO. Yellow-poplar seedlings tend to focus on height growth more than root establishment. Oak reproduction emphasizes root development early on rather than shoot growth (Kolb et al. 1990b). This results in young oaks with larger taproots and more root mass than equally sized yellow-poplars (Barnes and Van Lear 1998). Although beneficial for oak survival, this emphasis on root development can also be detrimental. Competing yellow-poplar can grow so rapidly in height that oaks have little or no chance to compete with it.

Regeneration Issues of Northern Red Oak

Problems exist in both natural and artificial regeneration of NRO (Loftis 1992c). Natural regeneration of NRO is generally less costly than artificial regeneration, but may require intense culture and competition control for one or more growing seasons. Natural regeneration includes seedlings, seedling sprouts, and stump sprouts. Stumps sprouts are considered to be the most competitive while seedlings are the slowest growing and therefore the least competitive (Smith 1992). This is because stump sprouts and seedling sprouts already have well established root systems (Loftis 1992c). Seedling sprouts are less competitive than stump sprouts, which benefit from large amounts of stored reserves from a larger root system (Smith 1986).

Areas with the greatest NRO regeneration problems have generally been on high site index land (>70 feet at base year of 50), especially where yellow-poplar and red maple are strong competitors (Kellison 1992). Concerns about competing yellow-poplar and red maple were first addressed in the mid-fifties in West Virginia. Hypotheses were formulated that yellow-poplar and red maple would overtake future stands at the expense of oak (Clark 1992). However, red maple and other associated oak species such as hickory *(Carya spp.* Nutt.*)* generally occur only as associates to oak and have limited long-term competitive abilities (Burns and Honkala 1990).

On low quality sites (site index less than 75 for NRO), the probability of occurrence for stump sprouting, seedling sprouting, and seedlings is considered to be high, moderate, and moderate, respectively. The overall concern for their regeneration is considered to be minimal, moderate, and severe, respectively (Smith 1992). On high quality sites (site index greater than 75 for NRO), the probability of occurrence for stump sprouting, seedling sprouting and seedlings is considered to be low, moderate, and moderate, respectively. The overall concern for their regeneration is considered to be moderate-severe, moderate-severe, and severe, respectively. This is indicated by a lesser amount of oak regeneration after a harvest or major disturbance than was present in the parent stand (Smith 1992). Further, McGee (1979) documented sparse regeneration of NRO on higher quality sites in the southern Appalachians.

Although volume increased, the average oak loss over a 15-year period was found to be 6.5 percent in and between the states of Indiana and Minnesota. Only 17 percent of the oak types were in the seedling or sapling stage, indicating that oaks are not replacing themselves. These trends indicate a conversion of the oak forest type into the beech-maple forest type at an annual rate of 1.9 percent (Spencer and Kingsley 1991). Dry oak-hickory forests that were cutover in the late 1800's in southwestern Indiana were found to return to oak-hickory and not beech-maple (Potsger and Friesner 1934). However, more yellow-poplar and less oak was found in southern Indiana on newly harvested stands (George and Fischer 1989).

A fairly strong relationship exists between the pre-harvest size of advanced oak growth and its post-harvest development, which can be used to predict the amount of oak in a future stand (Loftis 1992a). As large advanced oak reproduction increases, so does the potential of the stand to regenerate to oaks (Loftis 1992c). Advanced regeneration of NRO seedlings greater than one meter (m) in height have a much greater chance of survival following harvest for two main reasons (Kormanik et al. 1997).

Newly developed oak seedlings allocate a significant proportion of their photosynthates to early root development at the expense of early height growth. As mentioned previously, the growth of the seedlings will remain slow until the root system becomes well developed (Sander 1972, Dickson 1991, Schlarbaum et al. 1997). This allocation pattern could be detrimental to NRO seedlings. NRO has difficulty competing with more shade tolerant species in the lower canopy strata at low light levels and also with well established or faster growing shade intolerant species in open conditions (Hodges and Gardiner 1992). A stress reaction that may last for two-three years, from germination to initial stress release against newly germinated competitors is another growth characteristic (Schlarbaum et al. 1997). Resources such as water and sunlight could be inadequate leading to senescence.

On upland sites containing mature oaks, it is not uncommon to find 12,000 or more new germinants per hectare (ha) beneath an existing stand (Carvell and Tryon 1961, Beck and Hopper 1986, Merritt and Pope 1991). Unfortunately, many of these oak seedlings do not survive. The slow juvenile growth rate of oak seedlings and their slow response to release is still unresolved (Hodges 1987, Crow 1988).

Kolb et al. (1990a) have shown that through direct seeding with acorns, NRO seedlings averaged 15-20 and 20-50 cm after one and two growing seasons respectively. This slow height growth could be a problem since Kellison (1992) recommends that advanced oak reproduction should be greater than 122 cm (four feet) tall at time of regeneration treatment where common competitors such as yellow-poplar and red maple occur. Only 10 percent of new NRO seedlings that established after a good acorn crop were found to have survived after 10 years in the southern Appalachians (Loftis 1983). Predation has affected the success of young seedlings. Direct seeding has not been recommended in upland forest where predation occurs (Bowersox 1992).

Clark (1992) believes that we have been too impatient with oaks. Juvenile growth of oaks is slow even in plantations where competition has been eliminated (Loftis 1992c). Loftis (1992c) believes that slow early growth should be expected when artificially planting NRO. Slow juvenile growth also occurs even where deer browsing is uncommon or controlled on mesic sites (Lorimer 1992). When even aged harvests are conducted on good oak sites, the new stand will most likely be quite different without adequate advanced oak regeneration due to the slow juvenile growth of oaks (Clark 1992).

Artificial Regeneration of Northern Red Oak

Artificial regeneration of oaks is one possible solution that could help to mitigate certain natural regeneration problems such as insufficient seed sources, acorn predation, poor germination conditions, and heavy competition. Through tree improvement programs, the use of high quality seedlings from rapidly growing genetic families has made the outlook much better than in the past, but risks and costs are still high (Clark 1992, Clark et al. 2000, Buckley 2002). Great variation also exists in NRO planting success due to geographic, topographic, and climatic conditions. Even so, artificial regeneration may offer the best solution to many current and future oak regeneration problems (Loftis 1992c). The goal is to substitute planted oak on problem sites without natural oak regeneration (Clark 1992).

Planted seedlings are recommended to be at least 30 cm tall with a root collar diameter of at least six millimeters (mm), and have a multiple branched root system that is at least 25 cm long (Bowersox 1992). Artificially regenerated NRO seedlings have demonstrated the ability to become established before they are overtopped by competing vegetation by year five following harvest. However, little first year growth occurs on these seedlings as the roots become established and they recover from transplanting shock (Kormanik et al. 1995).

Seedlings with the greatest number of first-order lateral roots (FOLR) are believed to be the most competitive in the nursery and in the field (Kormanik and Muse 1986). A higher number of FOLR gives the seedlings an increased absorptive surface area for accessing soil water and nutrients. Those seedlings with the greatest number of FOLR generally have the largest stem caliper and height (Kormanik et al. 1995). In general, larger root systems represent a greater energy reserve since roots are important in carbohydrate storage. Greater numbers of FOLR have been correlated with after-planting growth potential (Ruehle and Kormanik 1986). At least six FOLR are needed for acceptable survival and growth in the prairie region of the central states (Schultz and

Thompson 1991). However, poor performance in plantations has been attributed to shoot to root ratios that were too high (Loftis 1992c). The logistics of planting oak seedlings are also a concern due to their large root systems and structure, which can be difficult to transport (Bowersox 1992).

Second year heights of two to three meters are not uncommon for high quality graded NRO seedlings, which can have upwards of 30 FOLR and root collar diameters (RCD) greater than 14 mm (Schlarbaum et al. 1997). These heights greatly increase the chances of survival for NRO because competition for available sunlight is intense between years two and five following harvest as stump sprouts and other seedlings rapidly develop. Although at least one release will be probably be needed to sustain development, a major limiting factor (access to sunlight) can be moderated using high quality oaks. Following a clearcut, large artificially regenerated NRO seedlings can effectively compete against severe competition. However, they may need release by age seven from faster growing stumps sprouts such as yellow-poplar (Kormanik et al. 1997). Competition control can include fire, herbicides and/or hand weeding to maintain NRO. This is very costly, but special efforts must be taken to ensure adequate reproduction and that competitors such as yellow-poplar and red maple are controlled (Kellison 1992).

Oak "regeneration is a process, not an event," and there is no single solution (Clark 1992). Successful NRO regeneration is difficult to achieve without silvicultural intervention and oak silvicultural management is far too complex to rely on standard prescriptions (Clark 1992, Smith 1992). The shelterwood method is considered to be one of the logical regeneration methods for establishing oak-dominated cohorts due to oak's advanced reproduction strategy (Loftis 1990). In order to maintain few canopy gaps, this basal area reduction technique sometimes results in the removal of little or no commercial timber. Basal area reduction techniques will only be effective if they provide for the development of large advanced oak while inhibiting yellow-poplar and shade tolerant sub-canopy species (Loftis 1992b). Loftis (1992b) defined stand densities that will hinder the establishment and growth of yellow-poplar. For site indices of 70, 80, and 90 feet, approximately 35-40 percent, 30-35 percent, and 25-30 percent of the basal area should be removed respectively. As site quality increases, so does the difficulty in obtaining successful oak regeneration (Loftis 1992c). Therefore, basal area retention should be greater on high quality sites to prohibit fast growing competitors.

Seedling development is also markedly improved if the understory/sub-canopy is removed (Loftis 1992c, Lorimer 1992). Another recommendation is to reduce stand basal area of mature stands from below with herbicides while leaving the main canopy intact, allowing existing small oaks to grow while prohibiting yellow-poplar which is intolerant of shade (Loftis 1992b). Loftis (1992b) believes that the oak seedlings should be large enough to compete with yellow-poplar after 10 years, and overwood removal could begin.

Increasing Northern Red Oak Competitiveness

Specific threshold levels of light, soil moisture and nutrients that maximize the rate of NRO seedling height growth in managed forests have not been conclusively established. There is a general consensus that rapid oak seedling height growth occurs above certain threshold levels of light, soil moisture and nutrient availability.

Identification of these specific levels would allow for the implementation of more precise management practices that promote rapid NRO seedling height growth. The survival rate of NRO seedlings would increase with rapid height growth. With greater NRO heights, they would have a better chance to out compete other tree species and escape deer browsing at an earlier age.

Different plant species are likely to have different competitive effects on the growth and survival of NRO seedlings. By identifying woody and/or herbaceous species that influence the growth of NRO seedlings and other individual plant species, more cost-efficient competition control treatments could be developed. This could reduce efforts and funds invested in competition control that have little or no beneficial effects on the growth and survival of NRO seedlings. Specific NRO genetic families may also differ in growth. If family differences could be detected among artificially regenerated NRO seedlings, then those that have the greatest growth and survival could be used in future studies to advance the competitiveness of planted NRO.

II. Objectives

This study had three main objectives. The first objective was to identify light, soil moisture, and nutrient levels within the immediate vicinity of NRO seedlings that lead to rapid height growth. The hypothesis behind this objective is that rapid NRO seedling height growth occurs above certain threshold levels of light, soil moisture, and nutrient availability. These levels can be identified best through observations across a wide range of treatments in the field. A full range of overstory removal treatments was explored in the experimental design.

Growth and resource measurements were taken for each individual oak seedling. Comparisons within treatments were made that resulted from smaller scale variations in the structure and composition of competing vegetation, PAR, and soil resources. Target levels of light, soil moisture, and nutrients that could lead to the refinement of management practices to maintain oak species in oak-dominated ecosystems were expected.

The second objective of this study was to establish potentially competing plant species that were the most important competitors limiting the height growth and survival of NRO seedlings. Differences in the competitive effects of different plant species on NRO seedlings could be substantial. Experimental approaches were used to document relationships between individual oak seedling height growth and the presence of specific potential competitors in their immediate vicinity. The results from this objective would provide a better understanding of the competition NRO seedlings face and allow for competition control treatments to target specific competitors of NRO seedlings more effectively.

The third objective was to identify differences in height growth and survival among genetic families used in this experiment. Identifying genetic families that have the greatest height growth and survival would allow future studies to advance the competitiveness of NRO in the field. Differences among families were based on seedling measurements taken before and after the first growing season.

III. Methods

Study Site and Experimental Design

This study was conducted at the University of Tennessee Forestry Experiment Station in Oak Ridge, Tennessee (36.01^{o} North, 84.26^{o} West) (Figure 1). The site is approximately 30 hectares in size and consists of oak-hickory forests that have experienced minimal disturbance over the past 50 years. Dependent variables were height growth and percent survival for all NRO seedlings. Height growth for each seedling was determined by subtracting the total height at the end of the first growing season in the field from the total height at the beginning of the first growing season in the field. Percent survival was expressed as the percentage of seedlings that showed vital signs (the appearance of any live buds or green wood) at the end of the first growing season in the field.

A randomized complete block design was used for this experiment. Three blocks were assigned based on stand structure, forest composition, and landscape position. Landform variation between the blocks is primarily due to topographic position. Six treatments were randomly assigned to equally sized plots and implemented within each block. They are the following in order of decreasing canopy cover: uncut (Control), 50% basal area retention (BAR), 25% BAR, 12.5% BAR, commercial clearcut (CCC), and silvicultural clearcut (SCC). The study site is dominated by the Fullerton soil series, which are generally poor soils for row crops, but have fair potential for hay crops and pasture (Olson 2003). Basal area retentions were marked to create uniformly distributed stands comprised of desirable trees. Target species for removal of higher market value

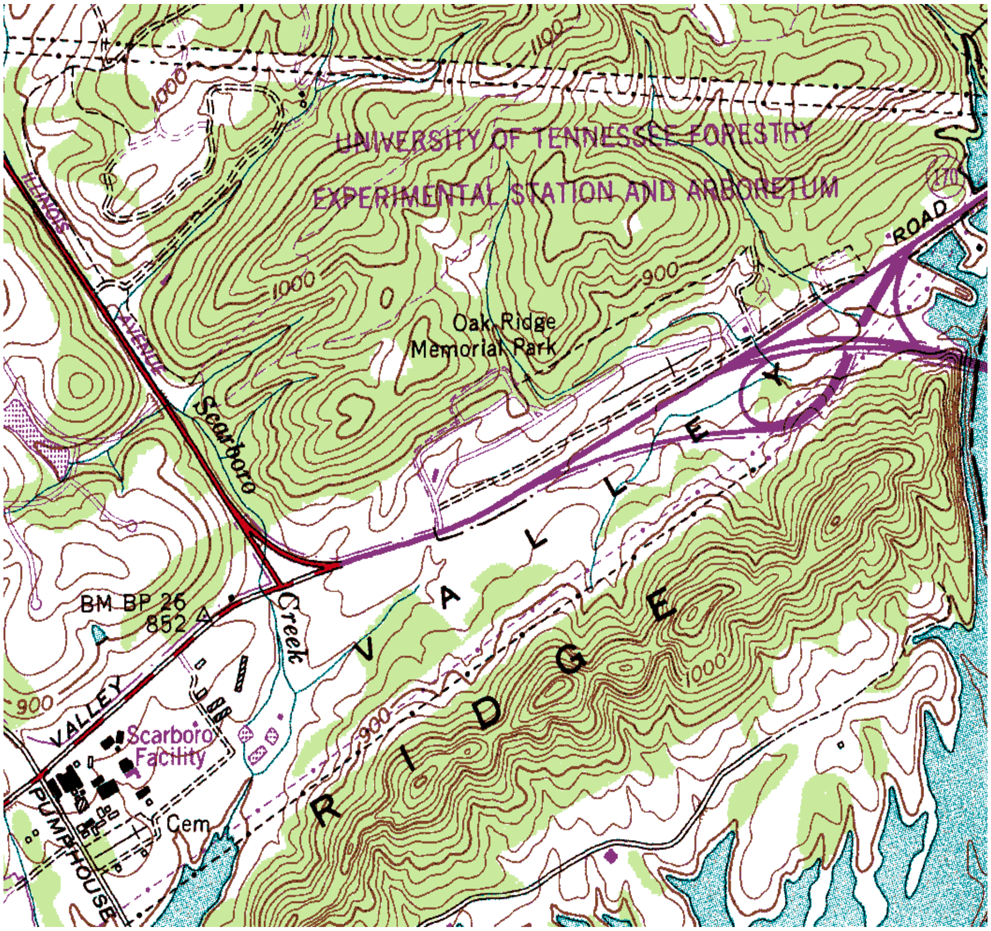

Figure 1. Topographic map of the University of Tennessee Forestry Experiment Station in Oak Ridge, Tennessee (DeLorme 1999).

were: white oak, chestnut oak *(Quercus montana* Willd.*)*, yellow-poplar, NRO, black oak, and southern red oak *(Quercus falcata* Michx.*)*. Trees in the 36-46 cm (14-18 inches) dbh category were favored for retention, but trees in other size classes were used as necessary to maintain an even distribution across all of the treatment units (Olson 2003). Blocks one, two, and three are: north facing, flat ridge top (generally), and south facing, respectively (Figure 2).

Planting Procedures

During the fall of 2001, acorns were collected from mother trees at the Watauga NRO seed orchard in Tennessee. These acorns were then planted in December of 2001 at the Georgia Commission Flint River Nursery near Montezuma, Georgia (Schlarbaum et al. 1997). In February of 2003, seedlings from these acorns from 18 different genetic families were undercut at 30 cm (12 inches) and lifted. They were transported to the Tennessee Division of Forestry's east Tennessee nursery in Etowah, Tennessee for cold storage. Between March and early April of 2003, their heights, root collar diameters, and first order lateral roots were measured. The seedlings were then planted on the study sites at the University of Tennessee Forestry Experiment Station in Oak Ridge, Tennessee in mid-April. Only the largest seedlings, which averaged 131 cm in total height, were selected for planting. These seedlings were classified as premium (*sensu* Clark et al. 2000).

Sixty NRO nursery seedlings were planted and equally spaced within all six treatments in each of the three replicate blocks for a total of 1080 seedlings. Each

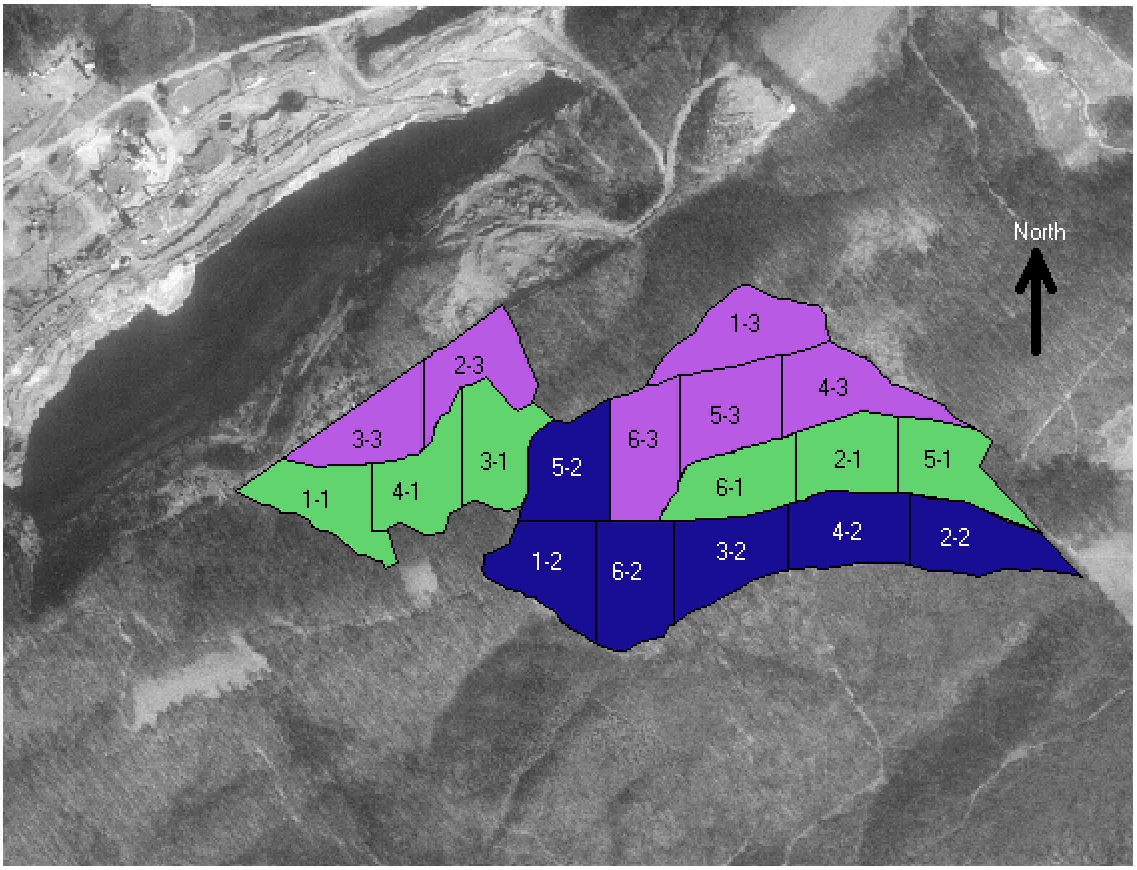

Figure 2. Study site at the University of Tennessee Forestry Experiment Station in Oak Ridge, Tennessee. Treatment numbers are indicated first, followed by block number. Treatments are: (1) uncut, (2) 50% BAR, (3) 25% BAR, (4) 12.5% BAR, (5) CCC, and (6) SCC.

*BAR = basal area retention
CCC = commercial clearcut
SCC = silvicultural clearcut

treatment was planted in two sub-plots, with 30 seedlings per sub-plot. All seedlings were planted on a 6.1 meter by 6.1 meter (20 feet by 20 feet) spacing (Figure 3). When possible, a one-chain (20.1 meters) buffer was formed around each treatment to minimize the edge effect from other treatments. Each treatment plot was divided into two sub-plots separated by a one-chain buffer for future studies involving sub-canopy and/or understory removals.

Evaluation of Optimum Oak Resource Levels

The first objective was to identify light, soil moisture, and nutrient levels in the immediate vicinity of the planted NRO seedlings that lead to rapid height growth. Measurements were taken on all 60 NRO seedlings from each treatment plot and block for a total of 180 measured seedlings for each of the six different overstory removal treatments. The total heights and root collar diameters were measured to the nearest centimeter and millimeter respectively, at the beginning and end of the first growing season in the field.

Light levels within the immediate vicinity of each seedling were quantified by measuring photosynthetically active radiation (PAR) immediately above the terminal leader of each seedling within all six treatments and all three blocks. PAR measurements were taken monthly during three two-hour periods during the day: morning (9:30 am-11:30 am), noon (12:30 pm-2:30 pm), and afternoon (3:30 pm-5:30 pm) during mid-May, mid-June, mid-July, and mid-August of the first growing season. All measurements were centered around solar noon. For example, if solar noon was at 1:33 pm, noon

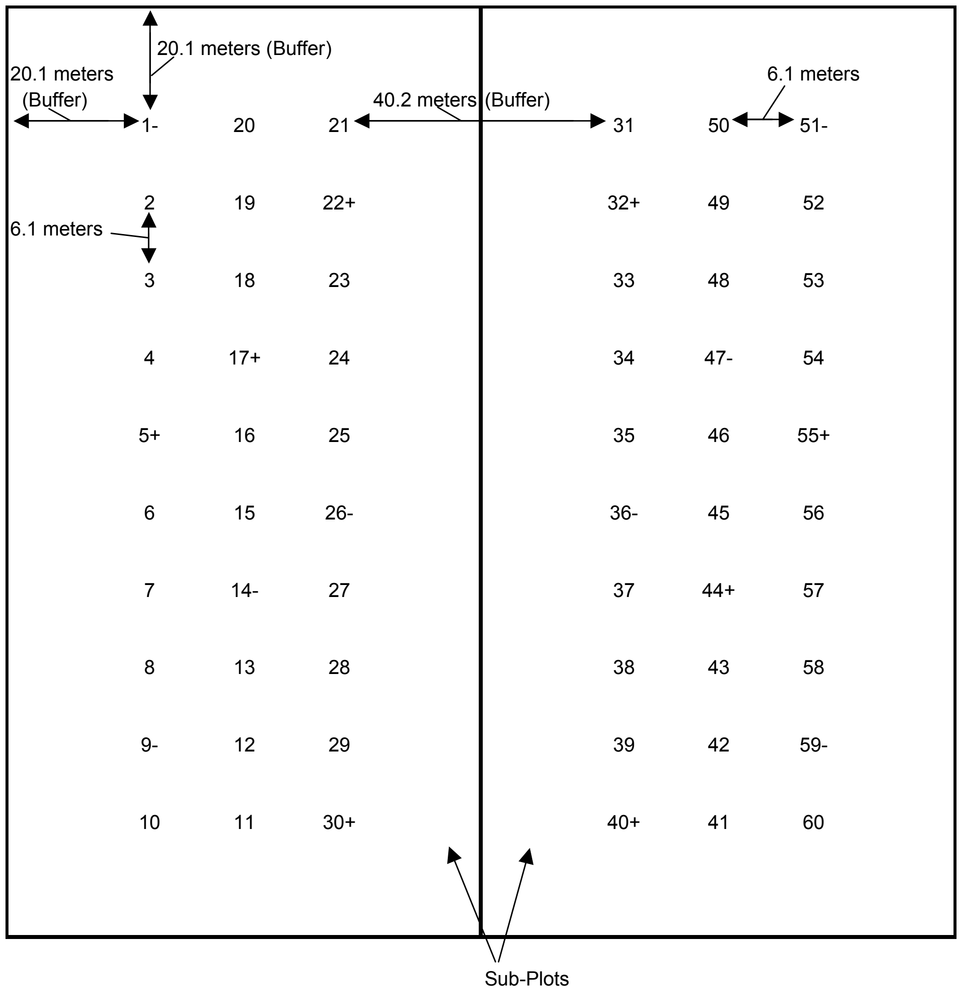

Figure 3. Schematic of 60 NRO seedlings planted within one treatment with sub-plot design for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. All treatment plots vary in shape, but the 6.1 meter spacing was maintained. Example schematic of plant root simulator probe design has also been shown.

*NRO = northern red oak
+ = positively charged PRS™-probes
- = negatively charged PRS™-probes

measurements were taken from 12:33 pm-2:33 pm. Morning measurements were obtained from 9:33 am-11:33 am and afternoon measurements were obtained from 3:33 pm-5:33 pm, leaving a one-hour rest period before and after the noon measurements. Table 1 lists the approximate times solar noon occurred during PAR measurements May through August of 2003.

A reference set of PAR measurements were taken in open sunlight at the same time as measurements within the treatments to serve as a reference for calculating percent full PAR in the vicinity of each seedling. All PAR measurements for each NRO seedling, were taken using two Decagon Accupar Ceptometers (Decagon Devices, Pullman, WA). The reference Ceptometer was placed at one of two logging decks, whichever was closest to the seedlings in treatments that were going to be measured for each particular day. PAR measurements in the field were taken no further than approximately 400 meters from the Ceptometer in the open. PAR measurements for each NRO seedling were calibrated to the reference Ceptometer receiving full sunlight. The same reference Ceptometer was used in the open throughout the summer.

Soil moisture from the 0 to 15 cm soil depth was quantified by measuring percent volumetric soil moisture within 15 cm (six inches) from the base of each seedling. Measurements were taken 15 cm from the base of each seedling because the lateral roots were trimmed to this length when they were graded. Therefore, percent soil moisture measurements should not have affected seedling growth. These measurements were collected once a month in the second half of May, June, July, and August of the first growing season. Percent soil moisture was measured with a portable Trase Time Domain Reflectometry (TDR) probe (Soil Moisture Corp., Goleta, CA).

Table 1. Approximate times of solar noon (+/- 1 minute) in Oak Ridge, Tennessee from May through August of 2003 during PAR measurements (Solar Noon 2003).

	Solar Noon
May	1:33:30 pm
June	1:38:30 pm
July	1:43:00 pm
August	1:41:30 pm

*PAR = photosynthetically active radiation

Nutrient availability was quantified at the treatment level and focused on macronutrient supplies using Plant Root Simulator (PRS)™-probes (Western Ag Innovations Inc., Saskatoon, SK). Sixteen PRS™-probes were systematically placed 15 cm from the base of 16 NRO seedlings (due to lateral roots) within each treatment plot (eight per sub-plot) for approximately eight weeks (mid-August through mid-October, 2003) (Figure 3). They were then sent to the manufacturer and analyzed for macronutrients. Eight of the PRS™-probes within each treatment were negatively charged allowing them to absorb cations and the other eight were positively charged, allowing them to adsorb anions. Nutrients measured were nitrate, ammonium, calcium, magnesium, potassium, phosphorus, iron, manganese, copper, zinc, borate, sulfur, lead, and aluminum. Total nitrogen was also determined by adding the nitrate and ammonium levels together. The systematic placement of the PRS™ probes allowed for a good, representative sample of the macronutrients within each treatment to be obtained.

Evaluation of Potential Oak Competitors

The second objective of this study was to establish competing plant species that limit the height growth and survival of the planted NRO seedlings. The vegetation next to 10 randomly selected NRO seedlings per treatment was sampled within each block for a total sample of 180 seedlings. Methods of determining competition adjacent to the randomly selected NRO seedlings are listed below:

1) Percent ground cover for all herbaceous species combined was estimated ocularly within a 0.5 m radius of each seedling.

2) Percent canopy cover for all herbaceous species above the crowns of the planted seedlings was recorded by species using a densiometer placed directly over each seedling.
3) Total percent cover of herbaceous and woody species combined was recorded using a densiometer placed directly over each seedling.
4) All woody species <150 cm tall within a 1 m radius were tallied by species using two size classes (0-50 cm, and 51-150 cm).
5) Total height, dbh and species were recorded for all woody species ≥150 cm tall within a 2 m radius.
6) Basal area was recorded using a factor 10 prism.

All heights were measured using a telescoping height pole or clinometer. The clinometer was used to measure heights of species greater than seven meters tall. Potentially competing overstory, sub-canopy, and understory species and their combined relative densities were quantified to see if different levels of occurrences within species affected NRO seedling height growth. The effects of a species with an average abundance greater than three percent per treatment among the different size classes were further analyzed.

Evaluation of Genetic Family Effects on Oak Growth and Survival

The third objective was to identify possible genetic family differences among the NRO seedlings. Genetic families were known and pre-planting height, RCD, and number of FOLR were recorded as possible factors contributing to post-planting growth and survival. Each sub-plot contained five blocks of six different families for a total of 30 seedlings per sub-plot (Figure 4). The six families per block within each sub-plot were randomly assigned. A total of 12 different families (six different families per sub-plot) within each overstory removal treatment were used resulting in a balanced incomplete block design (IBD) for family treatments. The design has 10 seedlings from every family occurring within each overstory removal treatment across the three blocks. Therefore, five seedlings from each family occur in only two of the three treatments across all three blocks within the experimental design. Differences in first growing season height growth and percent survival were compared among families. Height growth and percent survival were also analyzed with respect to pre-planting height, RCD, and number of FOLR.

Statistical Analysis

Statistical analysis was performed using SAS software (SAS Institute, 2001). All tests were conducted using a significance level of alpha = 0.05. Multiple linear regression was performed using the backward selection technique to determine which variables best explained differences in first year seedling height growth and percent survival for the planted NRO seedlings. All independent variables were initially entered into the model and the least significant variables were eliminated one at a time until all remaining variables were significant. Two separate models were created, one that included data from all seedlings in this study, and a second that included the 180 seedlings sampled in the second objective (10 percent of all seedlings). Independent variables tested were PAR, percent soil moisture, all macronutrients, seedling

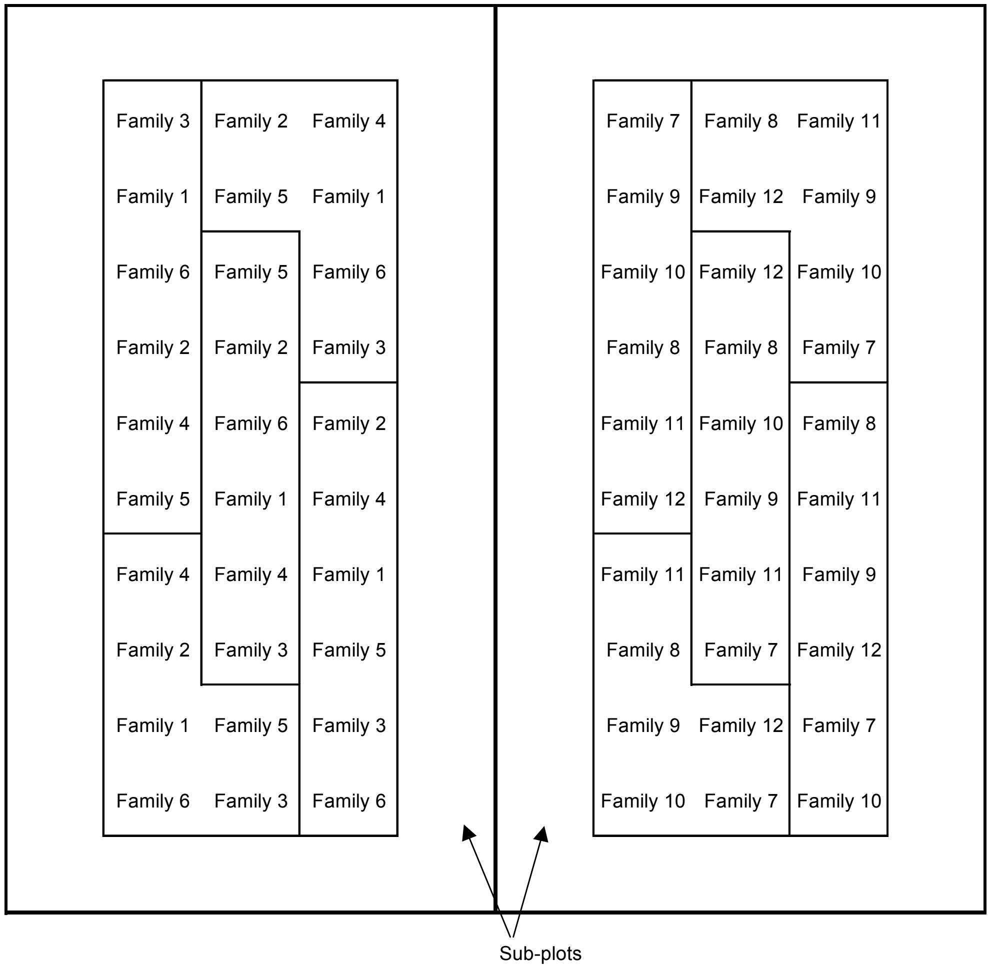

Figure 4. Example of how six of eighteen families were randomly assigned within each sub-plot for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. There were five blocks per sub-plot. Families were randomly assigned to all treatments within each block in a balanced manner.

characteristics (genetic family, planted height, planted RCD, and FOLR), and woody and herbaceous species.

Of the 1080 seedlings in this study, only 1067 seedlings were used in the first regression model. Three seedlings were accidentally not planted and another 10 seedlings from other genetic families were accidentally mixed into the study. Only the second model was able to incorporate data on herbaceous and woody species sampled in the vicinity of 180 seedlings. In order to keep the second model at the seedling level, just those seedlings for which this data was collected were used.

Mixed model analysis of variance (MMAOV; Proc Mixed, SAS 2001) was also used to test treatment effects and genetic family effects on height growth and percent survival of the planted NRO seedlings. MMAOV was used because it accounts for the variation created by random effects in the model (Saxton, 2002). Tukey's HSD was performed to determine if differences existed between the means of variables that were found to be significant from using multiple regression and MMAOV. Correlation analysis was also performed to see if any associations existed between these same variables.

These methods were expected to identify optimum threshold levels for PAR, soil moisture, nutrient availability and seedling characteristics that maximize the height growth of planted NRO seedlings. It was also possible to correlate the optimum resource levels identified with the type of overstory treatment applied. The effects of specific competing tree, shrub, and herbaceous species on the growth of the planted NRO seedlings was expected to give a better understanding on whether competition for light, competition for belowground resources, or both were important, and whether there were potentially any positive or benign interactions between the NRO seedlings and certain woody or herbaceous associates.

IV. Results

Effect of Treatments on PAR and Soil Moisture

Percent full PAR received by the six different treatments increased as canopy cover decreased (Figure 5). The Control treatments received the least percentage of full PAR at 3.8 percent and the SCC treatments received the greatest at 86.7 percent. Tukey's mean separation technique shows that the only treatment that was not significantly different from every other treatment was the CCC. The percent full PAR level received by the CCC was not significantly different from the 25% BAR and the SCC. The amount of basal area retained within each treatment was highly correlated with the percent level of PAR received by each treatment (Figure 6). Almost 91 percent of the variation in the percent full PAR received within each treatment can be explained by the basal area of that treatment (R^2=0.905).

The Control treatments contained an average basal area of 29.1 m^2/ha (126.7 $feet^2$/acre) (Figure 7). This basal area level allowed only 3.8 percent of available sunlight to reach the forest understory. As shown in Table 2, the actual mean value of PAR that reached the forest understory at this percentage was 46 *u*mol m^{-2} s^{-1}. The ratio of *u*mol m^{-2} s^{-1} to percent full PAR within the Controls is therefore 11.98. Corresponding treatments show similar ratios when comparing *u*mol m^{-2} s^{-1} values to percent full PAR (Table 2). If 46 *u*mol m^{-2} s^{-1} equals 3.8 percent full PAR, then 1198 *u*mol m^{-2} s^{-1} would equal 100 percent full PAR for the Controls. Compared to the SCC treatments whose PAR values equaled 1085 *u*mol m^{-2} s^{-1} at 86.7 percent full PAR, 100 percent full PAR would be approximately 1252 *u*mol m^{-2} s^{-1} with a ratio of *u*mol m^{-2} s^{-1} to percent full

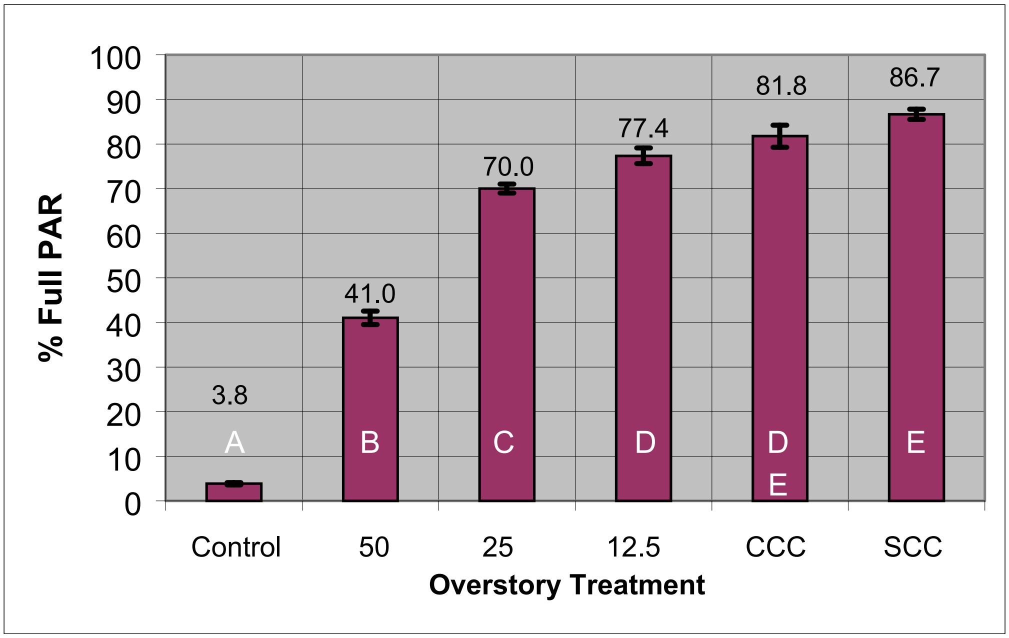

Figure 5. Percent full PAR received by planted NRO seedlings within all six overstory treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*PAR = photosynthetically active radiation
NRO = northern red oak

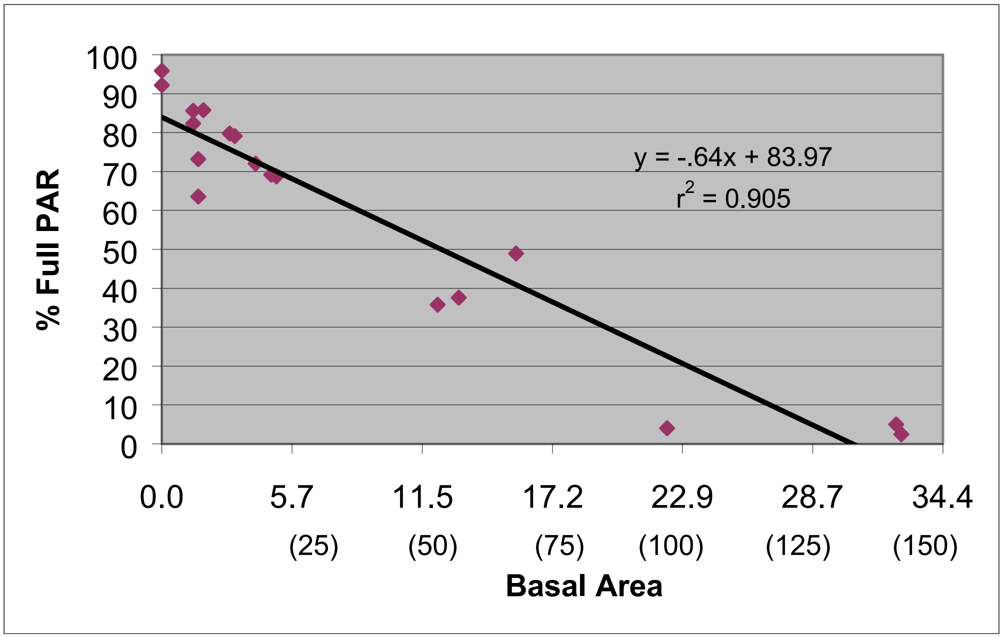

Figure 6. Percent full PAR received in treatments with corresponding basal areas in meter^2/hectare (feet^2/acre) for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*PAR = photosynthetically active radiation

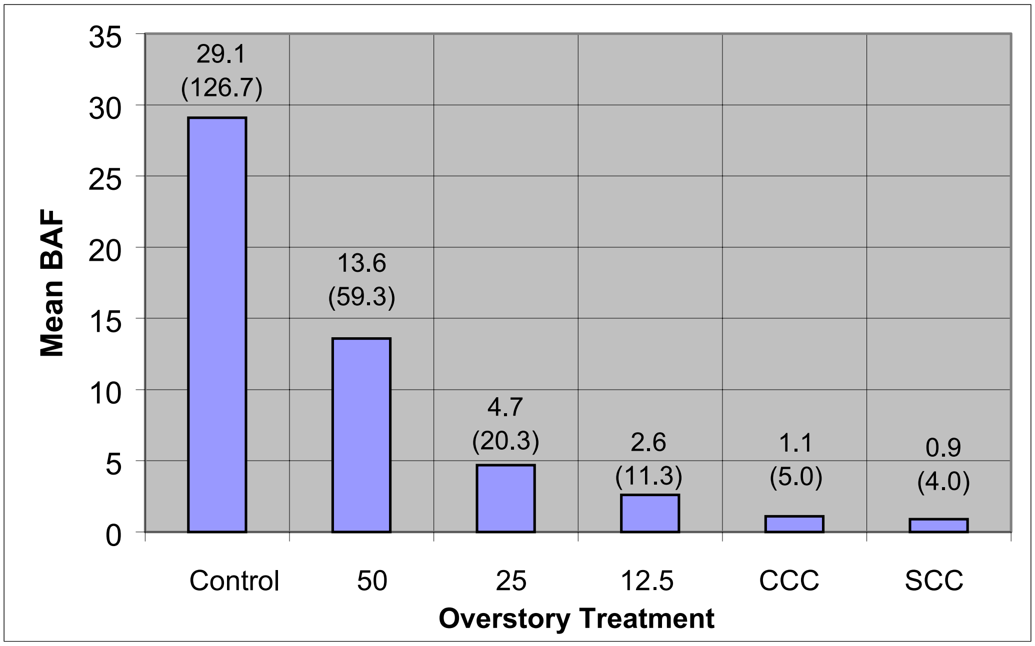

Figure 7. Basal area in meter^2/hectare (feet^2/acre) per treatment for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

Table 2. Mean PAR values received by planted NRO seedlings by treatment and month for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. Percent full PAR levels and ratios of mean PAR values compared to percent full PAR are also shown. Values are expressed in *u*mol m^{-2} s^{-1}.

Month	Control	50% BAR	25% BAR	12.5% BAR	CCC	SCC
May	55	255	593	664	815	1022
June	57	600	1071	1218	1228	1239
July	38	446	944	942	897	986
August	33	417	583	805	825	1091
Overall Mean	46	429	798	907	941	1085
% Full PAR	3.84	41.01	69.99	77.36	81.76	86.67
Ratio of Mean PAR Value to % Full PAR	11.98	10.46	11.40	11.72	11.51	12.52

*NRO = northern red oak
PAR = photosynthetically active radiation
BAR = basal area retention
CCC = commercial clearcut
SCC = silvicultural clearcut

PAR equaling 12.52.

Percent soil moisture levels were not significant ($p = 0.58$) in this study for predicting height growth. However, Tukey's mean separation technique was conducted to see if percent soil moisture differences existed between treatments (Figure 8). No differences were detected, but percent soil moisture for the Control treatments were the lowest at 13.0 percent and percent soil moisture for the 50% BAR treatments was the highest at 17.7 percent. The amount of precipitation in east Tennessee in the spring and summer of 2003 was greater than normal and could have affected these results (Table 3).

Effect of Blocking on PAR and Soil Moisture

Tukey's mean separation technique for percent full PAR levels among the three replicate blocks indicated that mean percent full PAR in block one was significantly lower than both blocks two and three (Figure 9). Although block two was not significantly different from block three, it did have a higher percent full PAR level than block three. Block one is north facing. Block two is on the ridge top and although somewhat north facing in some areas, is generally flat. Block three is south facing.

Again, percent soil moisture levels were not significant ($p = 0.58$) in this study for predicting height growth. However, Tukey's mean separation technique was conducted to see if differences existed between blocks (Figure 10). No significant differences were detected, but the mean percent soil moisture value for block two was higher than the values for blocks one and three. Percent full PAR levels and percent soil moisture levels by treatment for each block are shown in Appendices 1 and 2, respectively.

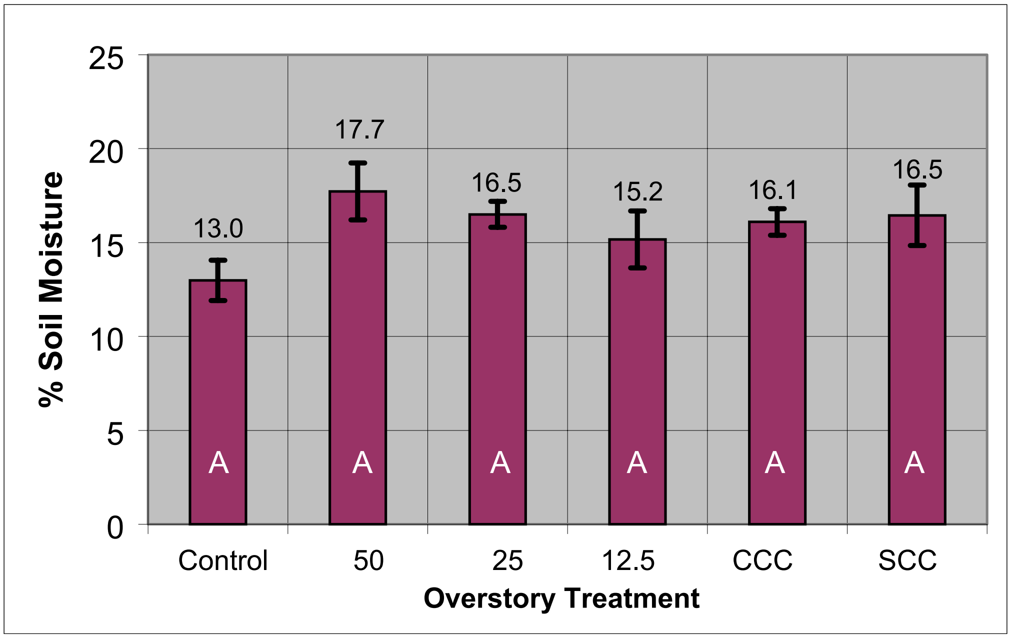

Figure 8. Percent volumetric soil moisture in the vicinity of planted NRO seedlings within all six overstory treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*NRO = northern red oak

Table 3. Precipitation averages for Knoxville, Tennessee. Knoxville is approximately 21 miles southeast of Oak Ridge, Tennessee (Weather 2003).

	2003 Average	Seasonal Average
May	19.1 cm	10.5 cm
June	5.8 cm	10.1 cm
July	18.2 cm	11.9 cm
August	14.6 cm	8.0 cm

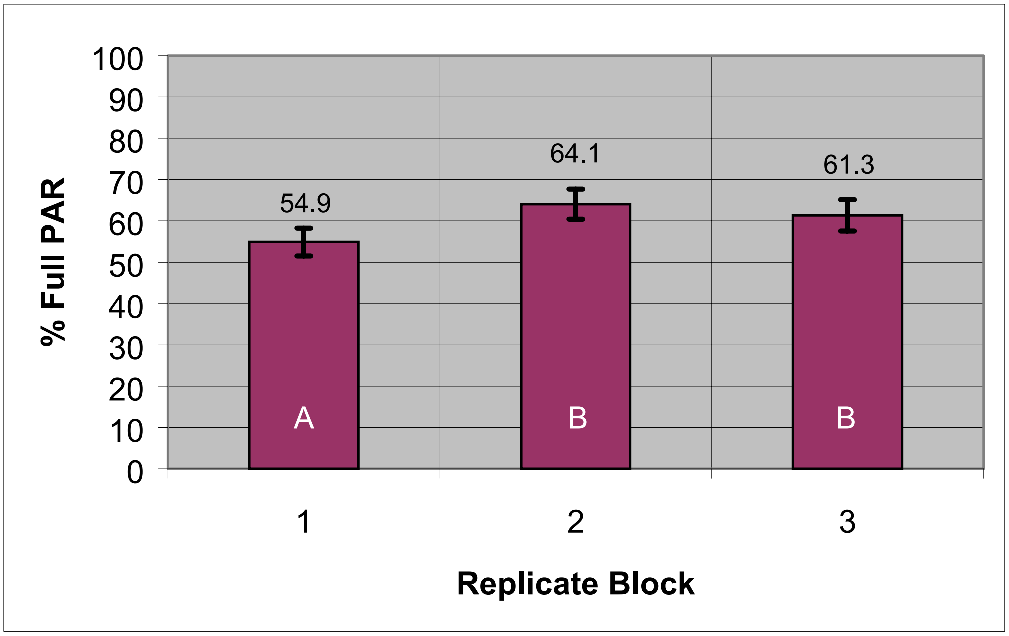

Figure 9. Percent full PAR received by planted NRO seedlings in each of the three replicate blocks for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*PAR = photosynthetically active radiation
NRO = northern red oak

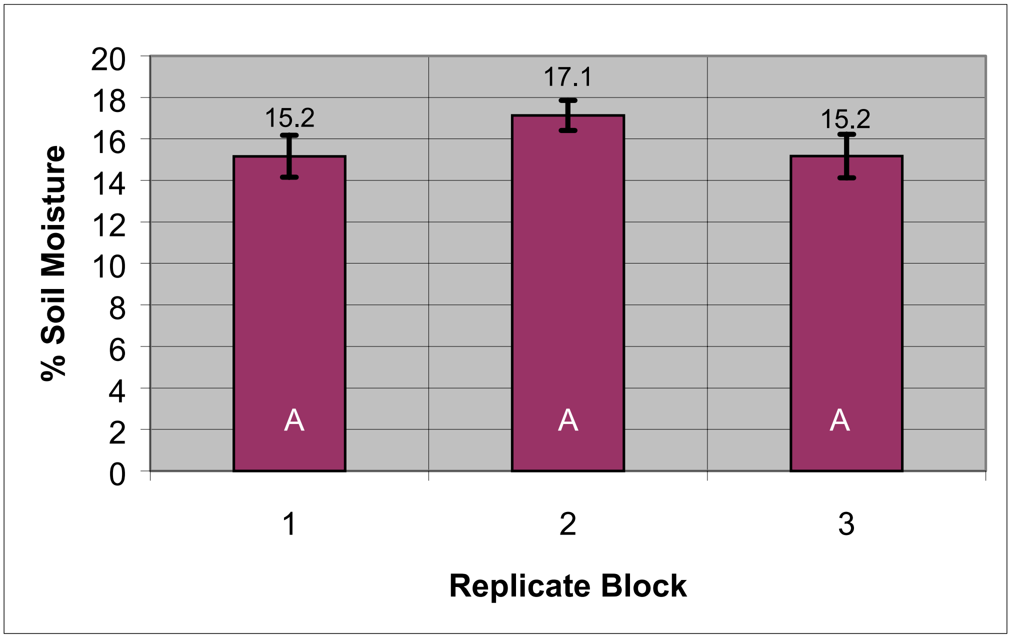

Figure 10. Percent soil moisture received by planted NRO seedlings within all three replicate blocks for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*NRO = northern red oak

Effect of Time of Day and Month on PAR

No differences in percent full PAR between morning, noon, and afternoon measurement periods were detected with Tukey's mean separation (Figure 11). Morning and noon mean percent full PAR levels differed the most (by 1.2 percent). Some differences in percent full PAR levels occurred between the months of May, June, July, and August (Figure 12). Mean percent full PAR in May was 59.3 percent, and peaked in June at 61.8 percent. Percent full PAR then decreased to 61.7 percent in July and to 57.6 percent in August. Measurements in June and August differed by 4.2 percent, and this difference was significant.

Percent full PAR levels for individual treatments across all four months are located in Table 4. All treatments except for the 12.5% BAR and CCC treatments had their lowest percent full PAR levels in August. The Control, 12.5% BAR, and SCC treatments had peak levels in June and then declined in July and August. The 25% BAR and CCC treatments had peak levels in July and the 50% BAR peaked in May. The Controls varied by no more than one percent between any of the months while the 12.5% BAR, CCC, and SCC treatments varied up to ten, eight, and seven percent respectively, between their highest and lowest months. The 50% BAR and 25% BAR varied by five percent and six percent respectively, between their highest and lowest months. Percent full PAR levels for time and month by block are shown in Appendices 3 and 4 respectively. Percent full PAR levels for treatment, block, and month by time period are shown in Appendices 5, 6, and 7 respectively.

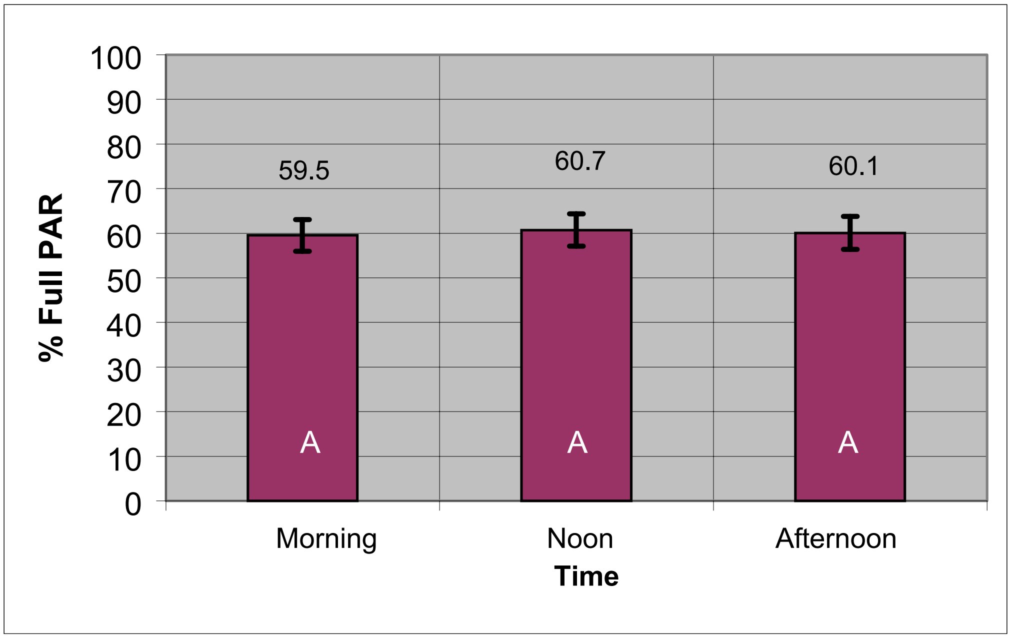

Figure 11. Percent full PAR received by planted NRO seedlings within all three time periods for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*PAR = photosynthetically active radiation
NRO = northern red oak

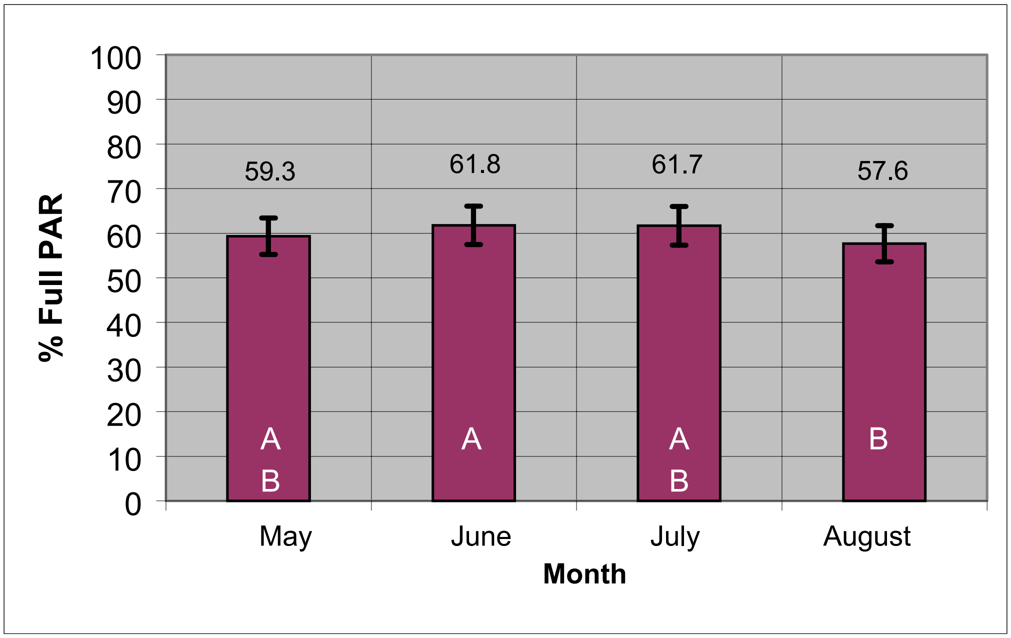

Figure 12. Percent full PAR received by planted NRO seedlings during all four months across for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*PAR = photosynthetically active radiation
NRO = northern red oak

Table 4. Percent full PAR received by planted NRO seedlings by treatments and month for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

Month	Control	50% BAR	25% BAR	12.5% BAR	CCC	SCC	Average
May	4	44	70	71	78	87	59
June	4	41	71	81	84	88	62
July	4	40	72	80	86	86	62
August	3	39	66	77	79	81	58
Average	4	41	70	77	82	86	

*NRO = northern red oak
PAR = photosynthetically active radiation
BAR = basal area retention
CCC = commercial clearcut
SCC = silvicultural clearcut

Herbaceous Competitors

Percent herbaceous and woody cover was determined within each treatment using a densiometer. These measurements were recorded during September of 2003, when vegetation on the study site was fully developed. All species identified in this study along with actual densities and percentages by woody species for each treatment are listed in Appendices 10-24. Eighty eight percent of the cover above the canopies of NRO seedlings in the Control treatments was comprised of woody competitors, while 12 percent was open sky (Table 5). No herbaceous species overtopped any of the NRO seedlings in the Control treatments. In the 50% BAR, 35 percent of the total cover was comprised of woody competitors, while one percent was herbaceous. Herbaceous cover increased up to seven percent within the 25% BAR, while woody cover decreased to 17 percent. In the 12.5% BAR, five percent of the cover above the canopies of the NRO seedlings was herbaceous cover and 27 percent was woody. Herbaceous cover was highest in the CCC at 12 percent. Woody cover decreased again to 10 percent within the CCC. In the SCC, five percent of total cover over the NRO seedlings was herbaceous cover, while six percent was woody. Within all treatments combined, five percent of the cover above the canopies of the NRO seedlings was herbaceous cover, while 27 percent was woody. Of the herbaceous competition overtopping the NRO seedlings in this study, 54 percent was fireweed *(Erechtites hieracifolia* L.*)*, 38 percent was horseweed *(Erigeron canadensis* L.*)*, and the other eight percent was either pokeweed *(Phytolacca americana* L.*)* or wild lettuce (*Lactuca spp*. L.) (Figure 13).

Table 5. Percentages of cover (by herbaceous and woody species) and open sky above planted NRO seedlings for all six treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

Treatment	% Woody Cover	% Herbaceous Cover	% Open Sky
Control	88	0	12
50% BAR	35	1	64
25% BAR	17	7	76
12.5% BAR	27	5	68
CCC	10	12	78
SCC	6	5	89
All Treatments	27	5	68

*NRO = northern red oak
BAR = basal area retention
CCC = commercial clearcut
SCC = silvicultural clearcut

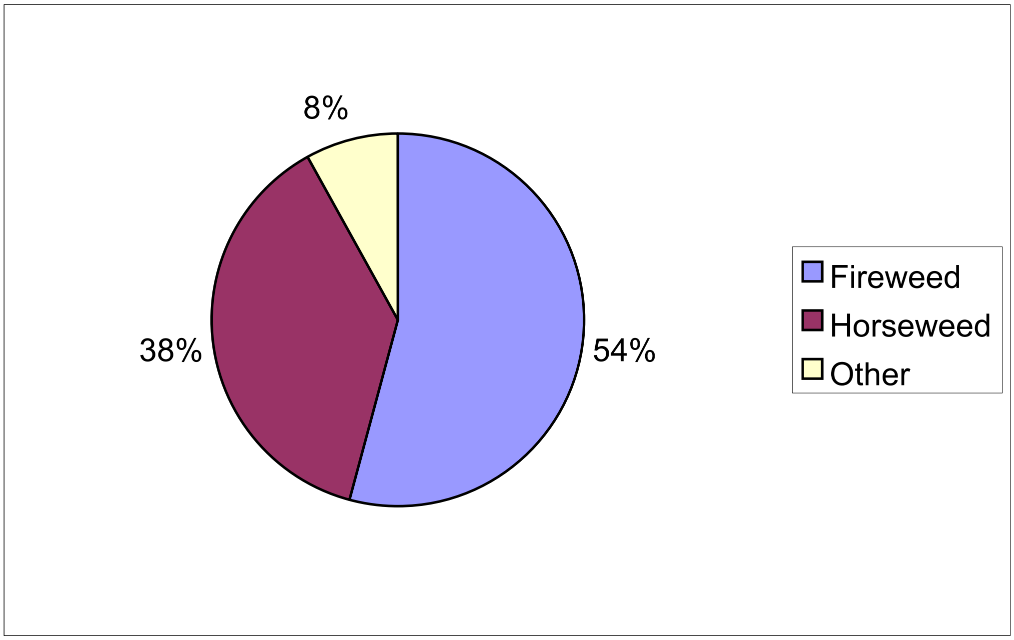

Figure 13. Composition of herbaceous species above planted NRO seedlings across all six overstory treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

Woody Competitors

Woody competitors were tallied in three size classes in this study: 0-50 cm, 51-150 cm, and ≥150 cm, respectively. The results from only three treatments (Control, 50% BAR, and SCC) will be presented here to show the variation in competition with decreasing canopy cover. For actual densities and percentages by woody species for all six treatments, see Appendices 11-24. In order to make the visualization of competitor effects easier, plot results have been presented as they were measured, and were not converted to stems per hectare.

Within the Control treatments, red maple and redbud *(Cercis canadensis* L.*)* were the most abundant individual species in the 0-50 cm height class with each occurring approximately three times per plot (Figure 14). Sassafras *(Sassafras albidum* (Nutt) Nees*)* and strawberry bush *(Euonymous americanus* L.*)* were also noticeably present, each occurring about two times per plot. For the 51-150 cm height class within the Control treatments, red maple and redbud were the most abundant arborescent species and greenbrier *(Smilax spp.* L.*)* was the most abundant woody vine.

Converting red maple and redbud values to whole numbers would result in them each occurring once within a 2.24 m radius plot in this size class, with actual density values of approximately 0.2 per plot at the one meter radius plot level for both species. For the ≥150 cm height class in the Control treatments, red maple was the most abundant species and occurred just over five times within a two meter plot radius of each NRO seedling. Sugar maple *(Acer saccharum* Marsh.*)* and white oaks, which includes both white oak and chestnut oak, were the next most abundant species and

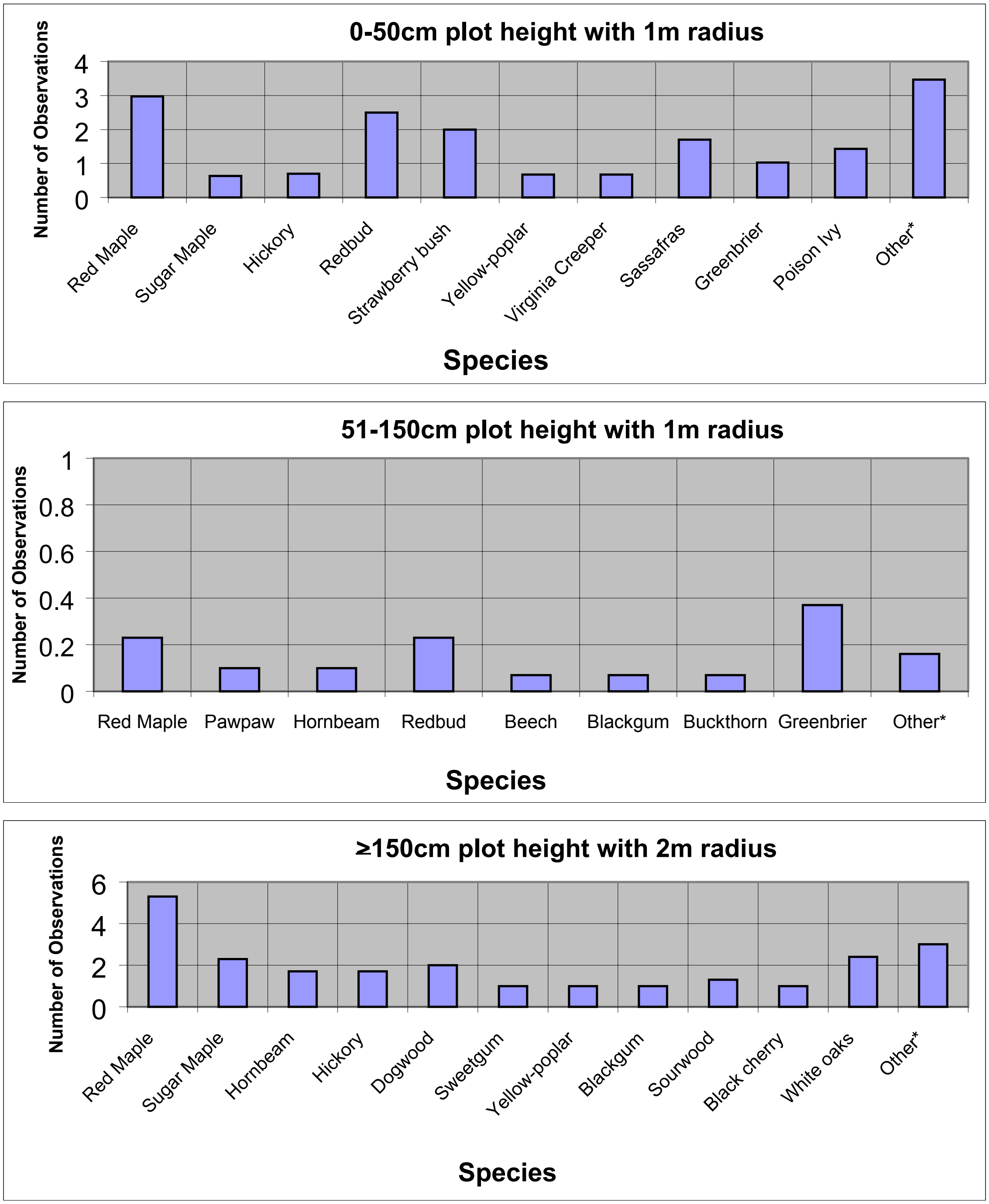

Figure 14. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the Control treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

*NRO = northern red oak

occurred just over two times per plot.

Within the 50% BAR treatment, yellow-poplar and sassafras were the most abundant individual species in the 0-50 cm height class, with each occurring nearly 12 and eight times per plot, respectively (Figure 15). Red maple and redbud occurred at approximately the same densities in this treatment as in the Control treatments, with densities of three and two, respectively. For the 51-150 cm height class within the 50% BAR, red maple and redbud were again the most abundant tree competitors in this size class, with redbud over twice as abundant as in the Control treatments. Converting red maple and redbud values to whole numbers would result in them each occurring two and five times respectively within a 3.16 m radius plot in this size class, with actual density values of 0.2 and just over 0.5 per plot at the one meter radius plot level for both species respectively. For the ≥150 cm height class in the 50% BAR, redbud was the most abundant species and occurred two times within a two meter plot radius of each NRO seedling. Red maple, sugar maple, and yellow-poplar were the next most abundant species with each occurring approximately 1.5 times per plot.

For the 0-50 cm height class within the SCC, yellow-poplar and sassafras were again the most abundant individual species with each occurring approximately thirteen and five times per plot, respectively (Figure 16). Red maple occurred at approximately the same level in this treatment as in the Control and 50% BAR with a density of almost three, but redbud was no longer as abundant. For the 51-150 cm height class within the SCC, red maple and winged sumac *(Rhus copallina* L.*)* were the most abundant tree competitors in this size class, each occurring about 0.4 times per plot.

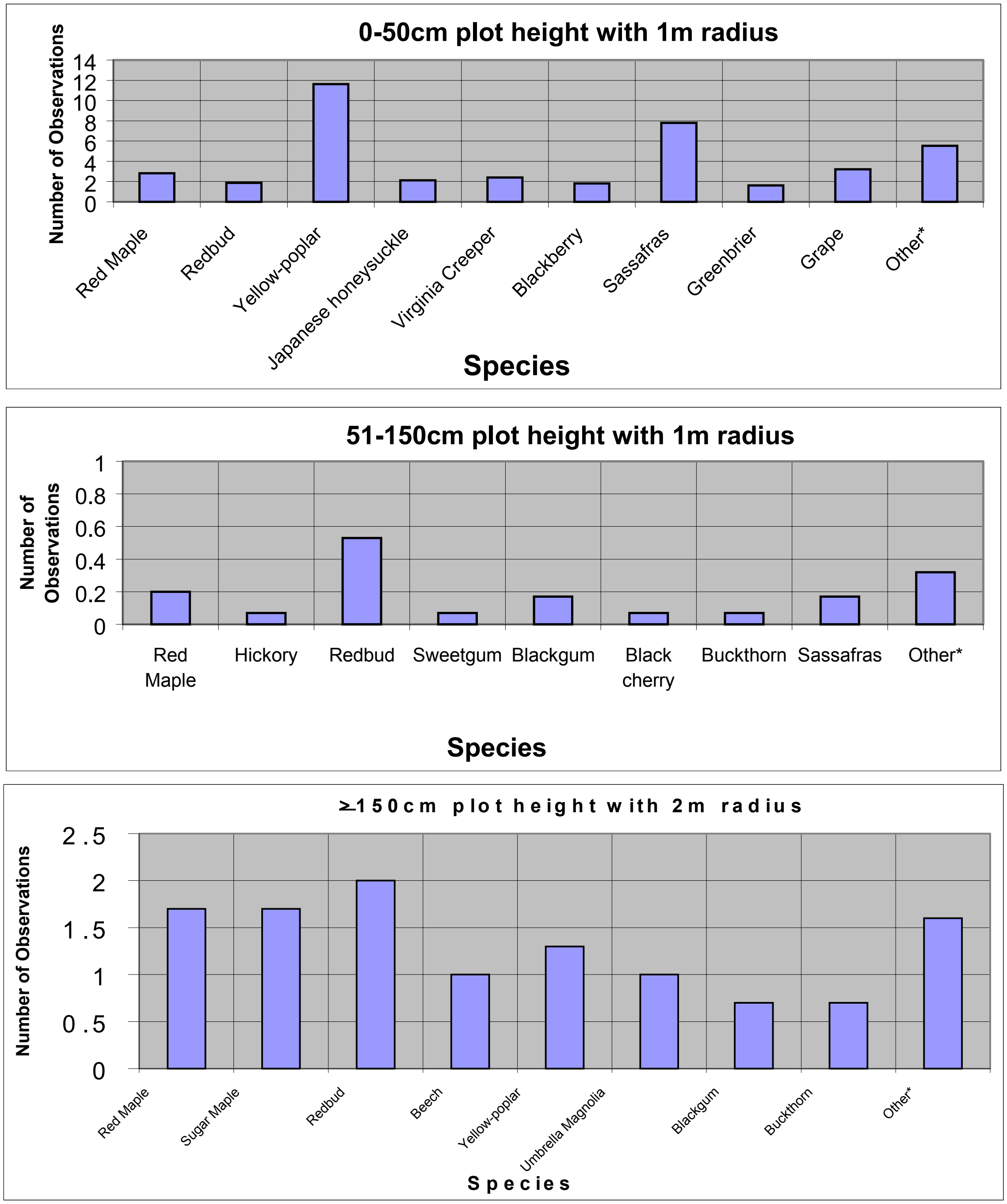

Figure 15. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the 50% BAR treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

*NRO = northern red oak
BAR = basal area retention

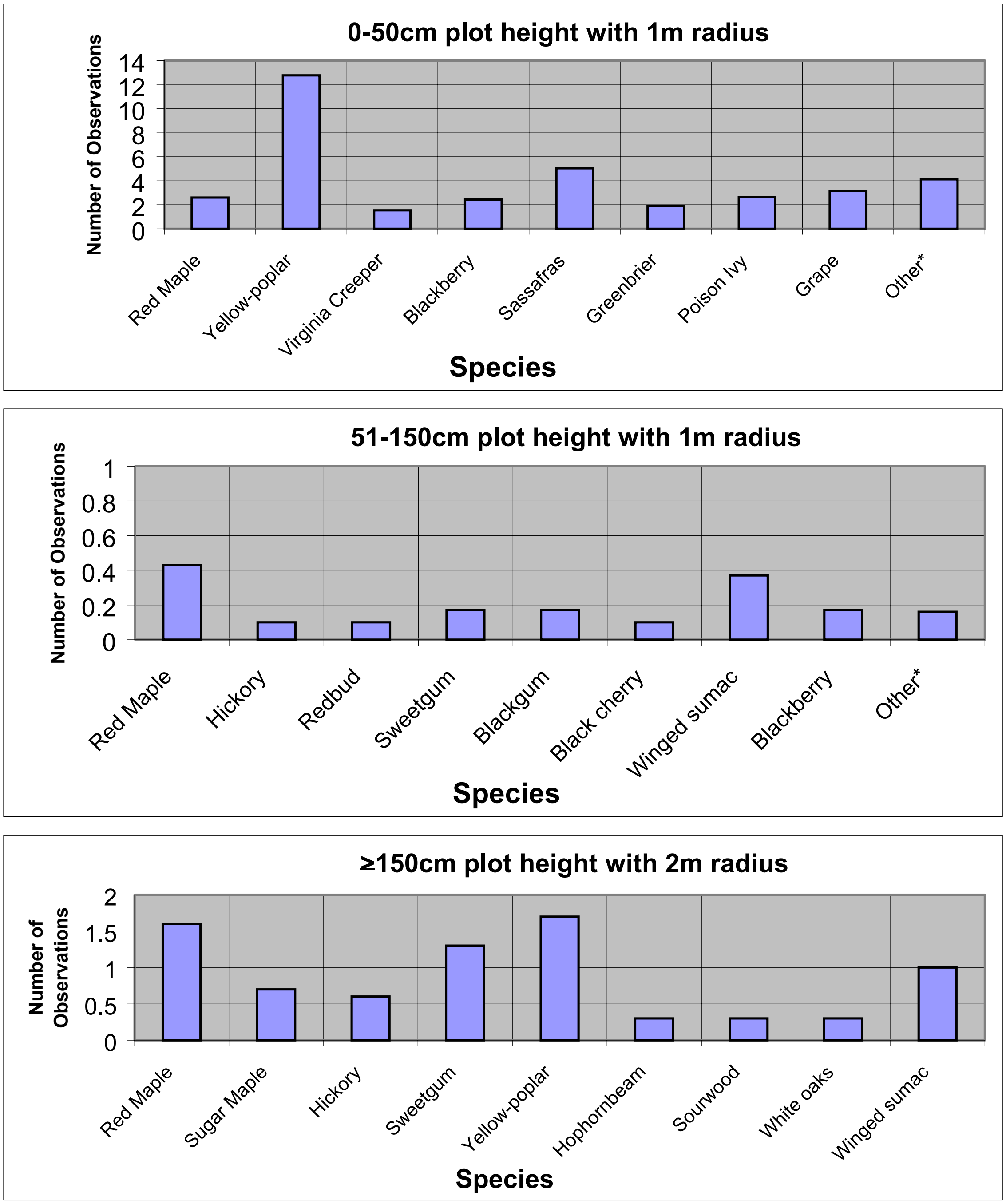

Figure 16. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the SCC treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

*NRO = northern red oak
SCC = silvicultural clearcut

Converting red maple and winged sumac values to whole numbers would result in them each occurring approximately two times within a 2.24 m radius plot in this size class. For the ≥150 cm height class in the SCC, red maple and yellow-poplar were the most abundant species, each occurring upwards of two times within a two meter plot radius of each NRO seedling. Sweetgum *(Liquidambar styraciflua* L.*)* and winged sumac were the next most abundant species, each occurring approximately once per plot.

Oak Seedling Growth

Total heights were recorded at the beginning and end of the 2003 growing season for all planted NRO seedlings. Height growth for each seedling was determined by subtracting the total height at the end of the first growing season in the field from the total height at the beginning of the first growing season in the field. Mean beginning and end of growing season total heights of all seedlings (regardless of block or treatment) were 131 and 154 cm, respectively. Mean overall growth was 23 cm. Seedling growth distribution is shown in Figure 17. Fifty seedlings had no growth (5 percent of all seedlings), 616 seedlings had between 8 and 31 cm of growth (57 percent), and thirty seedlings had 60 cm of growth or greater (<3 percent). Of the thirty seedlings that grew 60 cm or more, 17 were in the Control, five were in the 50% BAR, three were in the 25% BAR, one was in the 12.5% BAR, three were in the CCC, and one was in the SCC treatment.

Results from MMAOV showed the Control to be the only treatment that differed from all other treatments in height growth (Figure 18). NRO seedlings in the Controls

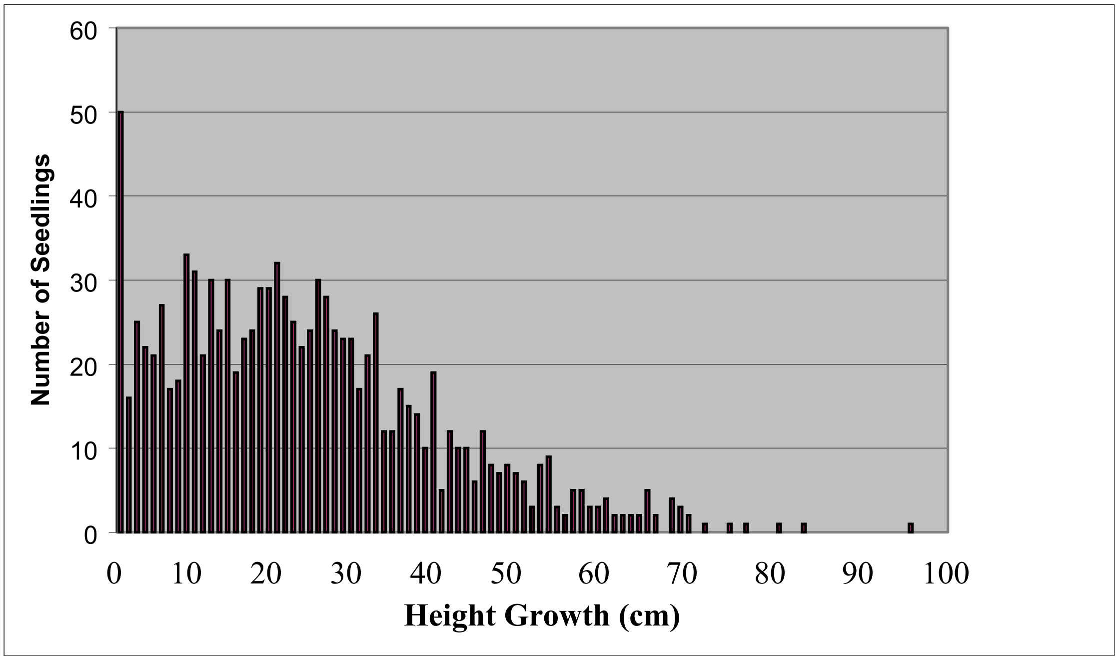

Figure 17. Height growth distribution among planted NRO seedlings for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

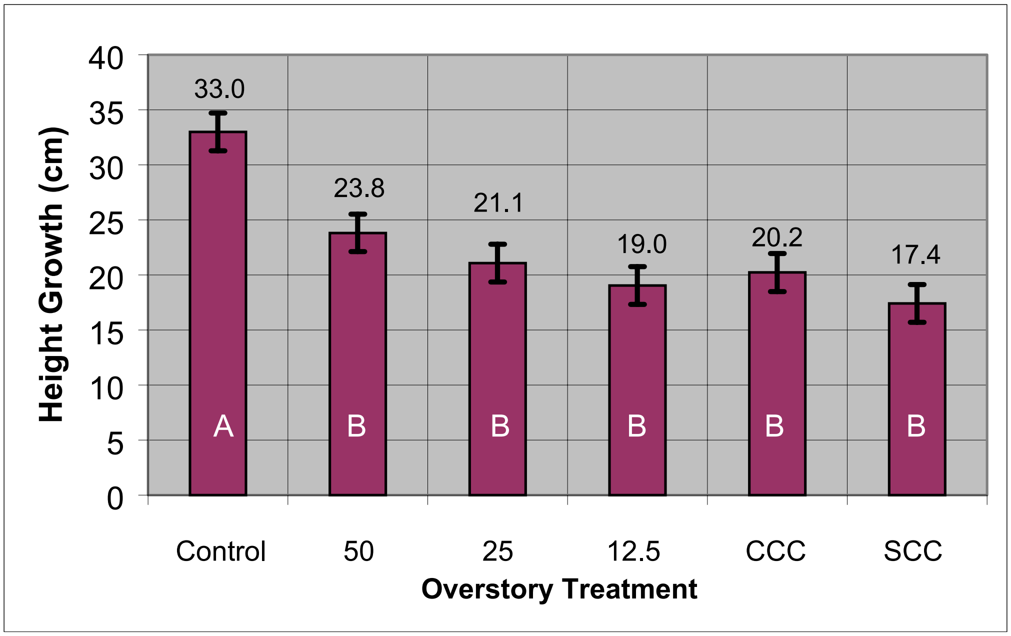

Figure 18. Estimated height growth of planted NRO seedlings by treatment for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*NRO = northern red oak

grew an estimated 33 cm, which was nine centimeters more than growth in the 50% BAR, the closest treatment in terms of height growth, and over 15 cm more than the SCC. On average, NRO seedlings in the Controls put 40 and 90 percent more height growth than the 50% BAR and SCC, respectively. No differences occurred between blocks in height growth (Figure 19).

Comparison of the effects of treatments on height growth by block reveals that blocks two and three both had growth patterns that tended to generally decrease as canopy cover decreased (Figure 20). Block one, which is north facing, shows no clear pattern of height growth in relation to canopy cover. Height growth and basal areas for each treatment by block are shown in Appendix 8.

Since the Controls had significantly greater estimated height growths than all of the other treatments, MMAOV was rerun without data from the Controls (Figure 21). This was done to see if the Control treatments were influencing height growth estimates in all other treatments that were otherwise not significantly different. Compared to Figure 18, height growth estimates among the overstory removal treatments changed no more than less than one centimeter per treatment after the Control data was removed.

Oak Seedling Survival

NRO seedling survival was defined as the percentage of seedlings that showed vital signs at the end of the first growing season in the field. MMAOV found the Control to be significantly different from every treatment except the 50% BAR (Figure 22). The 50% BAR was not significantly different from any of the treatments. All treatments

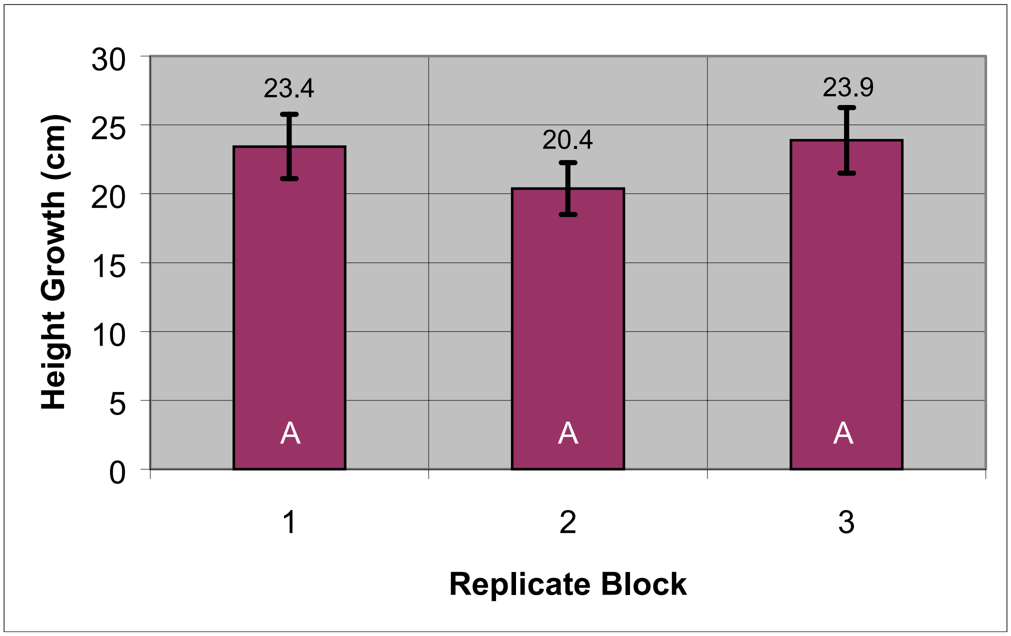

Figure 19. Mean height growth of planted NRO seedlings by replicate block for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*NRO = northern red oak

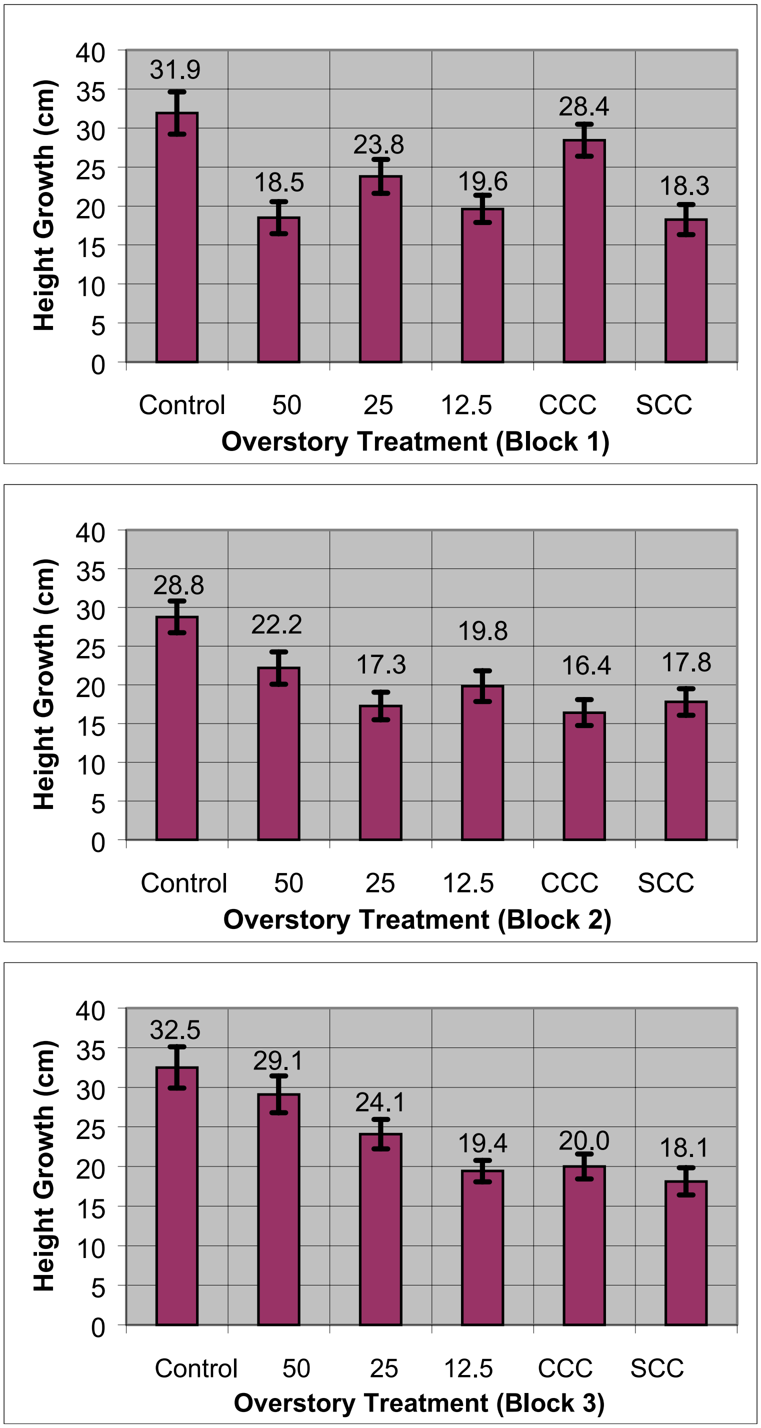

Figure 20. Mean height growth of planted NRO seedlings by overstory treatment and replicate block for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak.

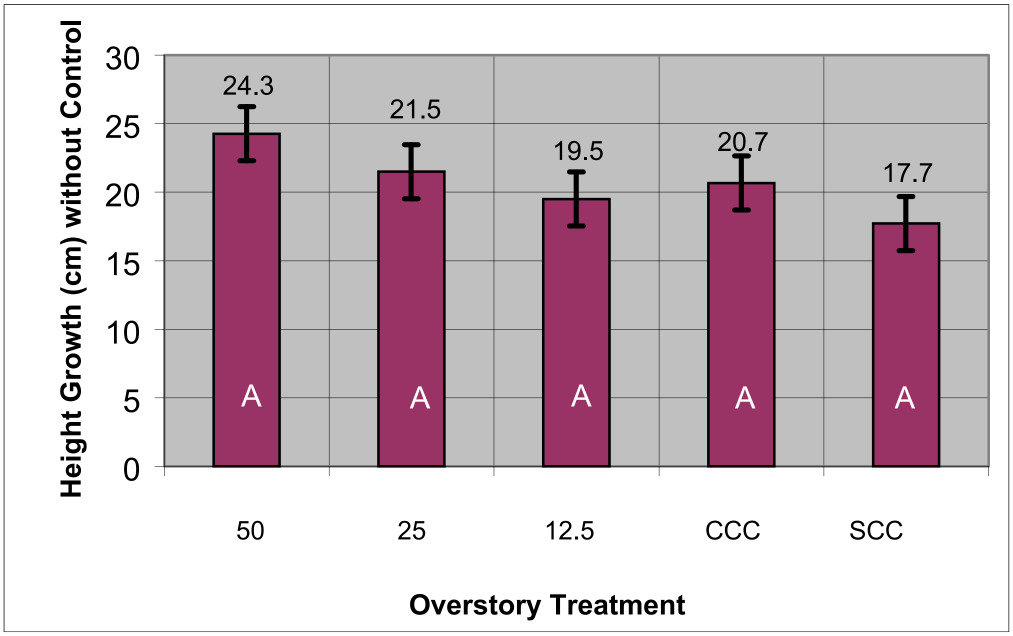

Figure 21. Estimated height growth of planted NRO seedlings by treatment (without Control) for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*NRO = northern red oak

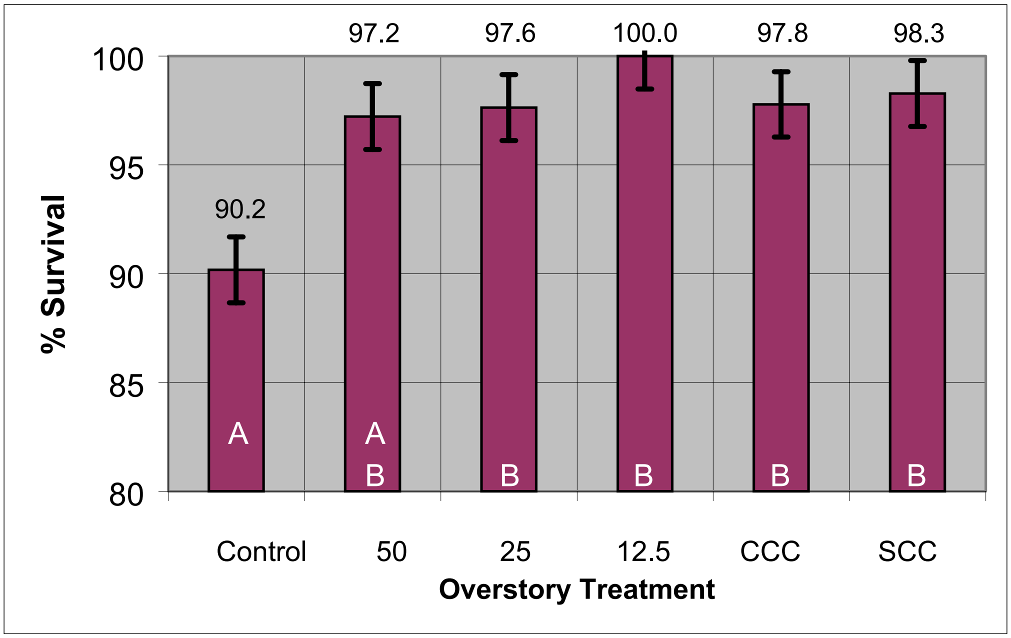

Figure 22. Estimated percent survival of planted NRO seedlings by treatment for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*NRO = northern red oak

except for the Control were not significantly different from one another. Percent survival in the Control, which had the lowest survival, was approximately 90 percent. Every other treatment had 97 percent survival or greater and the 12.5% BAR had the highest at 100 percent. Blocking had no effect on survival as all three blocks had survival rates between 96 percent and 98 percent (Figure 23). NRO seedling survival for each treatment by block is located in Appendix 9.

Genetic Family Effects on Growth and Survival

End of first growing season height growth and percent survival were analyzed and compared to pre-planting height, RCD, and number of FOLR to determine if there were any genetic family effects. Genetic families were ranked numerically based on their estimated first growing season height growth in the field using MMAOV. The family with the greatest estimated height growth from all treatments was ranked number 1 and the family with the lowest estimated height growth was ranked 18 (Figure 24). Actual genetic family codes are listed in Appendix 25. All corresponding figures with genetic families are labeled based on those from Figure 24 for easy comparisons of height growth and other measured variables. MMAOV was also used to estimate percent survival by genetic family (Figure 25). With an estimated height growth of 29.2 cm, family 1 had the greatest growth, and family 18 grew the least with 17.1 cm of height growth. Genetic families 1, 4, and 13 had 100 percent survival. Family 14 exhibited 92 percent survival, which was the lowest survival rate.

MMAOV was rerun to analyze family height growth without data from the

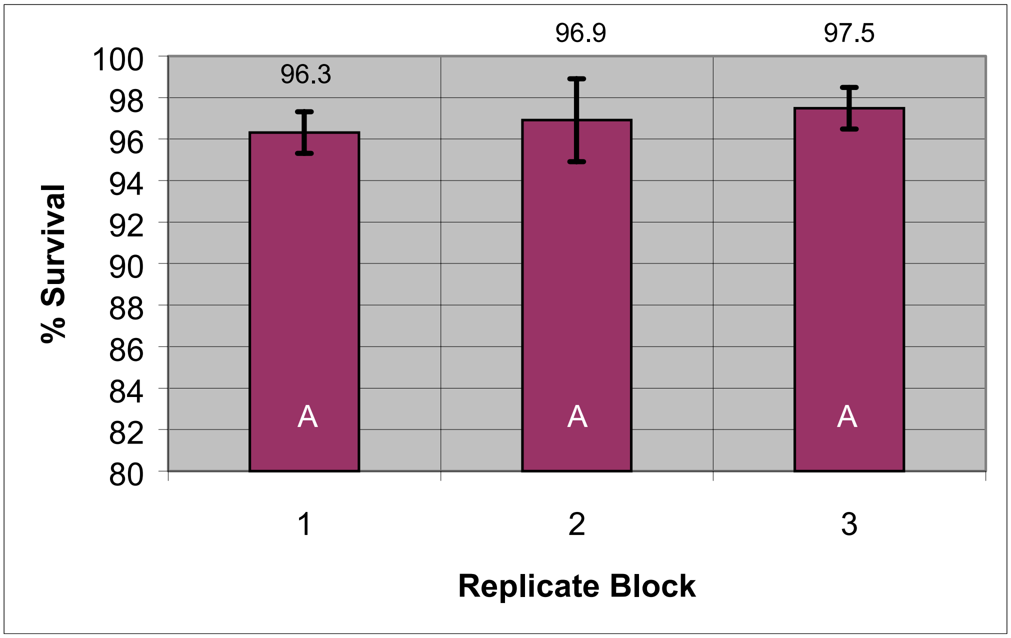

Figure 23. Percent survival of planted NRO seedlings by replicate block for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

*NRO = northern red oak

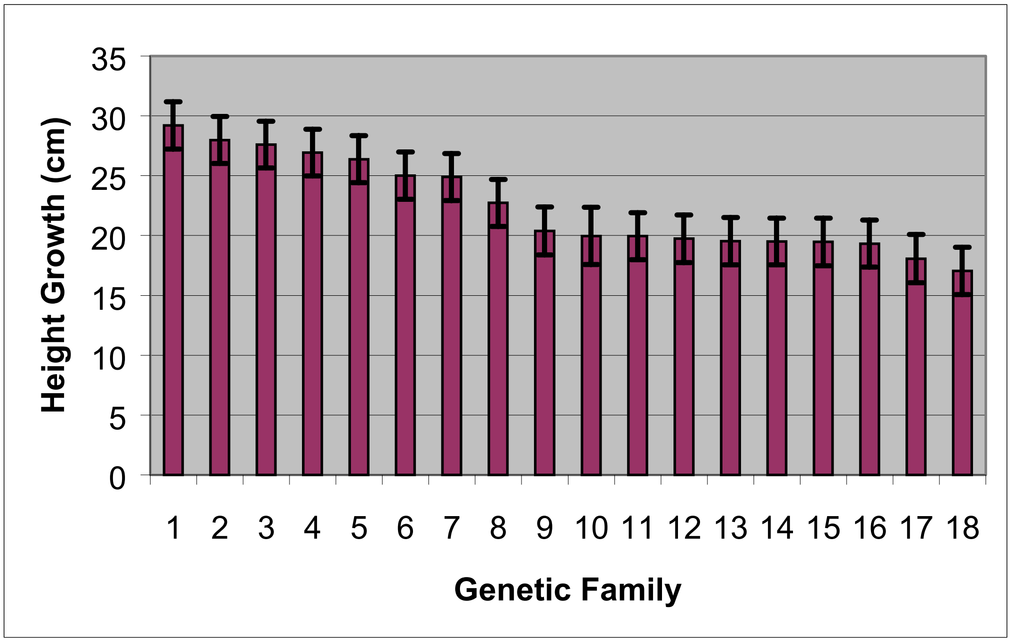

Figure 24. Estimated height growth of planted NRO seedlings by genetic family for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

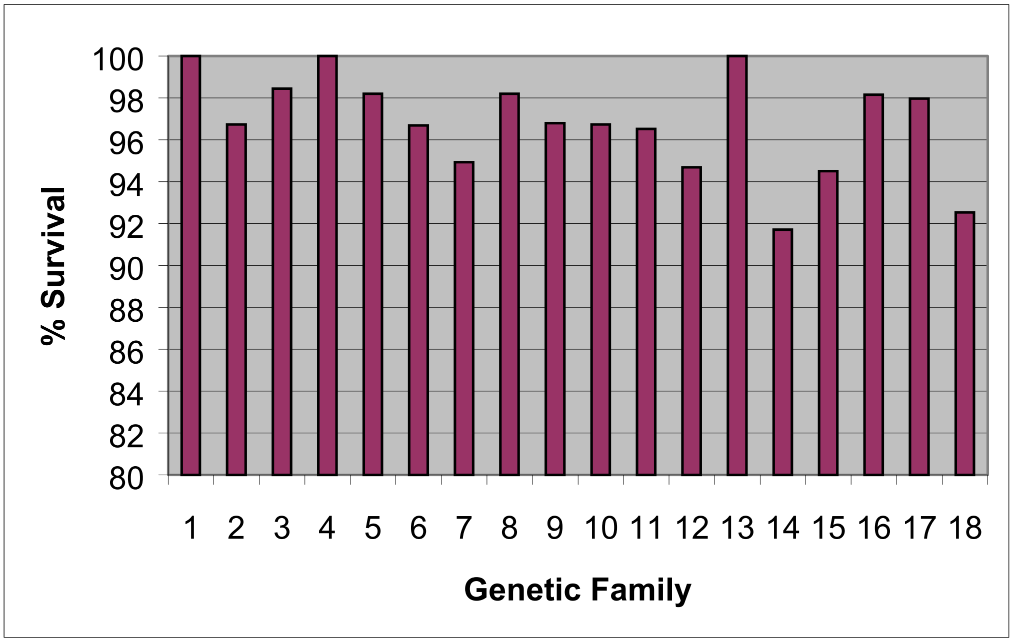

Figure 25. Estimated percent survival of planted NRO seedlings by genetic family for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

Control since it had significantly larger estimated height growths than all of the other treatments, (Figure 26). This analysis was conducted to determine if the Control treatments had influenced height growth estimates among the 18 different genetic families and if so, by how much. Compared to estimates in Figure 24, there were some new differences as genetic family 4 had the greatest estimated height growth at 26.1 cm, 0.8 cm less than originally predicted (Table 6). Genetic family 1 had an estimated height growth of 25.9 cm when MMAOV was conducted without the Control. This value was over three centimeters less than originally predicted at 29.2 cm, indicating that the Control treatments had the greatest influence on genetic family 1.

Tukey's mean separation technique was conducted using MMAOV among the different genetic families for both height growth and percent survival. Table 6 shows that more differences were detected when the Control treatments were included in the dataset. Genetic family differences with the Control treatments included in the dataset shows that genetic family 1 was significantly different from families 11 through 18 and genetic family 18 was significant different from families 1 through 5. Genetic family differences after the Control treatments were removed from the dataset suggest that all genetic families were not significantly different from one another except for genetic family 15, which differed from families 1, 2, 4, 5 and 6. No differences were detected among the different families for percent survival.

Planted heights of the NRO seedlings used in this study by genetic family are shown in Figure 27. Genetic family 7 was the tallest family planted and family 2 was the shortest. At the end of the first growing season in the field, genetic family 7 remained the tallest family at approximately 168 cm, just above family 1 (which was the fifth tallest

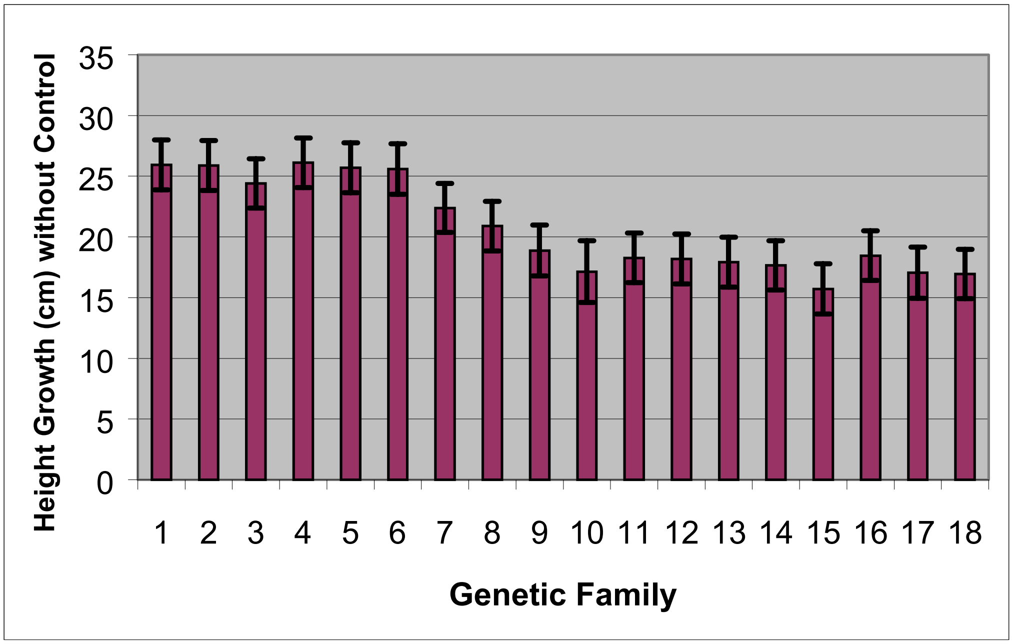

Figure 26. Estimated height growth of planted NRO seedlings by genetic family after Control treatment data was removed from dataset for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

Table 6. Growth (cm) and survival (%) estimates by genetic family and differences among families using Tukey's mean separation technique for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. Growth values were estimated with and without the Control treatments in the dataset.

Genetic Family	Growth		Growth (No Control)		% Survival	
1	29.20	A	25.93	A	100.00	A
2	27.98	AB	25.88	A	96.73	A
3	27.59	AB	24.40	AB	98.44	A
4	26.93	ABC	26.11	A	100.00	A
5	26.38	ABC	25.69	A	98.20	A
6	25.01	ABCD	25.59	A	96.69	A
7	24.89	ABCD	22.39	AB	94.93	A
8	22.73	ABCD	20.89	AB	98.20	A
9	20.38	ABCD	18.88	AB	96.80	A
10	19.97	ABCD	17.14	AB	96.74	A
11	19.95	BCD	18.27	AB	96.52	A
12	19.74	BCD	18.18	AB	94.68	A
13	19.53	BCD	17.92	AB	100.00	A
14	19.51	BCD	17.66	AB	91.71	A
15	19.47	BCD	15.72	B	94.50	A
16	19.33	BCD	18.46	AB	98.15	A
17	18.07	CD	17.05	AB	97.97	A
18	17.05	D	16.95	AB	92.53	A

(Means with the same letter in a column are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

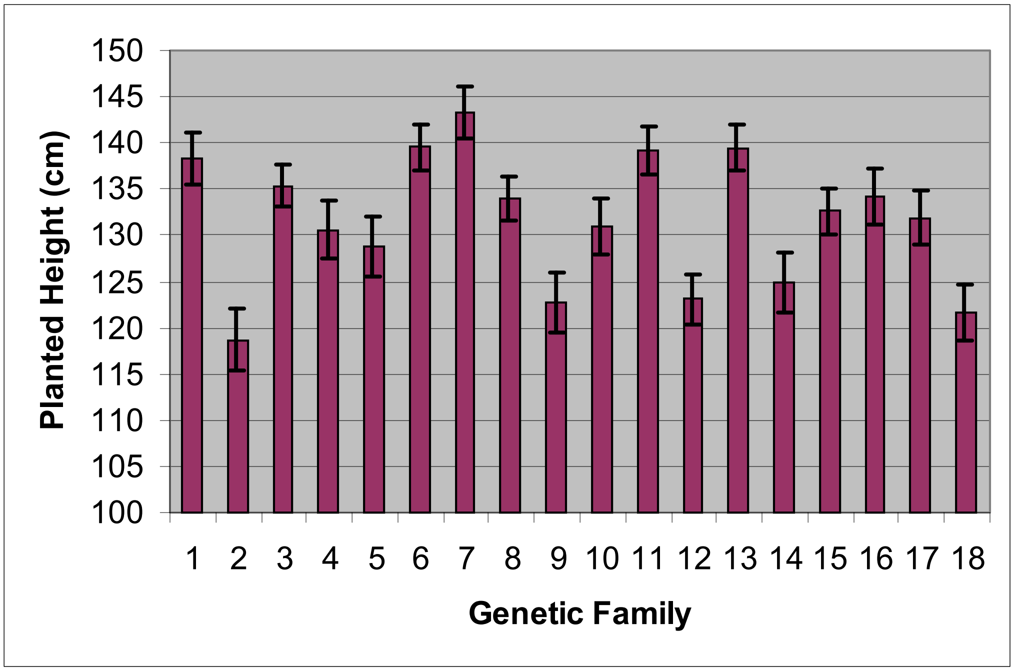

Figure 27. Planted heights of NRO seedlings by genetic family for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

family when planted) at 167 cm (Figure 28). With a mean height of 149 cm, genetic family 2 was no longer the shortest family after the first growing season. In fact, genetic family 2 surpassed four other families in total height by then end of the growing season. Genetic family 18 was the shortest family at the end of the first growing season.

The planted RCD of the NRO seedlings used in this study are shown by genetic family in Figure 29. Genetic family 7 was not only the tallest family when planted, but also the family with the largest RCD (13.5 mm). Eight genetic families had planted RCD values below 12 mm. Genetic families 3, 9, and 10 had the smallest planted RCD values of approximately 11.6 mm. The number of FOLR by genetic family are shown in Figure 30. Genetic family 17 had the highest number of FOLR when planted (approximately 20) and families 5 and 9 had the lowest (slightly more than seven).

Figure 31 shows the frequency of NRO seedlings by number of FOLR. Five seedlings had less than three FOLR (<1 percent of all seedlings), 447 seedlings had between five and nine FOLR (41 percent of all seedlings), 112 seedlings had seven FOLR (10 percent of all seedlings), and 32 seedlings had more than 22 FOLR (<3 percent of all seedlings). The average height growth of NRO seedlings used in this study by number of FOLR is shown in Figure 32. All seedlings that had between four and 21 FOLR when planted had an average height growth between 19 and 25 cm.

Predicting Oak Seedling Growth

Two separate multiple regression models will be presented that best predicted oak seedling growth. Model 1 included data from all seedlings in this study and Model 2

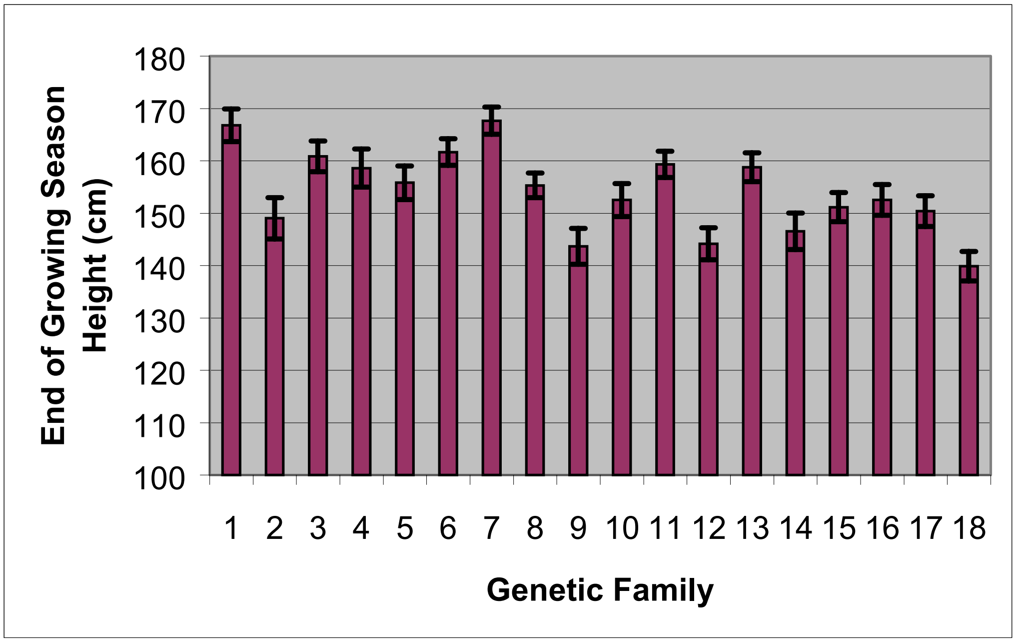

Figure 28. End of growing season heights of NRO seedlings by genetic family for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

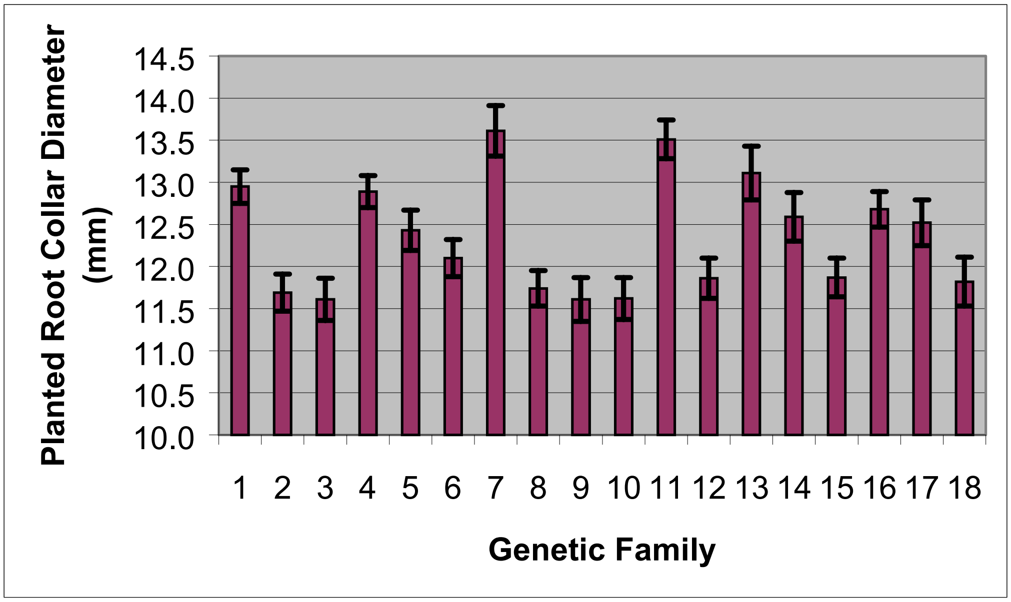

Figure 29. Planted root collar diameters of NRO seedlings by genetic family for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

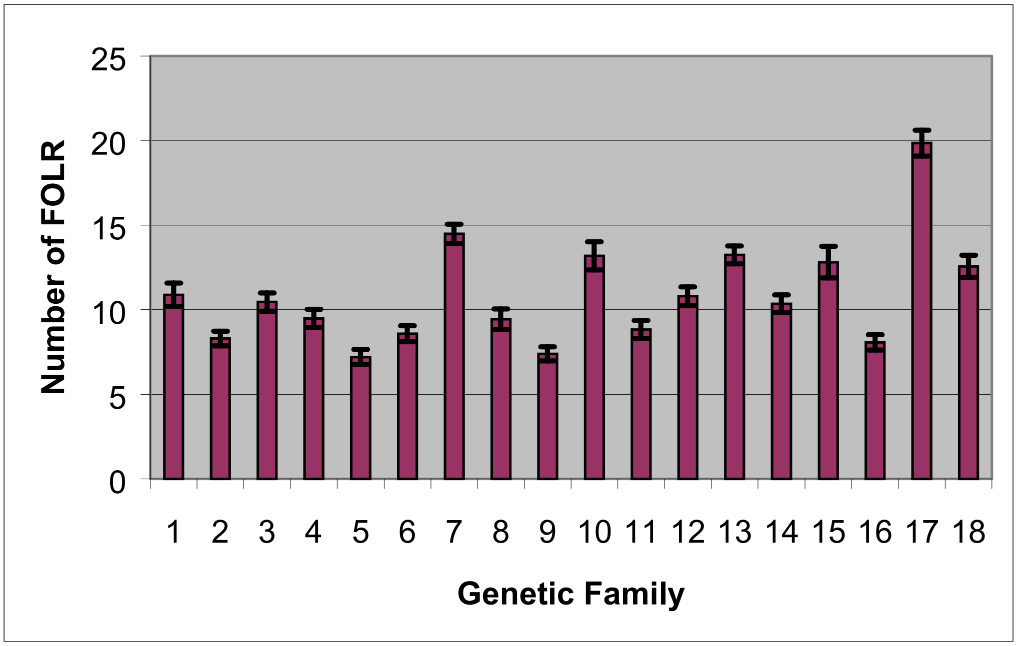

Figure 30. Mean number of FOLR by genetic family for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*FOLR = first order lateral roots

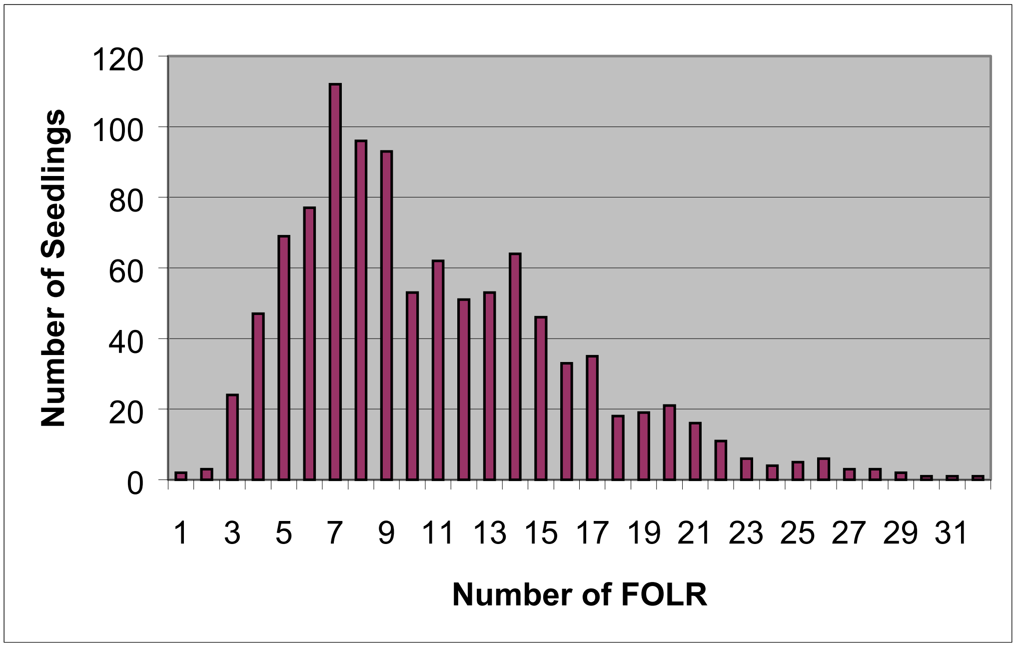

Figure 31. Frequency of NRO seedlings by number of FOLR for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak
FOLR = first order lateral roots

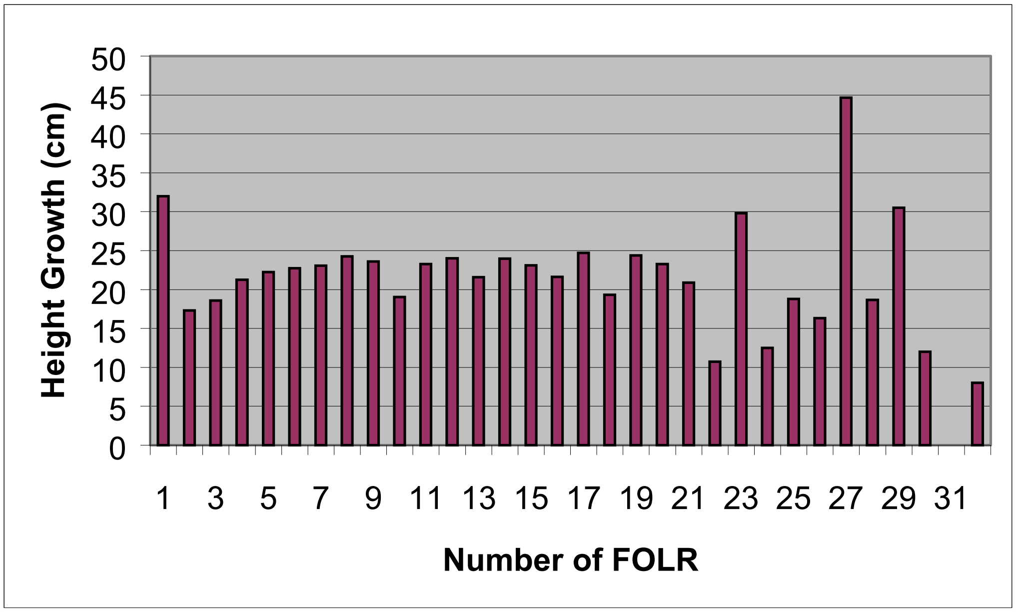

Figure 32. Mean height growth of NRO seedlings by number of FOLR for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak
FOLR = first order lateral roots

included the 180 seedlings from the second objective in this study (10 percent of all seedlings). Model 2 allowed incorporation of data on herbaceous and woody species sampled in the vicinity of 180 seedlings (10 seedlings per treatment plot). Table 7 shows the results from these two models.

Model 1 had four independent variables that were significant in predicting NRO seedling growth with an R^2 of 20.1 percent. In order of decreasing importance based on standardized estimates, they were: initial height after planting, percent full PAR, initial RCD after planting, and the mean amount of nitrate (NO_3^- N) at the plot level for each NRO seedling. Initial height, percent full PAR, and the amount of NO_3^- N all had negative slopes in this model. Actual levels of NO_3^- N in relation to height growth per treatment are shown in Figure 33. Initial RCD after planting was the only independent variable in this model with a positive slope.

Model 2 had nine independent variables that were significant in predicting NRO seedling growth with an R^2 of 36.4 percent. In order of decreasing importance based on standardized estimates, they were: initial height after planting, percent full PAR, total number of woody competitors in the 51-150 cm size class, number of redbud in the 51-150 cm size class, number of redbud in the 0-50 cm size class, initial RCD after planting, number of blackgum in the 51-150 cm size class, number of chestnut oak in the $\geq$150 cm size class, and number of redbud stump sprouts in the $\geq$150 cm size class. FOLR was also left in the model because it was marginally significant in this study at alpha = 0.07. Percent full PAR, initial height after planting, total number of woody competitors in the 51-150 cm size class, number of redbud in the 0-50 cm size class (Figure 34), and number of FOLR all had negative slopes in this model. Initial RCD after planting,

Table 7. The two models that best predict NRO seedling growth using multiple regression and the backward selection technique for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. Model 1 included all NRO seedlings planted. Model 2 included only those seedlings from which herbaceous and woody competition data was collected.

Model 1= All Seedlings			
R^2=0.2005	Parameter Estimate	P value	Standardized Estimate
Intercept	47.17786	<.0001	0
Initial Height	-0.28031	<.0001	-0.39831
% Full PAR	-0.13813	<.0001	-0.27368
Initial RCD	1.87256	<.0001	0.22986
NO_3^- N	-0.06117	0.0124	-0.07654
Model 2= 180 Seedlings			
R^2=0.3637	Parameter Estimate	P value	Standardized Estimate
Intercept	68.44397	<.0001	0
Initial Height	-0.31474	<.0001	-0.42761
% Full PAR	-0.21555	<.0001	-0.40571
Initial RCD	1.23580	0.0259	0.15740
FOLR	-0.37752	0.0731	-0.12343
Blackgum (51-150cm Size Class)	2.87628	0.0425	0.15407
Chestnut oak (≥150cm Size Class)	11.56658	0.0240	0.14817
Redbud (0-50cm Size Class)	-0.86134	0.0163	-0.16250
Redbud (51-150cm Size Class)	5.34253	0.0030	0.22784
Redbud Stump Sprouts (≥150cm Size Class)	30.71325	0.0260	0.14145
Density of all Species (50-150cm Size Class)	-1.94911	0.0020	-0.26005

*NRO = northern red oak
PAR = photosynthetically active radiation
RCD = root collar diameter
NO_3^- N = nitrate
FOLR = first order lateral roots

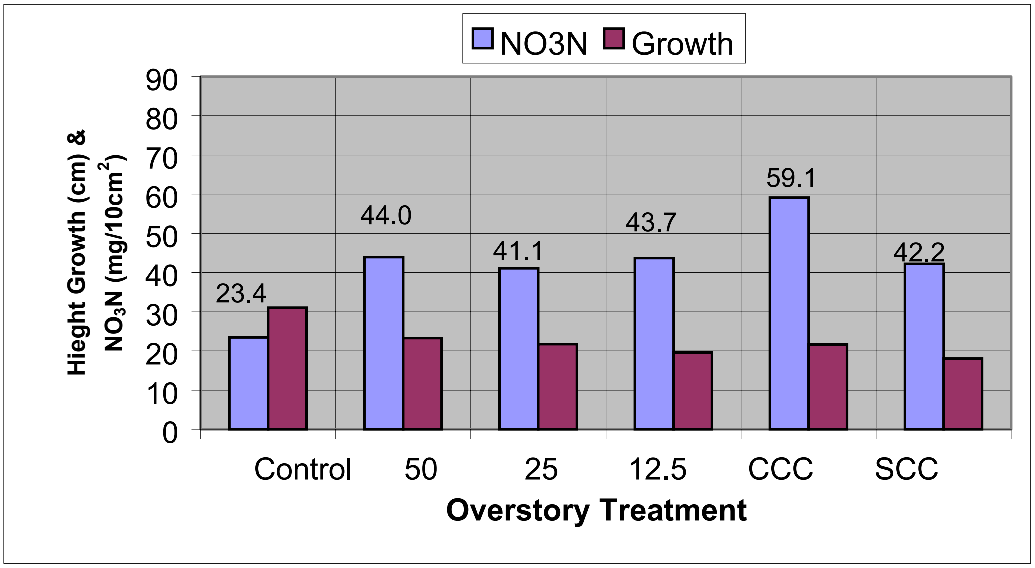

Figure 33. Level of NO_3^- N within each treatment and height growth per treatment of planted NRO seedlings for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (See Appendix 26 for NO_3^- N levels per treatment by individual blocks.)

*NRO = northern red oak
NO_3^- N = nitrate

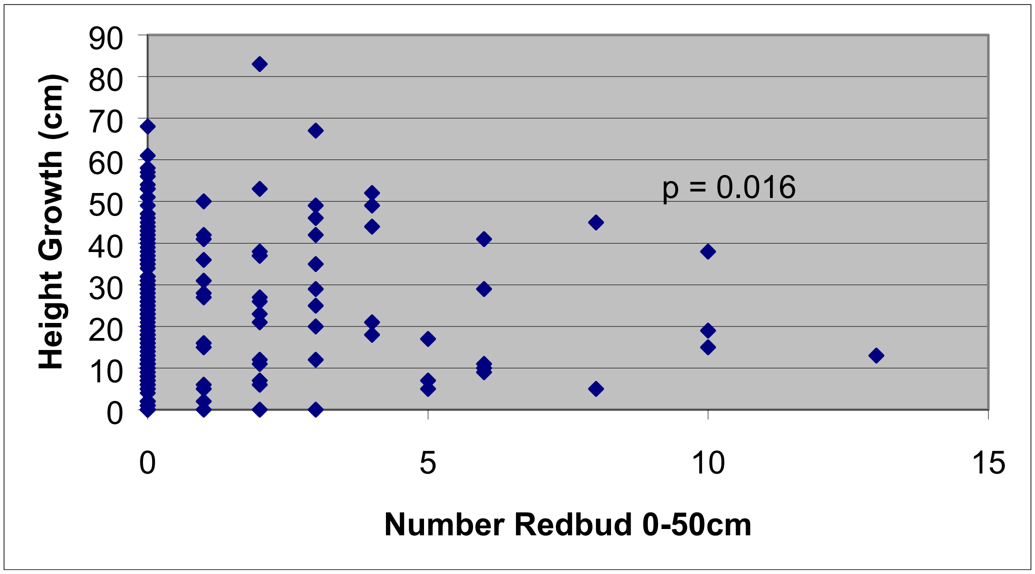

Figure 34. Relationship between height growth of 180 randomly selected NRO seedlings and the number of redbud that were 0-50 cm tall within a one meter radius of each seedling for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

number of redbud in the 51-150 cm size class (Figure 35), number of blackgum in the 51-150 cm size class (Figure 36), number of redbud stump sprouts in the $\geq$150 cm size class, and number of chestnut oak in the $\geq$150 cm size class all had positive slopes in this model. The number of redbud stump sprouts and chestnut oak in the $\geq$150 cm size class totaled only one (within the 50% BAR) and six, respectively (five were in the Control, and one was in the SCC).

Correlations among independent variables used in Models 1 and 2 as well as height growth were compared (Table 8). Height growth and PAR (at the treatment plot level) was the only correlation that was highly correlated. PAR and NO_3^- N, blackgum (51-150 cm) and all species (51-150 cm), and redbud (51-150 cm) and all species (51-150 cm) were moderately correlated. Height growth and PAR (at the seedling level), growth and percent full PAR, treatment and NO_3^- N, initial height after planting and initial RCD after planting, and number of FOLR and initial RCD after planting were all weak to moderately correlated.

Due to the high correlation between growth and PAR at the treatment level, simple linear regression was conducted on these two variables at the treatment level (Figure 37). Over 67 percent of the variation in mean height growth within each treatment can be explained by the mean percent full PAR received by that treatment (R^2=0.672).

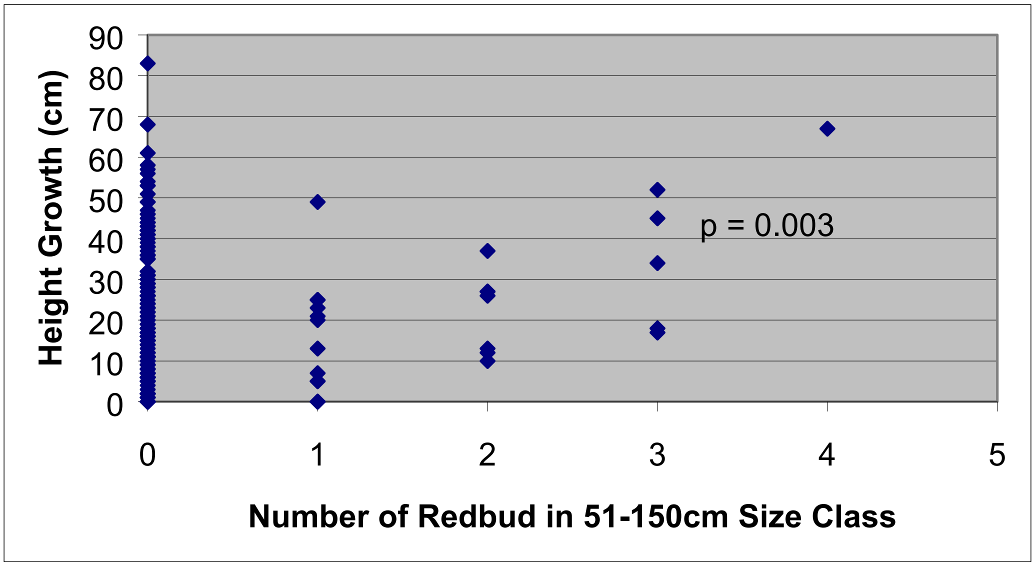

Figure 35. Relationship between height growth of 180 randomly selected NRO seedlings and the number of redbud that were 51-150 cm tall within a one meter radius of each seedling for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

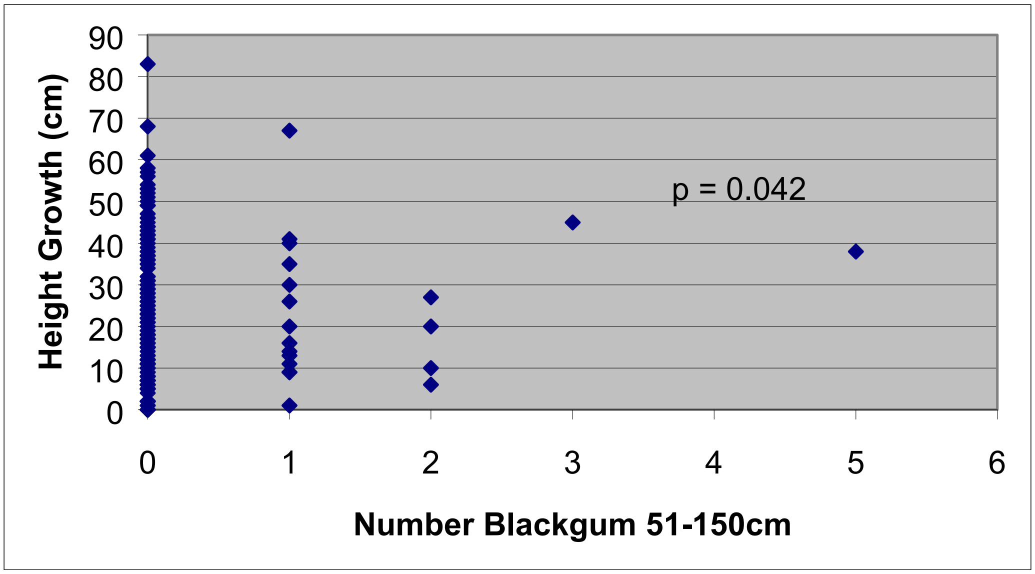

Figure 36. Relationship between height growth of 180 randomly selected NRO seedlings and the number of blackgum that were 51-150 cm tall within a one meter radius of each seedling for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*NRO = northern red oak

Table 8. Correlation of independent variables used in Models 1 and 2 for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. Only those variables that had correlations greater than 0.3 or less than -0.3 are presented.

Variables	Correlation	P value
Height Growth x PAR (seedling level)	-0.36	<.0001
Height Growth x PAR (treatment plot level)	-0.82	<.0001
Initial Height x Initial RCD	0.35	<.0001
PAR x NO_3^- N	0.41	<.0001
FOLR x Initial RCD	0.31	<.0001
Blackgum (51-150 cm) x All species (51-150 cm)	0.47	<.0001
Redbud (51-150 cm) x All species (51-150 cm)	0.44	<.0001

*NRO = northern red oak
PAR = photosynthetically active radiation
RCD = root collar diameter
NO_3^- N = nitrate
FOLR = first order lateral roots

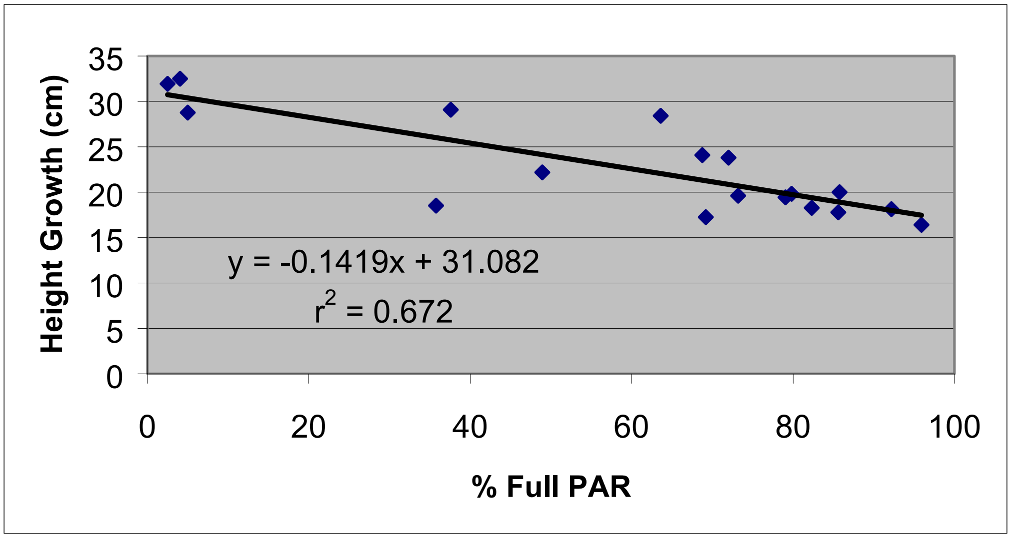

Figure 37. Mean height growth compared to mean percent full PAR received by all 18 treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

*PAR = photosynthetically active radiation

V. Discussion

Effect of PAR on Oak Seedling Growth

Significant differences in percent full PAR existed primarily between overstory treatments with greater canopy cover (i.e., Control, 50% BAR, and 25% BAR, Figure 5). The percentages of PAR received by treatments containing little or no canopy cover (i.e., 12.5% BAR, CCC, and SCC) did not differ as much as those with greater canopy cover due to the existence of few or no overstory trees. Basal area measurements taken within each treatment support this conclusion and show that treatments with little or no basal area had PAR levels that were relatively similar (Figure 6).

Analysis of block effects on percent full PAR revealed that block one was significantly different from blocks two and three (Figure 9). Block one is north facing, and thus receives less sunlight than block two, which is on the ridge top, and block three, which is south facing. Although adjacent landforms can also influence daily incoming radiation, these results suggest that north facing slopes can receive approximately nine and six percent less full sunlight than ridge tops and south facing slopes, respectively, in the Tennessee Ridge and Valley. Although percent slope measurements were not taken in this study, slope variations of Fullerton soils (which occur in three variants within this study site) range from 5-45 percent (Olson 2003). The north facing slopes in block one seemed to be generally steeper than the south facing slopes of block three.

PAR measurements, which were taken three times per day during each month, suggested no differences in the percent full PAR received within these three different time periods (Figure 11). In fact, none of the percent full PAR levels within the three time periods differed from the mean of the three time periods by more than one percent. Percent full PAR should not be affected by the time of day to the same extent as actual PAR values in *u*mol m^{-2} s^{-1}. Raw PAR data measurements indicate that noon had much higher *u*mol m^{-2} s^{-1} values than morning or afternoon (Appendix 27). Raw PAR values also show the Control treatment in block one was often below 30 m^{-2} s^{-1}, which Hanson (1986) suggested NRO needs in order to maintain a positive carbon balance. This indicates that NRO seedlings within the Control treatment in block one might sustain higher mortality rates than all other treatments in the near future.

This study did not focus on *u*mol m^{-2} s^{-1} values as much as percent full PAR levels because actual *u*mol m^{-2} s^{-1} values could vary greatly depending on whether there was cloud cover on the days PAR measurements were taken. Measurements were taken on mostly cloudless days to avoid this, but there were a few days that PAR measurements were taken when clouds were present. Percent full PAR levels appeared to be consistent between cloudless days and the few days that were cloudy, indicating that percent full PAR measurements eliminate the variability due to changes in cloud cover.

Treatments with greater canopy cover appeared to have less variation between months. As stated earlier, the Controls varied by no more than one percent between any of the months while the 12.5% BAR, CCC, and SCC treatments varied up to ten, eight, and seven percent respectively, between their highest and lowest months (Table 4). The 50% BAR and 25% BAR varied by five percent and six percent respectively, between their highest and lowest months. This is most likely due to the consistent level of shade provided by greater basal areas. Stands with little or no basal area, such as the 12.5% BAR, CCC, and SCC were affected more by the position of the sun across the four different months measurements were taken. Fireweed and horseweed also became noticeably taller than most NRO seedlings in these three different treatments by July and August. These two species likely lowered percent full PAR received by NRO seedlings in these three treatments, many of which were receiving percent full PAR levels of 100 percent in May and June.

The negative relationship between percent full PAR levels and NRO seedling height growth within each treatment was counterintuitive. Height growth tended to decrease as potential PAR increased within each treatment. The greatest height growth of seedlings in the Control treatments was likely the result of etiolation. Although more elongated than seedlings in other treatments, many of these seedlings had a paler and flimsier appearance with weaker stems and smaller leaves as described by Kimmins (1987) and Taiz and Zaiger (1991).

NRO seedlings in all other treatments, particularly the 50% BAR and 25% BAR, tended to have much healthier appearances. They appeared to have larger leaves and greater stem diameters than those within the Control treatments. Further evidence for the poor condition of seedlings in the Controls is their higher mortality rates. Although first-year mortality was less than 10 percent within the Controls, many of these seedlings will probably continue to die within the next few years. Previous research on this site has demonstrated only 52, 55, and 72 percent survival using premium and good NRO seedlings within the Control treatments of blocks one, two, and three, respectively, after one year in the field (Olson 2003). The same developmental response leading to etiolation in the Controls could be occurring in the BAR treatments (that is currently not physically visible), but to a lesser degree than in the Control treatments.

Results for all treatments suggested that height growth generally decreased as percent full PAR levels increased (Figure 37). Greater levels of percent full PAR could have been associated with greater exposure to heat and wind in treatments with little or no canopy cover, leading to reduced height growth. During field measurements, it was noticed that some of the planted NRO seedlings were exposed to the sun all day and appeared to be under great stress, particularly those in the SCC, CCC, and 12.5% BAR. Some of these seedlings exhibited leaves that were small, somewhat brownish in color, and even wilted. NRO seedlings on the south facing slopes and ridge top were more exposed to the sun than those on the north facing slopes. The decrease in height growth with decreased canopy was much more consistent in blocks two and three than in the more shaded north facing slopes of block one (Figure 20).

Block one showed no pattern of height growth in relation to canopy cover, possibly because it received more shade from standing timber and the adjacent ridges than the blocks on the south facing slope and ridge top. An alternative explanation for increased height growth on the north facing slopes and at lower levels of PAR could be that seedlings were responding similarly, but not to the same extent, as seedlings in the Controls to reduced levels of light. Etiolation is accompanied by large increases in shoot to root ratio, and seedlings in the heavier shelterwoods and on the north slope could have redirected additional resources to shoot growth (Kimmins 1987). Destructive sampling to determine shoot to root ratios in all treatments and blocks would be required to test this alternative explanation.

Effect of Soil Moisture on Oak Seedling Growth

Percent soil moisture levels were not significant at alpha = 0.05 for predicting height growth for the planted NRO seedlings. Nor were any differences detected between treatments using Tukey's mean separation technique (Figure 8). However, mean percent soil moisture was the lowest in the Control treatments. The high basal area and dense overstory canopy in the Controls may transpire and intercept a great deal of moisture, reducing overall soil moisture. Basal area retention may only be effective in promoting soil moisture retention on south facing slopes. As indicated in Appendix 2, the SCC had percent soil moisture levels that were somewhat similar to the 50% BAR treatments in both blocks one and two, which are north facing and on the ridge top, respectively.

Precipitation levels in east Tennessee in the spring and summer of 2003 were greater than normal, possibly making the detection of significant differences in percent soil moisture levels between different treatments more difficult (Table 3). With greater amounts of rain, the forest floor did not to dry out enough so that percent soil moisture levels between treatments could potentially have been detected.

Effect of Macronutrients on Oak Seedling Growth

Macronutrient supplies within the different treatments did not explain results in first year oak seedling height growth as hoped. There could have been variation between soil types on much smaller scales than at the plot level, which was the scale at which nutrients were measured. NO_3^-N was the only macronutrient that proved to be significant in explaining NRO seedling growth within this study (Table 7). NO_3^- N levels tended to slightly increase as canopy cover decreased (Figure 33). This is consistent with other studies in which increased rates of soil nitrogen mineralization in forest ecosystems accompany canopy removal (Kim 1994). However, the negative relationship between amounts of NO_3^- N and height growth was surprising. Higher levels of NO_3^- N tended to result in less height growth. Although too much NO_3^- N could lead to toxic accumulation levels, these results contrast with the popular belief that nitrogen mineralization is one of the more important factors limiting tree growth (Kramer and Kozlowski 1979, Kimmins 1987, Taiz and Zaiger 1991, Kim 1994). Other factors such as PAR and competition for other resources may have had stronger effects on oak seedling growth than NO_3^- N levels.

Effect of Herbaceous Competitors on Oak Seedling Growth

Fireweed and horseweed together made up 54 percent and 38 percent of the total herbaceous cover overtopping the NRO seedlings, respectively. None of the herbaceous species that overtopped the NRO seedlings proved to be significant in predicting seedling height growth. However, fireweed and horseweed were very abundant in treatments with little or no canopy cover. These two species, as well as pokeweed and wild lettuce began to overtop the planted NRO seedlings in July and August. The effect of these species on PAR received by planted seedlings is reflected in the decrease in percent full PAR received within these treatments over the course of the summer (Table 4). Although density was not recorded for these species, they appeared to occur at high stem densities within treatments receiving high levels of sunlight, indicating that they were not only heavily competing for available resources such as light, but probably soil moisture and soil nutrients as well. The actual effect of these herbaceous species on seedling growth in treatments with low levels of canopy cover is difficult to distinguish from other factors such as exposure, but herbaceous vegetation could contribute to reduced height growth in treatments with low levels of canopy cover.

Effect of Woody Competitors on Oak Seedling Growth

Although yellow-poplar and red maple were not significant in predicting NRO seedling height growth, they were two of the most abundant species on the study site (Appendices 23-24). These two species will probably play a more important role in the success or failure of the planted NRO seedlings in the future. Many yellow-poplar seedlings were not serious competitors due to their small size during the growing season of 2003. They dominated (by density) all of the treatments except for the Controls in the 0-50 cm size class, yet were almost non-existent in the 51-150 cm size class in every treatment. Their existence in the ≥150 cm size class was mainly based on whether they were harvested or retained during harvesting operations in the summer of 2002. However, both seedlings and stump sprouts in the ≥150 cm size class within the SCC occurred frequently, most likely due to the higher levels of percent full PAR received within this treatment (Appendices 21-22).

Red maple's consistent existence in every treatment and every size class is a good example of its adaptability to a wide variety of conditions. Its presence tended to increase with an increase in size class and it was most dominant (by density) in the ≥150 cm size class within the CCC and SCC treatments, mainly from stumps sprouts (Appendices 11-24). If red maple has an effect on the planted NRO seedlings in the future, it will probably be most noticeable in these two treatments.

Redbud, sassafras, and blackgum were also somewhat abundant potential competitors. Redbud occurred mainly in treatments with greater canopy cover for the 0-50 cm size class. It was the most dominant species in the 51-150 cm size class overall, being most abundant in the 50% BAR treatment. Redbud in the ≥150 cm size class was virtually non-existent in the Control, CCC, and SCC treatments, yet occurred frequently within the 50% BAR, 25% BAR, and 12.5% BAR treatments, and was the most dominant species within the 50% BAR and 12.5% BAR (Appendices 11-24). According to the regression model, the number of both redbud stump sprouts ≥150 cm tall and redbud seedlings in the 51-150 cm size class had positive relationships with planted NRO seedling height growth, while redbud seedlings in the 0-50 cm size class had a negative relationship with oak seedling height growth (Table 7).

Redbud stump sprouts and redbud in the 51-150 cm size class primarily occurred within the shelterwood treatments. Their positive relationship with planted NRO seedling growth could possibly be explained by the fact that redbud was not particularly competitive in the clearcut treatments where yellow-poplar and red maple tended to be more dominant. They were more prevalent in treatments with canopy cover, suggesting that they thrive under similar conditions as planted NRO seedlings at a young age, which also tended to grow taller with increased canopy cover. It cannot be ruled out that redbud promotes NRO growth, but it is also possible that it prefers to grow under conditions where less competition might exist. Similar to the “stress tolerant” growth strategy of

NRO, redbud is also tolerant of nutrient deficiencies (Grime 1979, Burns and Honkala 1990).

Sassafras occurred frequently throughout all treatments within the 0-50 cm size class, somewhat frequently in the 51-150 cm size class, and was virtually non-existent in the ≥150 cm size class. Although it was not significant in explaining NRO seedling height growth, it was a somewhat abundant pioneer species within the study site and natural seedling regeneration could possibly become more competitive in the future.

Blackgum rarely occurred within the 0-50 cm size class. It was somewhat frequent in the 51-150 cm size class and was most dominant (by density) in the 25% BAR and CCC treatments. Blackgum ≥150 cm showed no pattern of dominance (by density) in any particular treatment. It did not occur within the 12.5% BAR or SCC in this size class, but was found to be moderately abundant in all other treatments (Appendices 11-24). Blackgum in the 51-150 cm size class also had a positive relationship with NRO seedling height growth in the regression model (Table 7). This relationship is more difficult to interpret compared to redbud due to the unclear pattern of blackgum within different treatments. Blackgum seedlings in this size class appeared to grow best in moderate to full sunlight, having the most dominance within the 25% BAR, which was the third best treatment for NRO seedling height growth. It can only be speculated that blackgum is utilizing the opportunity to grow where understory competition has yet to establish from the harvest operation in the summer of 2002.

The relationship of redbud and blackgum to NRO seedling height growth appears to be somewhat similar, particularly in the 51-150 cm size class. They both tended to occur under conditions that promoted NRO seedling growth. The effect of yellow-poplar and red maple may be very different in the near future. These two species will be competing for the majority of the study site receiving high levels of PAR (>70 percent).

Optimum Site Conditions for Oak Seedling Success

Based on the results of this study, certain conditions appeared to be more favorable for NRO seedling height growth and survival. Seedlings in the 50% BAR and 25 % BAR had the second and third highest height growth rates among treatments respectively, without the signs of etiolation as in the Controls. However, this could be a milder form of the developmental response leading to etiolation that is currently not physically noticeable. PAR levels for the 50% BAR and 25% BAR averaged 41 percent and 70 percent, respectively. This suggests that PAR levels somewhere between 41 percent and 70 percent could be ideal conditions for NRO seedlings to grow under.

Factors such as soil moisture and macronutrient levels were inconclusive, possibly due to higher seasonal precipitation levels than normal during the time field measurements were taken. Competition effects indicated that redbud and blackgum could potentially be good site indicators of where growth of planted NRO seedlings would be maximized, which tended to be in the shelterwood treatments.

Effect of Treatment on Oak Seedling Survival

NRO survival rates in all cutting treatments were 97 percent or better, and the Controls had over 90 percent survival (Figure 22). The 12.5% BAR treatment had 100 percent survival across all three blocks. Three different genetic families had 100 percent survival, and the lowest among all families was 91 percent (Figure 25). These results are likely due to the greater than normal precipitation levels during the growing season of 2003 and the early stage of development of competitors that could compete with the planted NRO seedlings.

Genetic Family Effects on Growth and Survival

All 18 genetic families appeared to be doing well following their first growing season in the field with height growths above 17 cm and survival rates above 91 percent for every family. Precipitation levels that were greater than normal during this year may have played an important role in these first year results. Although differences were detected between genetic families in height growth, more time is needed to assess whether these differences will lead to long term seedling success. It is believed that large artificially regenerated NRO seedlings can effectively overcome severe competition following a clearcut, but they may need release by age seven from faster growing stumps sprouts such as yellow-poplar (Kormanik et al. 1997). With time, competition within the study site will become more severe and the true competitiveness of the planted NRO seedlings will be revealed.

Results indicated that initial seedling height after planting was negatively related to first year height growth, while initial RCD was positively related (Table 7). However, total seedling height may be more important than first year height growth as taller NRO seedlings will be above more potentially competing vegetation than shorter seedlings. RCD showed a weak to moderately positive correlation with FOLR (0.31), leading to the assumption that the thicker the RCD is for a seedling, the more FOLR it will have (Table 8). Seedlings with the greatest number of FOLR are believed to be the most competitive in the nursery and in the field (Kormanik and Muse 1986). A higher number of FOLR would give the seedlings an increased absorptive surface area for accessing soil water and nutrients (Kormanik et al. 1995).

FOLR results in this study showed that as FOLR decreased, height growth slightly increased. This negative relationship contradicts some past research (Ruehle and Kormanik 1986). However, damage from lifting the seedlings and pruning their FOLR could have resulted in first year transplanting shock. As discussed with NO_3^- N, other factors such as percent full PAR and competition could also have had stronger effects on oak seedling growth, thus masking the effects of FOLR. As the NRO seedlings become more established, FOLR might play a greater role in their success or failure.

VI. Conclusions

Percent full PAR, initial seedling height after planting, and initial RCD after planting were the most significant variables in explaining NRO seedling height growth for the first growing season in the field. The 50% BAR and 25% BAR had the healthiest looking seedlings, with those in dense shade being etiolated, and those in heavy sunlight suffering from exposure (i.e., small browning leaves and wilting) more so than in other treatments.

Percent soil moisture and macronutrient levels were not important in explaining NRO seedling growth in this study. Although NO_3^- N appeared to be significant in predicting height growth, it had a negative relationship with height growth. This could have occurred because of the high variation in soil microsites that appeared to exist within treatments, or because other variables had a stronger effect on oak growth. Percent soil moisture, which was also non-significant in explaining seedling growth in this study, may have been more significant if the precipitation levels for the spring and summer of 2003 were not abnormally high. Soils did not to dry out enough so that percent soil moisture levels between treatments could potentially have been detected.

Redbud and blackgum 51-150 cm tall were significant in explaining NRO seedling height growth, both having a positive relationship with height growth. Number of FOLR was marginally significant, but also showed a negative relationship to NRO seedling height growth. Thus, the effects of more important variables such as PAR, initial height after planting, and initial RCD after planting, may have masked its effects. Damage from lifting and pruning may also have resulted in transplanting shock.

Differences were detected in height growth among genetic families, but more time will be needed to see if these differences remain the same.

Seedling survival was greater than 90 percent within all treatments and for all genetic families in this study. The 12.5% BAR had 100 percent survival within all three blocks and three different genetic families had 100 percent survival. No differences were detected among families for survival, but survival within the Controls was significantly different from all cut treatments except for the 50% BAR. The Controls may suffer greater losses within the next few years due to etiolation of seedlings and heavy shade within this treatment, particularly in block one (north facing), which often received less than 30 *u*mol m^{-2} s^{-1}. All seedlings appeared to be doing well in the cutting treatments, but more time is needed to assess whether they continue to thrive or not.

Determining whether artificial regeneration of NRO seedlings can be used and recommended as a successful alternative to natural regeneration will take time. Seedling performance needs to be monitored for several years. The seedlings in this study will face increasing competition over the next few years and only then can conclusions be made about their true competitive nature. The seedlings used in this study grew under close to optimal conditions during their first year in the field. They had above average rainfall and few well-established competitors after harvesting in the preceding year. The success of these seedlings in their first growing season is a good sign, but long term monitoring of their performance is warranted.

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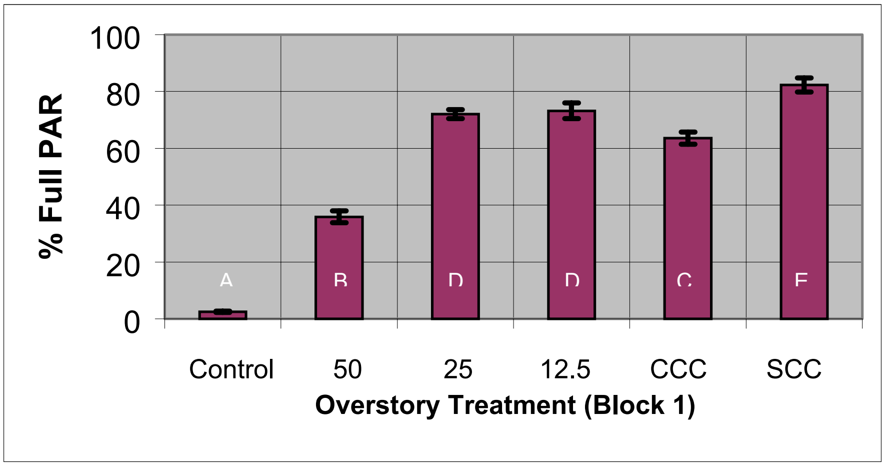
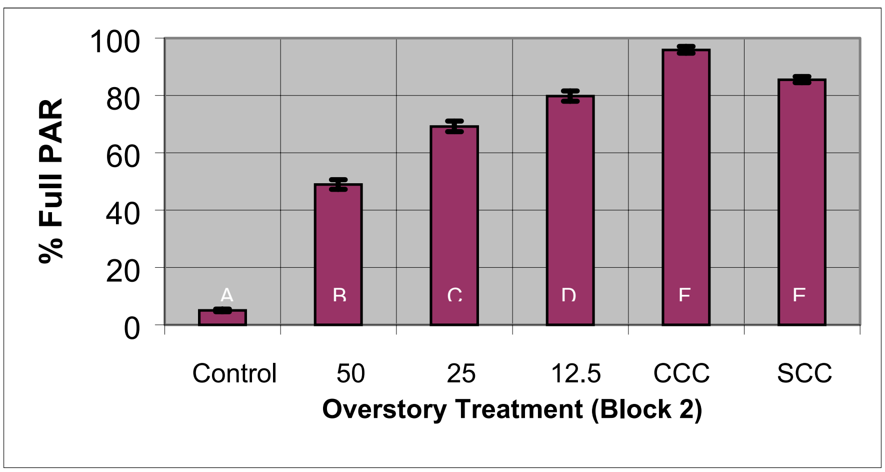
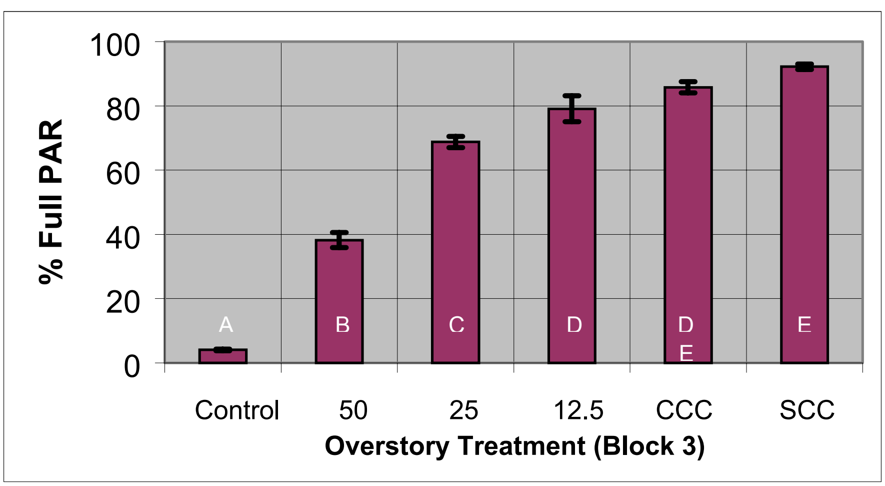
Appendices

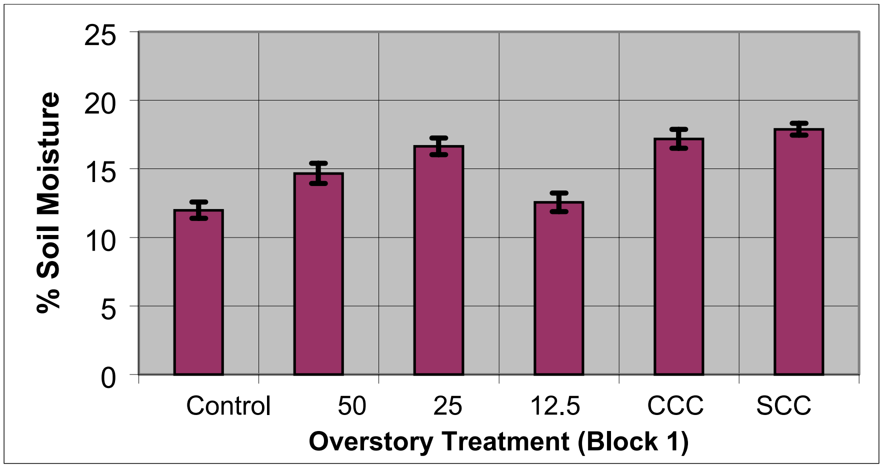
Appendix 1. Percent full PAR received by planted NRO seedlings by replicate block within all six overstory treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

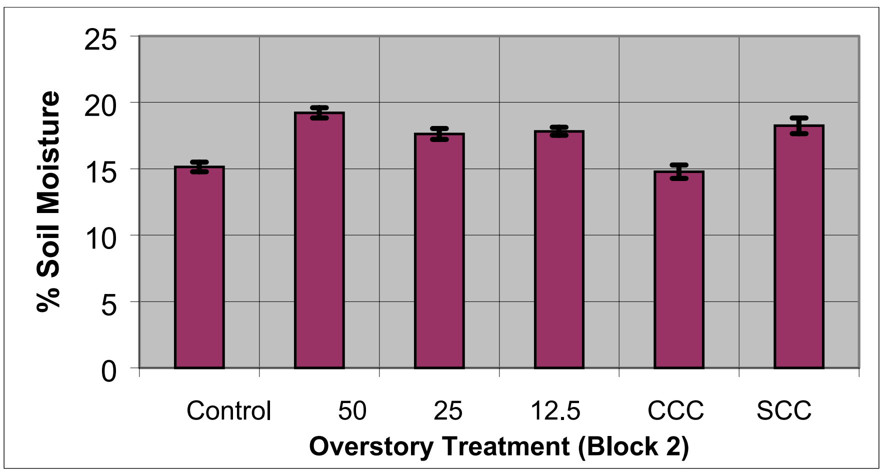


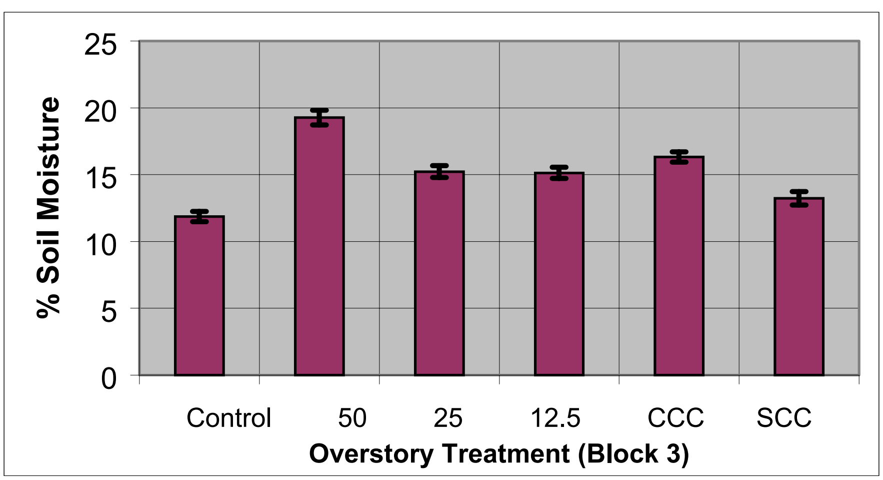




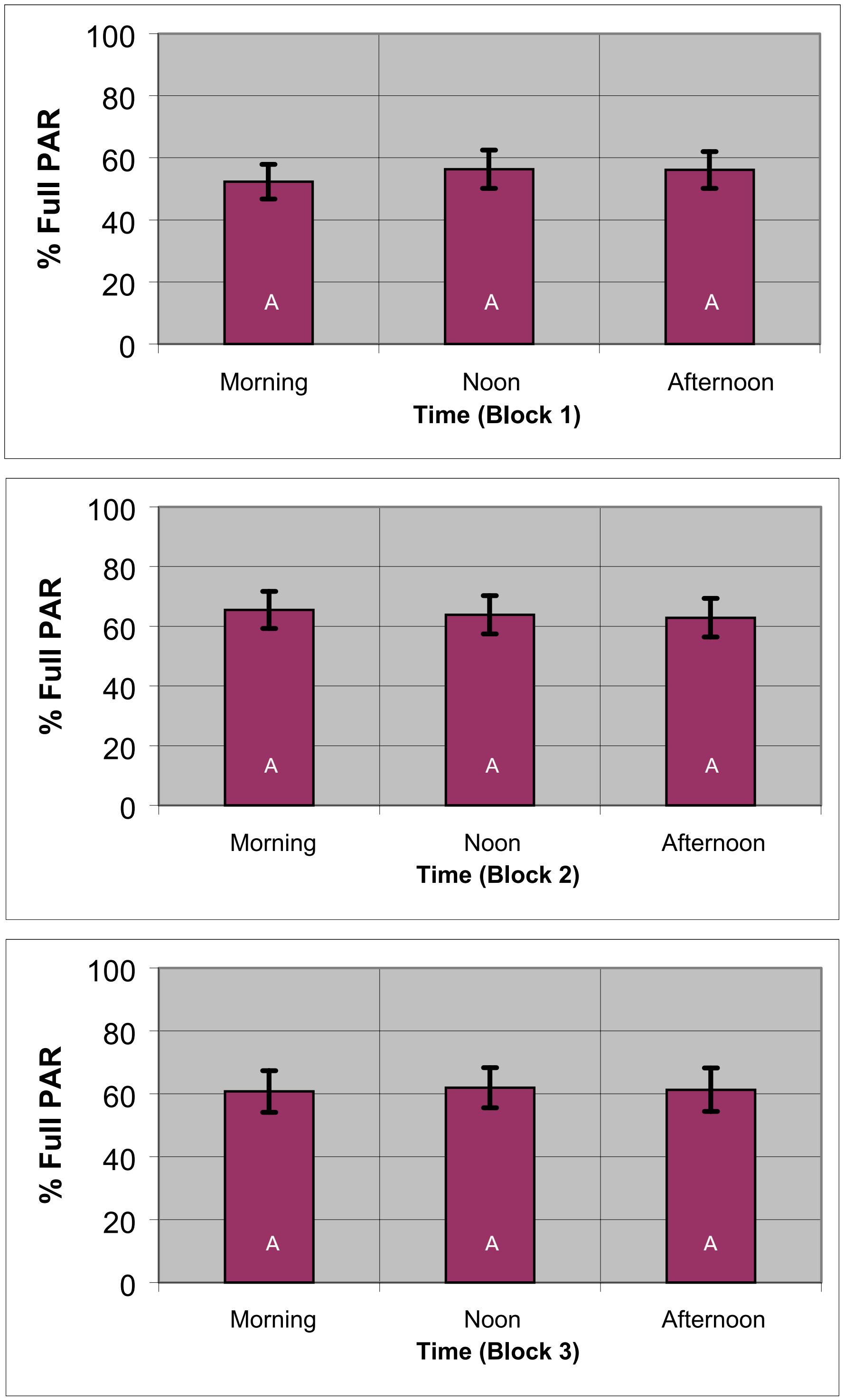
Appendix 2. Percent soil moisture received by planted NRO seedlings by replicate block within all six overstory treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.



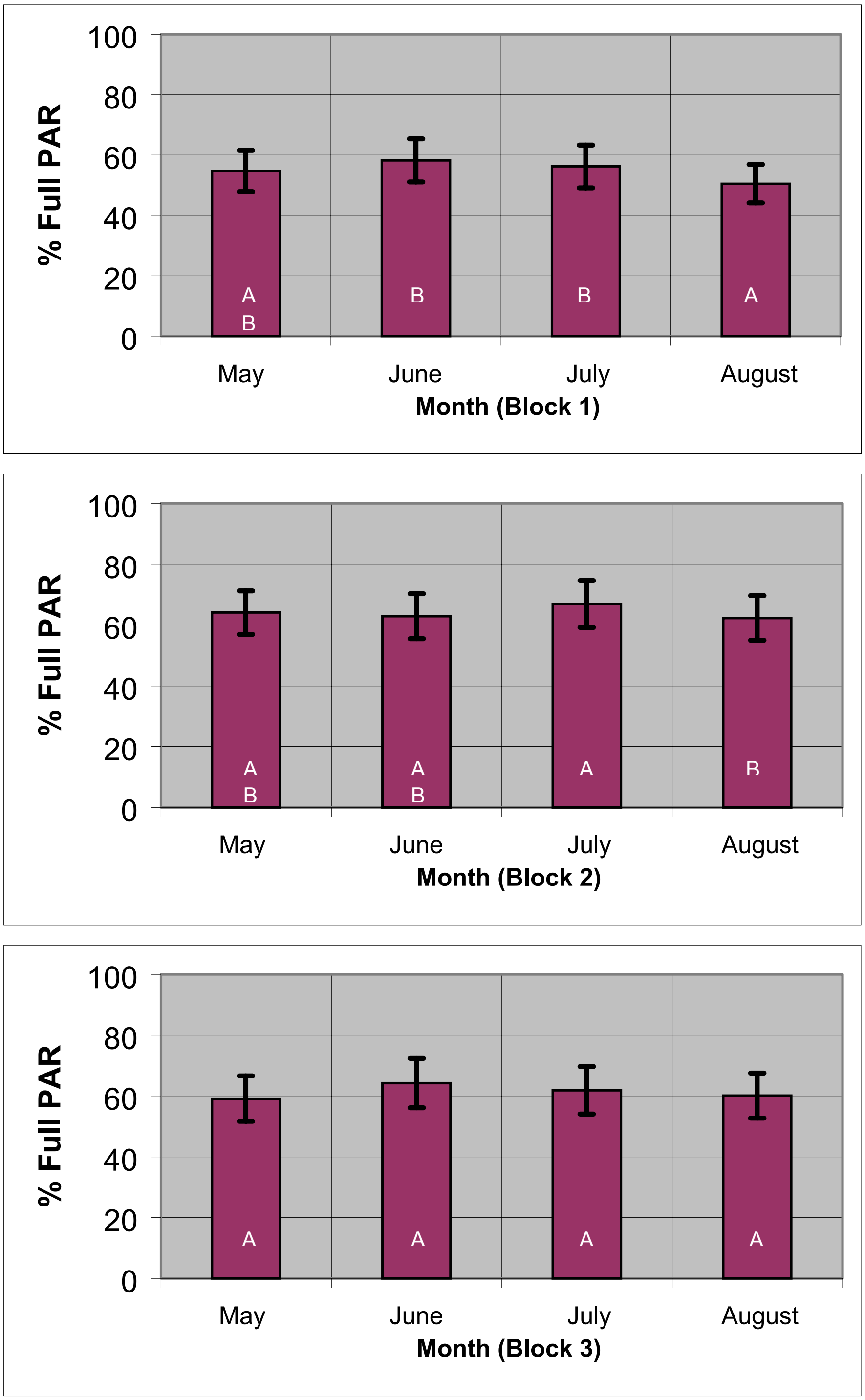




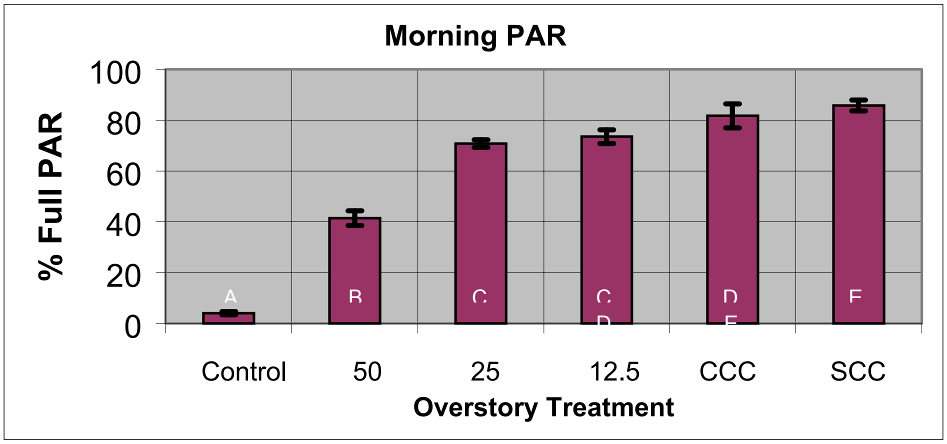
Appendix 3. Percent full PAR received by planted NRO seedlings by replicate block within all three time periods for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

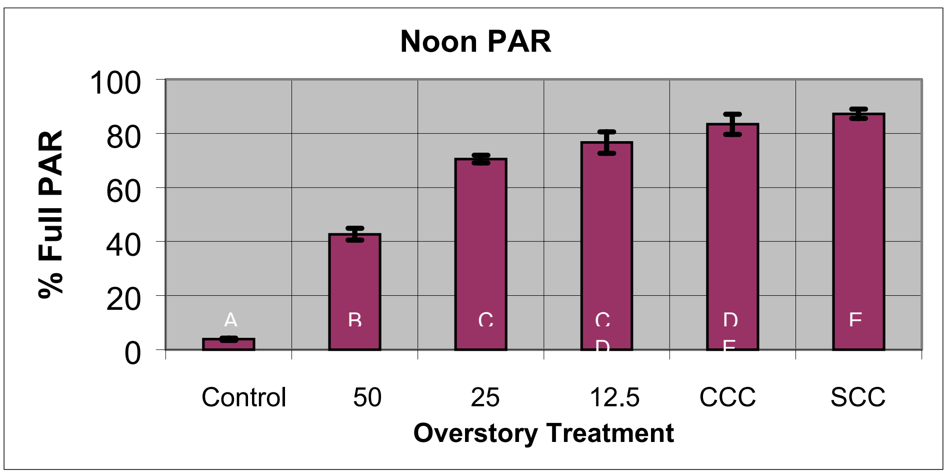


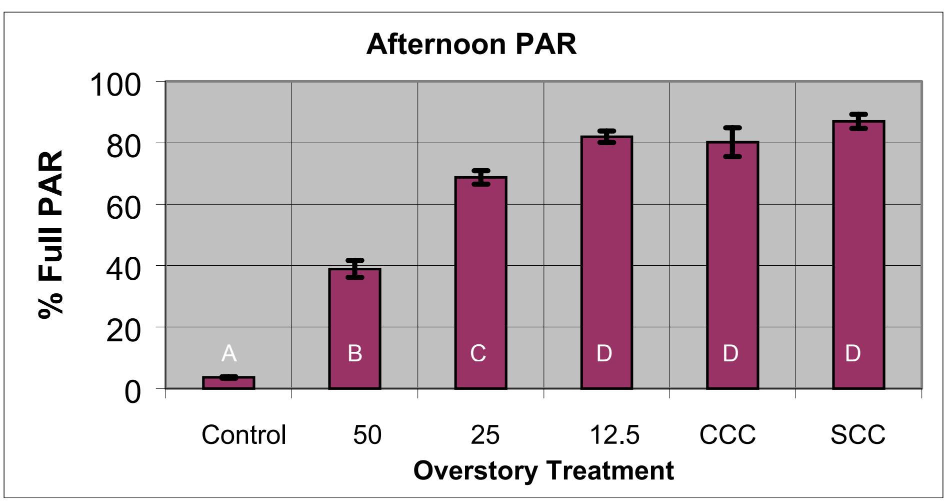
Appendix 4. Percent full PAR received by planted NRO seedlings during all four months by replicate block for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)



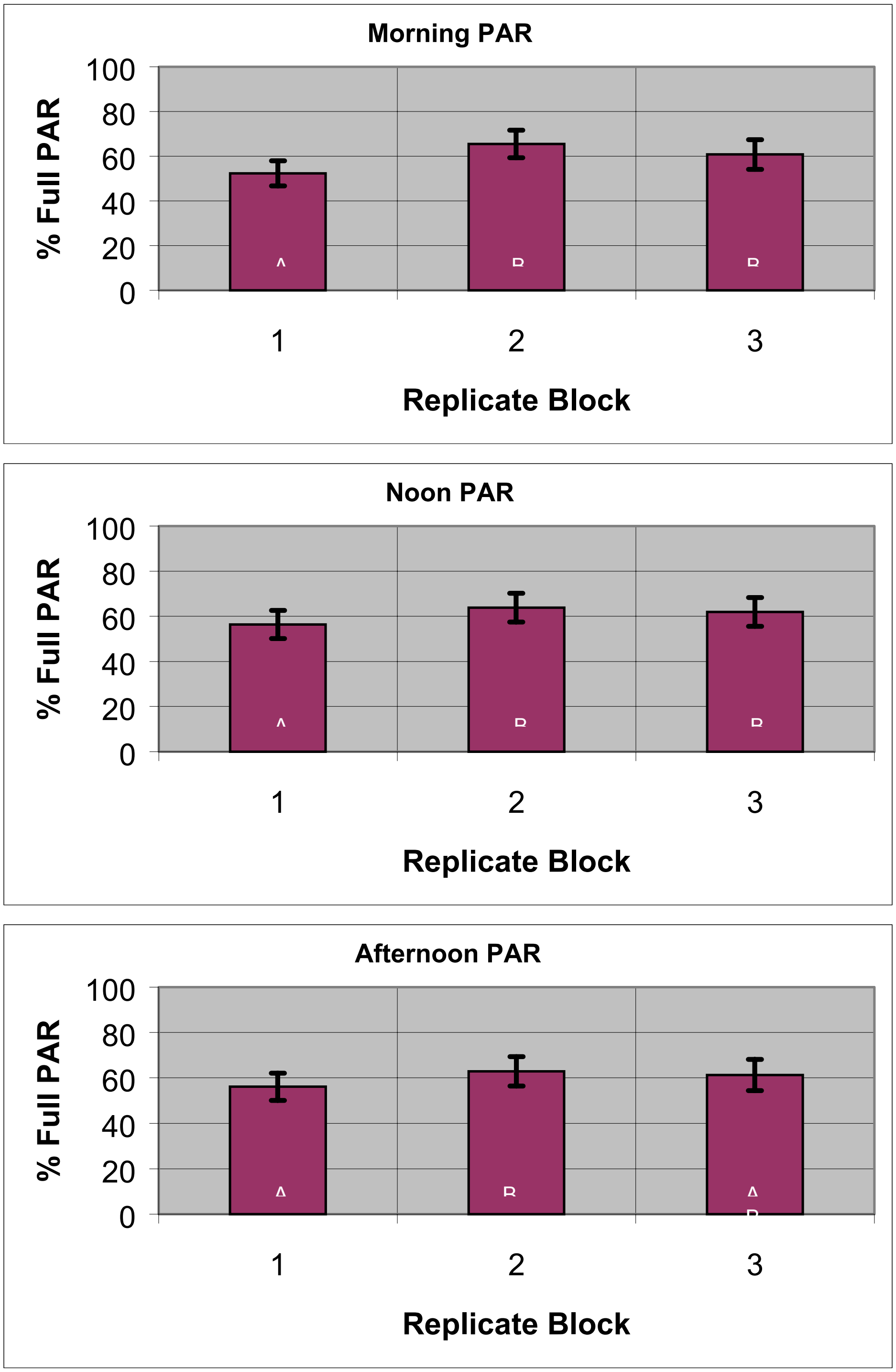
Appendix 5. Percent full PAR received by planted NRO seedlings within all six overstory treatments by time period for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)



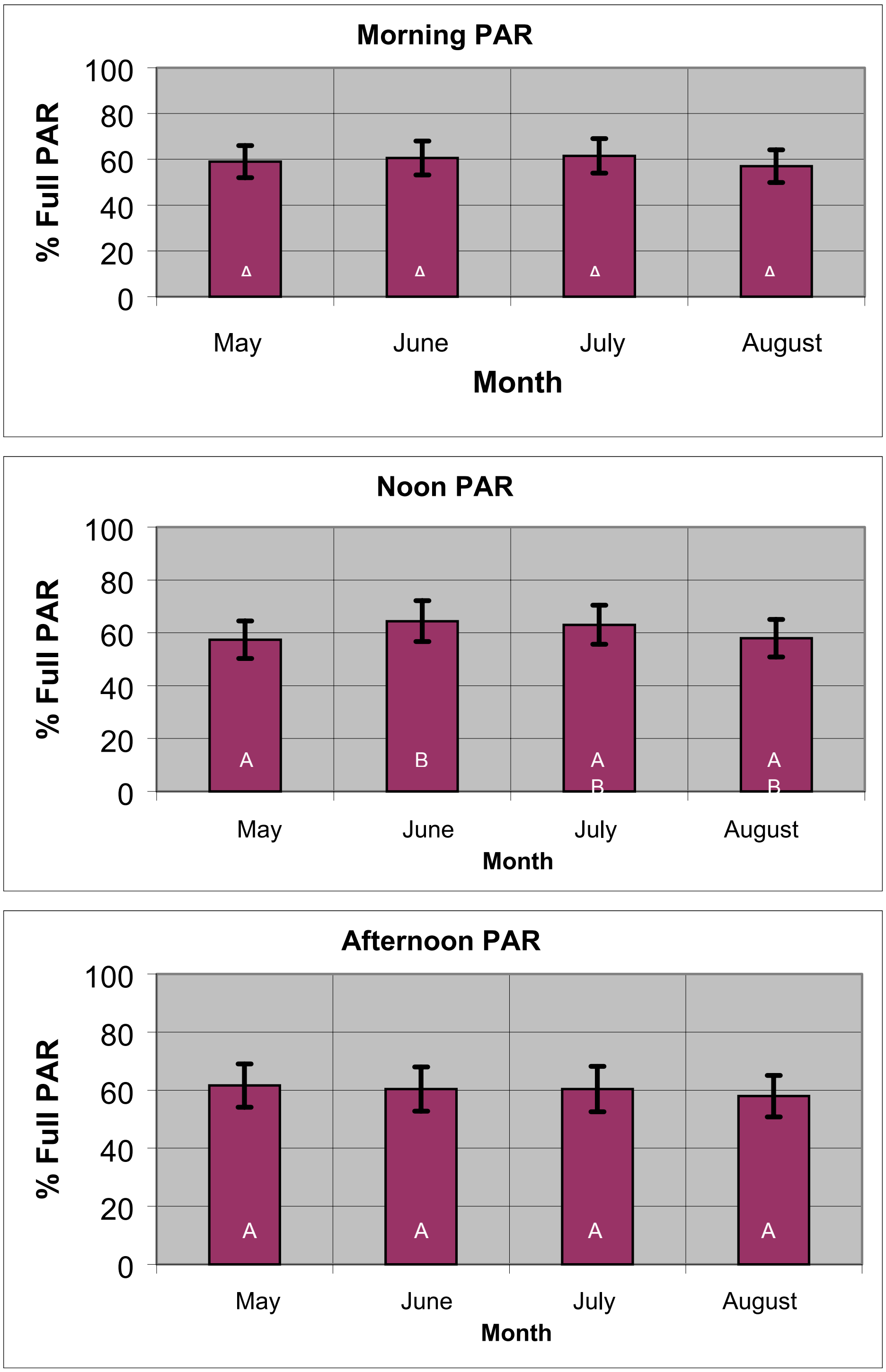




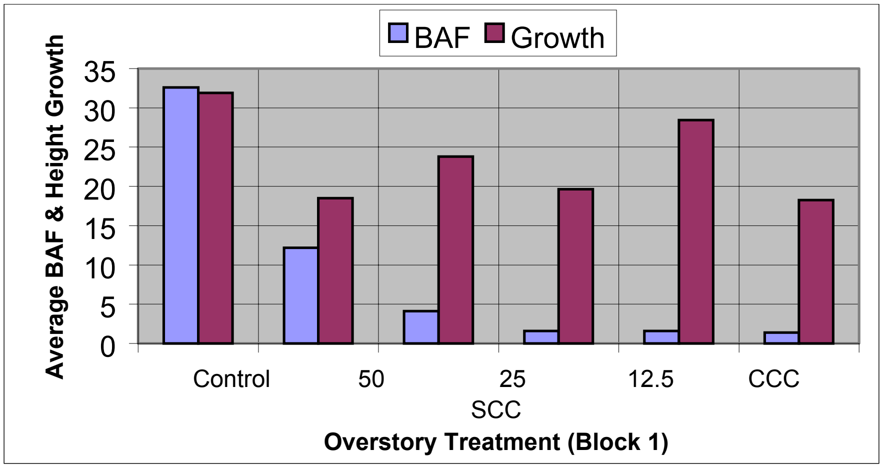
Appendix 6. Percent full PAR received by planted NRO seedlings within all three replicate blocks by time period for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)

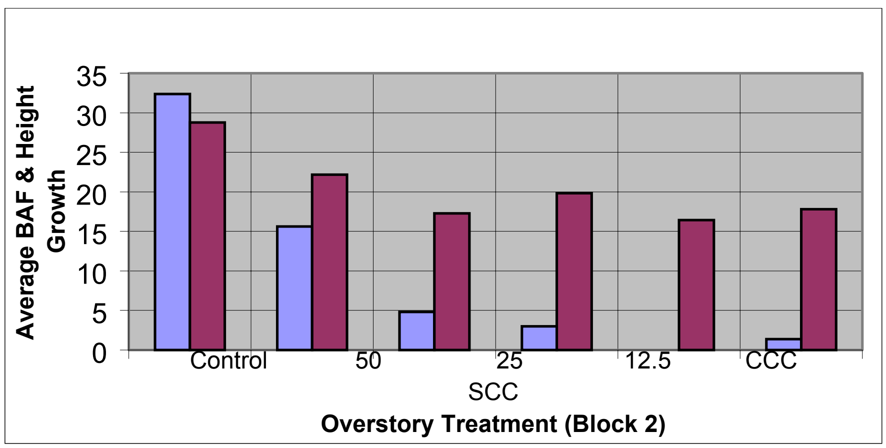


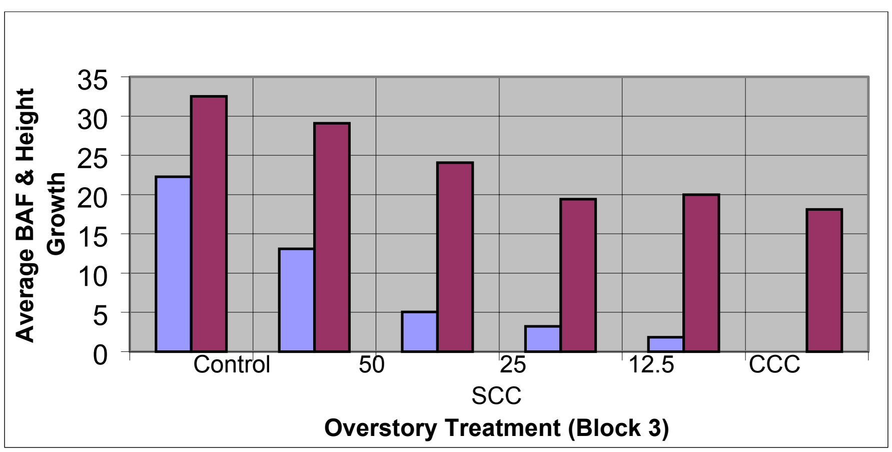
Appendix 7. Percent full PAR received by planted NRO seedlings during all four months by time period for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Means with the same letters are not significantly different at alpha = 0.05 using Tukey's mean separation technique.)



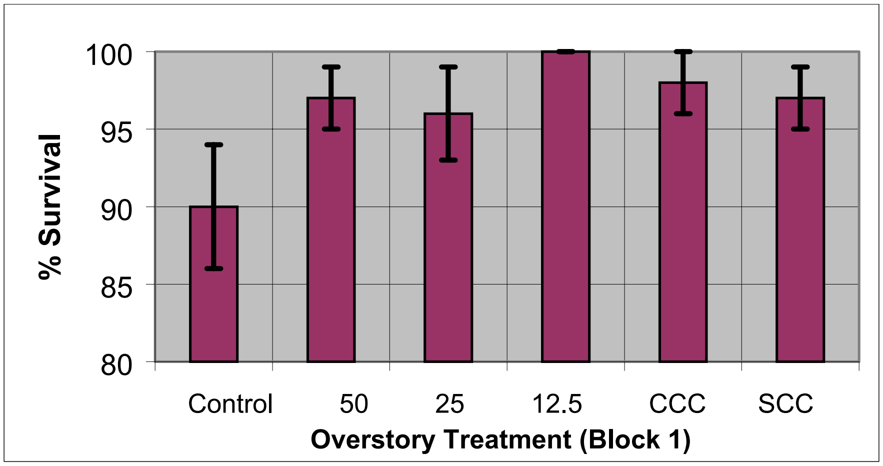
Appendix 8. Basal area (meter^2/hectare) and height growth (cm) per treatment by replicate block for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

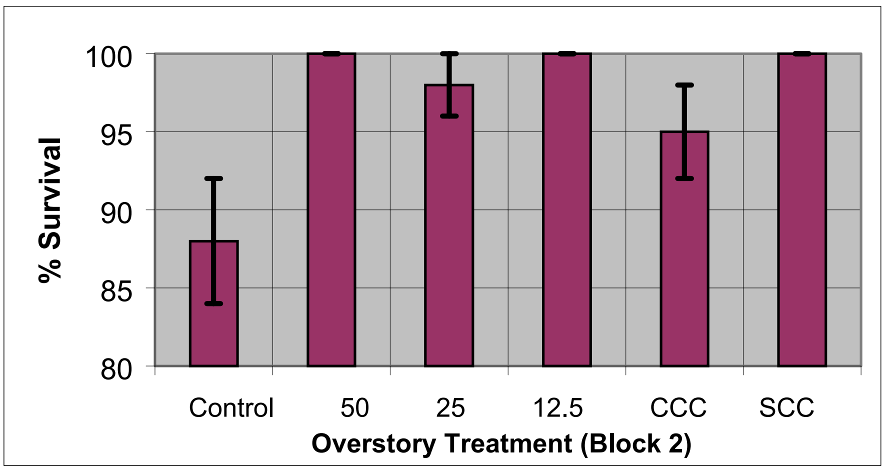


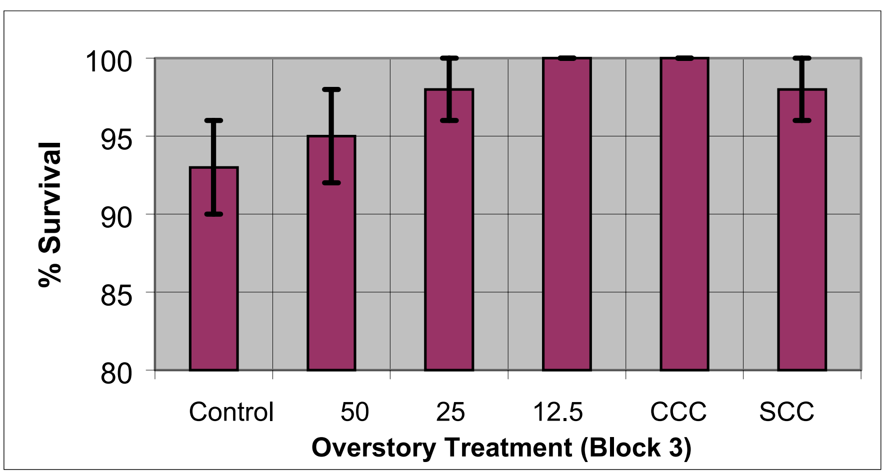




Appendix 9. Estimated percent survival of planted NRO seedlings by treatment and replicate block for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.







Appendix 10. Species list for plants identified during September of 2003, approximately 13 months after harvest for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

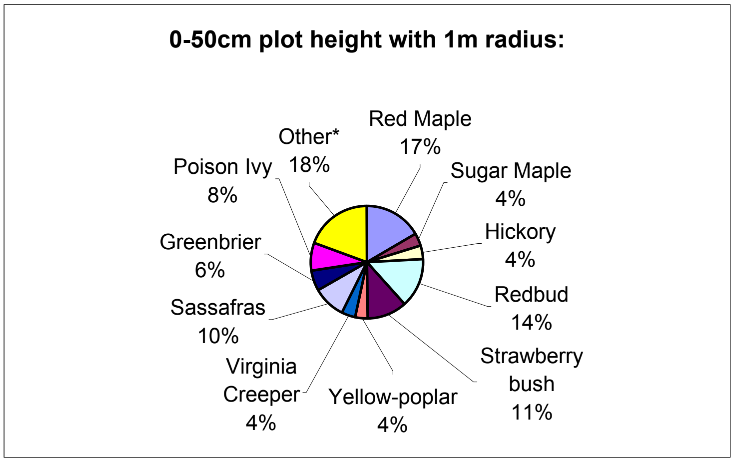
Woody Species

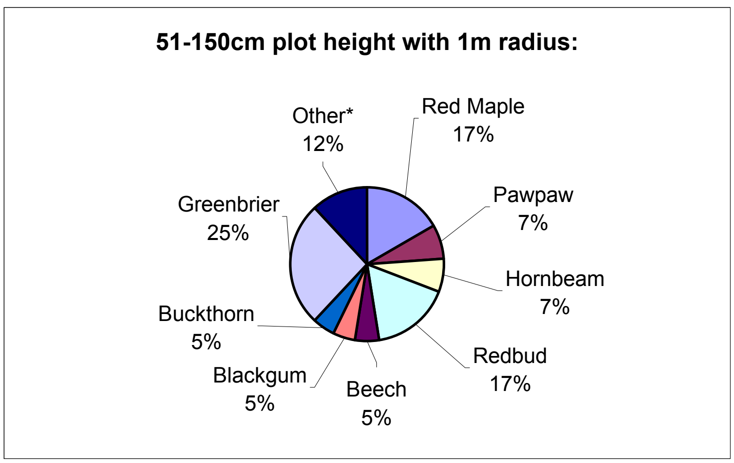
red maple	*Acer rubrum*
sugar maple	*Acer saccharum*
pawpaw	*Asimina triloba*
American hornbeam	*Carpinus caroliniana*
pignut hickory	*Carya glabra*
mockernut hickory	*Carya tomentosa*
redbud	*Cercis canadensis*
flowering dogwood	*Cornus florida*
strawberry bush	*Euonymous americanus*
American beech	*Fagus grandifolia*
white ash	*Fraxinus americana*
green ash	*Fraxinus pennsylvanica*
eastern red cedar	*Juniperus virginiana*
spicebush	*Lindera benzoin*
sweetgum	*Liquidambar styraciflua*
yellow-poplar	*Liriodendron tulipifera*
Japanese honeysuckle	*Lonicera japonica*
cucumber magnolia	*Magnolia acuminata*
umbrella magnolia	*Magnolia tripetala*
red mulberry	*Morus rubra*
blackgum	*Nyssa sylvatica*
eastern hophornbeam	*Ostrya virginiana*
sourwood	*Oxydendrum arboreum*
Virginia creeper	*Parthenocissus quinquefolia*
American sycamore	*Platanus occidentalis*
black cherry	*Prunus serotina*
white oak	*Quercus alba*
scarlet oak	*Quercus coccinea*
southern red oak	*Quercus falcata*
chestnut oak	*Quercus montana*
northern red oak	*Quercus rubra*
post oak	*Quercus stellata*
black oak	*Quercus velutina*
Carolina buckthorn	*Rhamnus caroliniana*
winged sumac	*Rhus copallina*
smooth sumac	*Rhus glabra*
blackberry	*Rubus spp.*
sassafras	*Sassafras albidum*
greenbrier	*Smilax spp.*
poison ivy	*Toxicodendron radicans*
blueberry	*Vaccinium spp.*
grape	*Vitis spp.*
slippery elm	*Ulmus rubra*

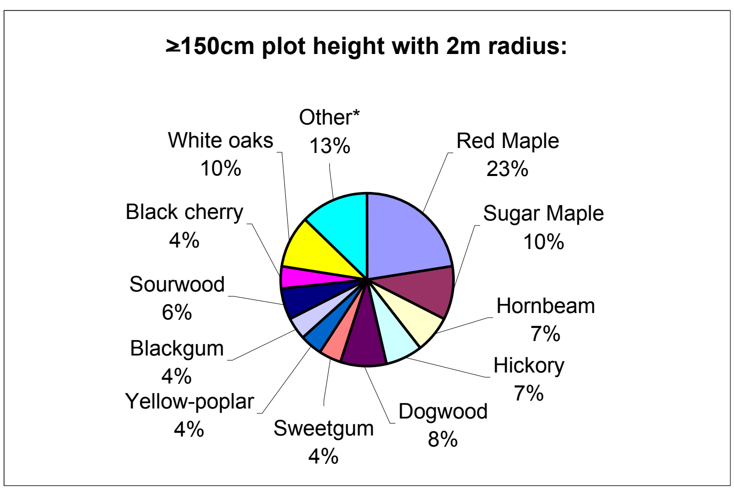
Herbaceous Cover

fireweed	*Erechtites hieracifolia*
horseweed	*Erigeron canadensis*
wild lettuce	*Lactuca spp.*
pokeweed	*Phytolacca americana*

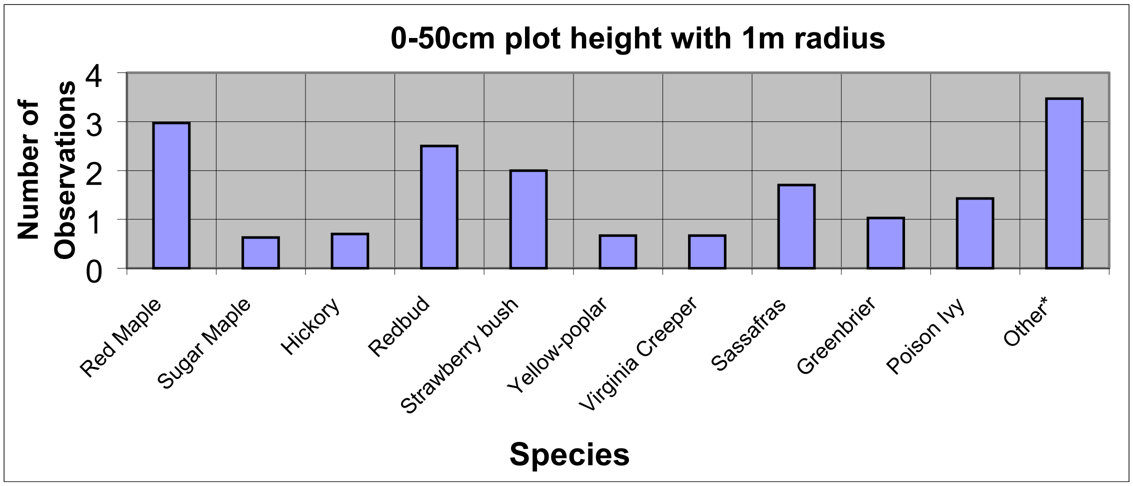
Appendix 11. Percent relative densities for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of the 10 randomly selected NRO seedlings within the Control treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

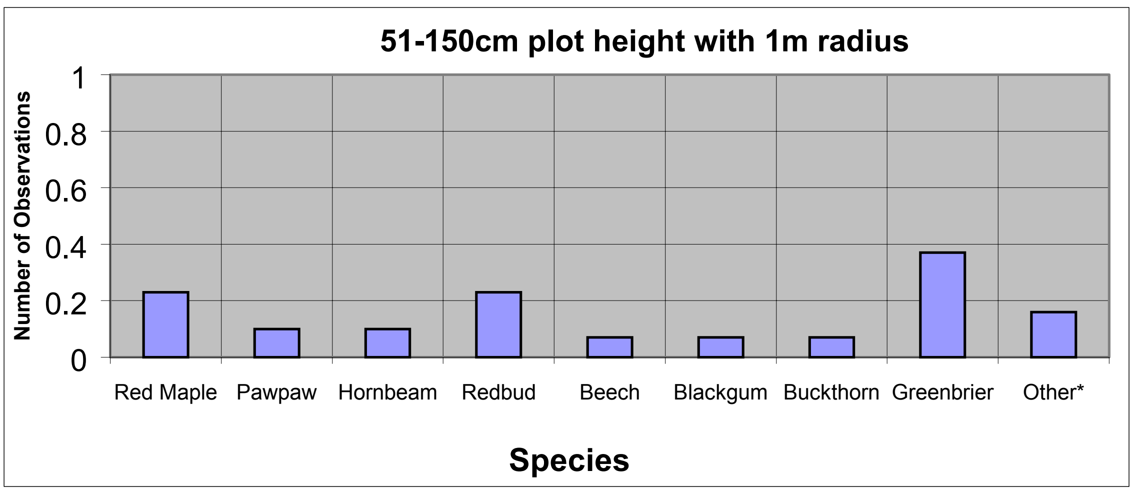


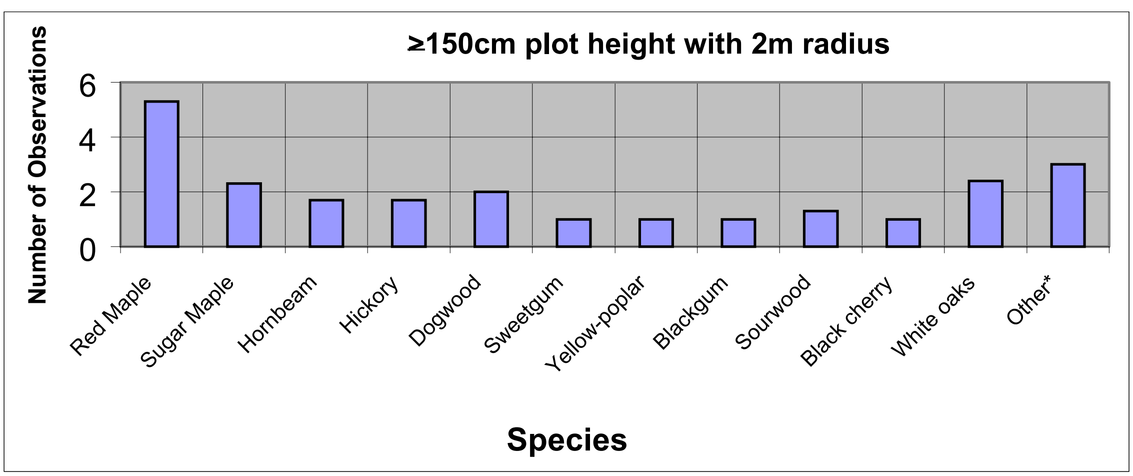




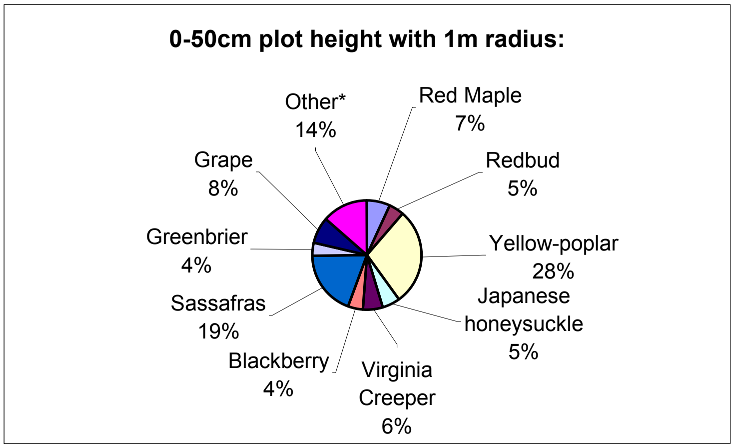
Appendix 12. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the Control treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

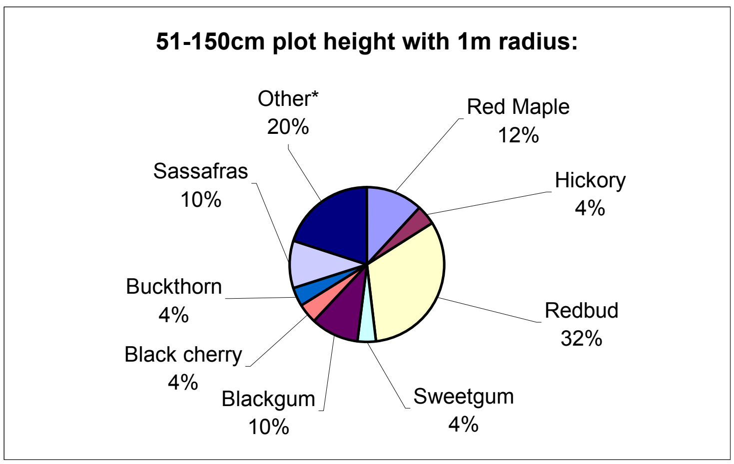


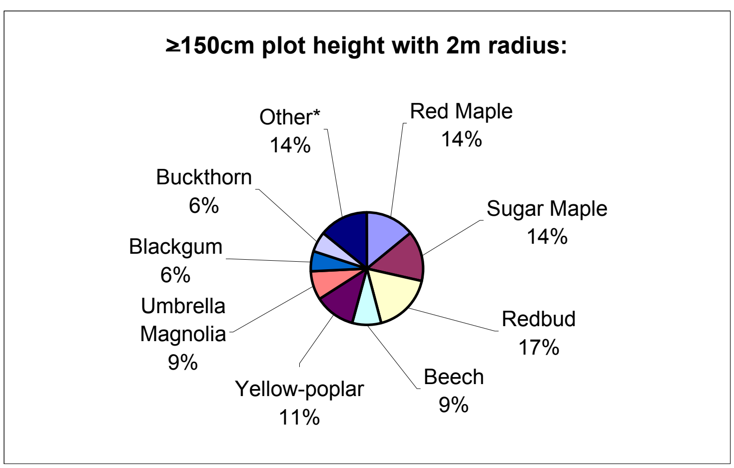




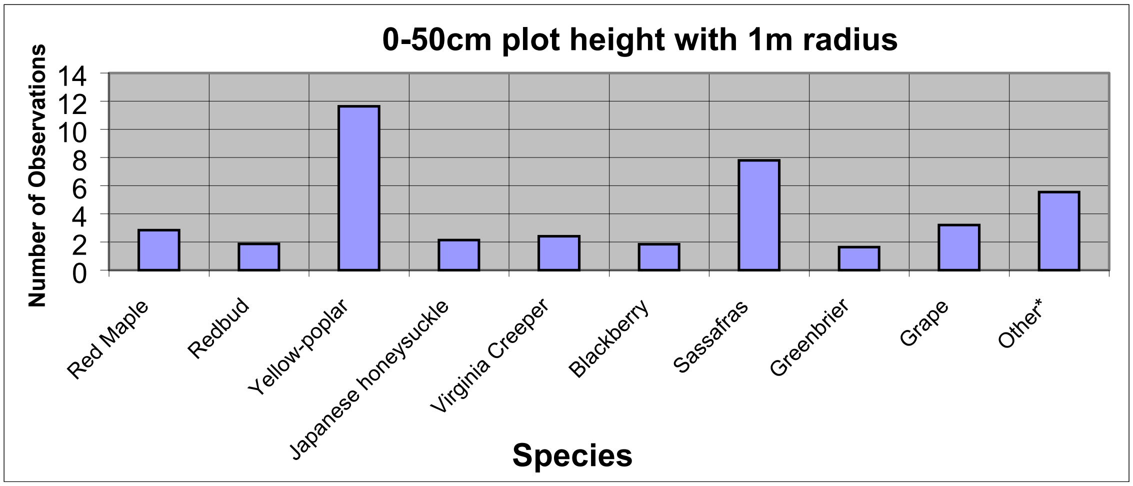
Appendix 13. Percent relative densities for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of the 10 randomly selected NRO seedlings within the 50% BAR treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

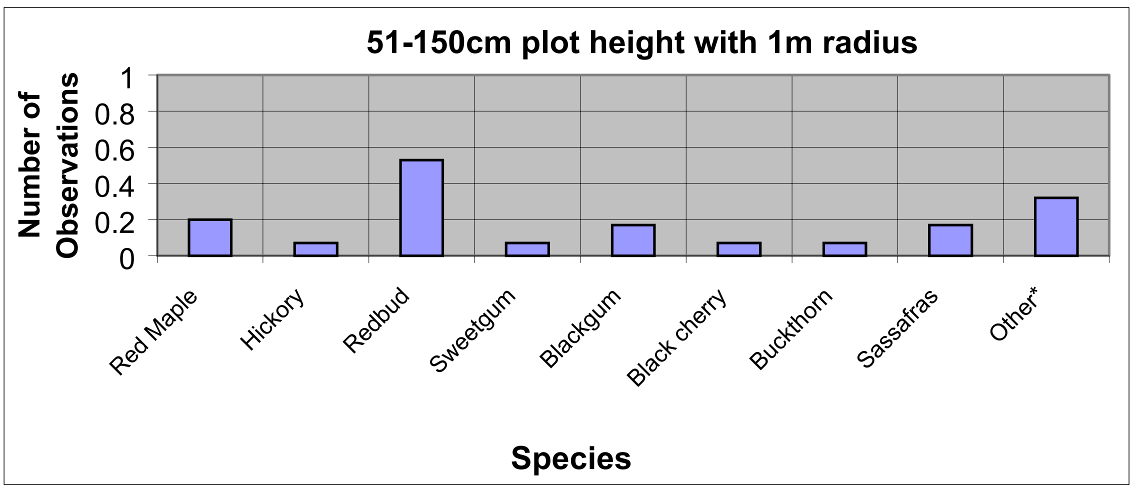




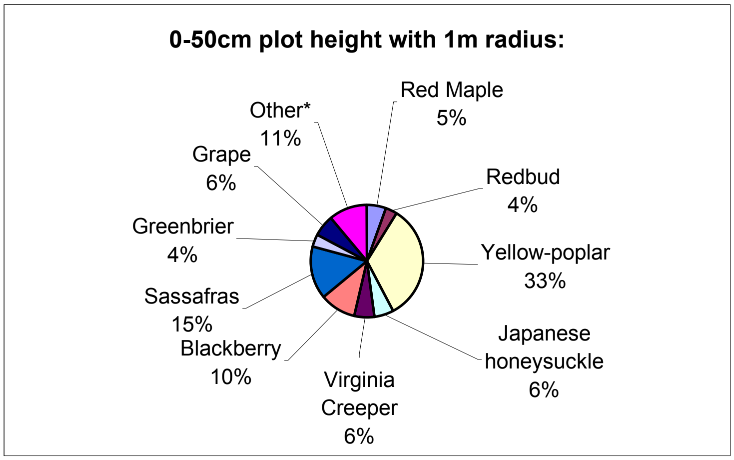


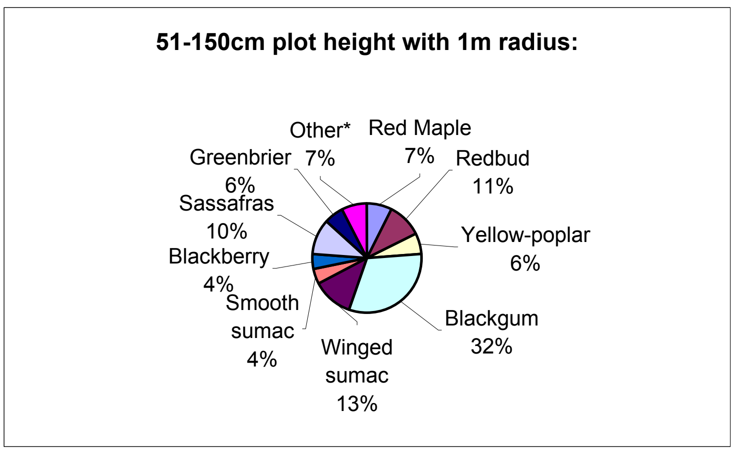
Appendix 14. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the 50% BAR treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

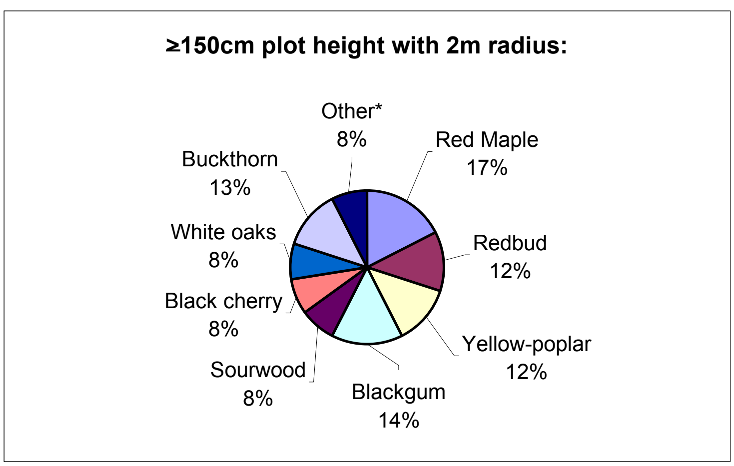




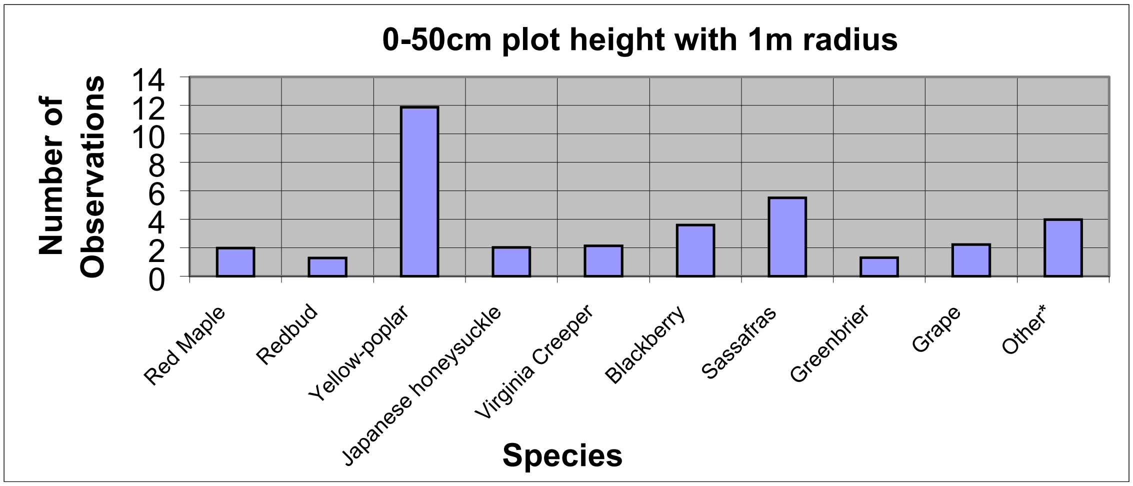
Appendix 15. Percent relative densities for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of the 10 randomly selected NRO seedlings within the 25% BAR treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

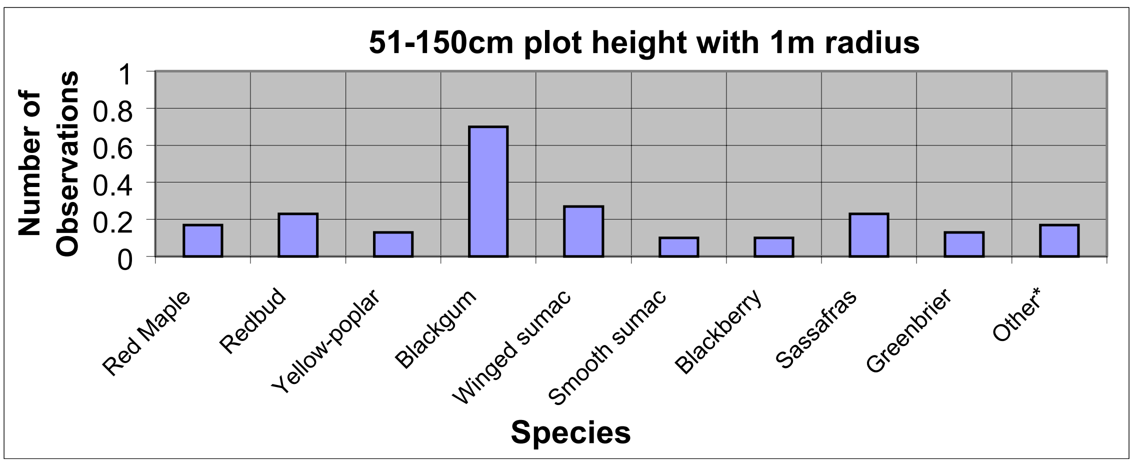




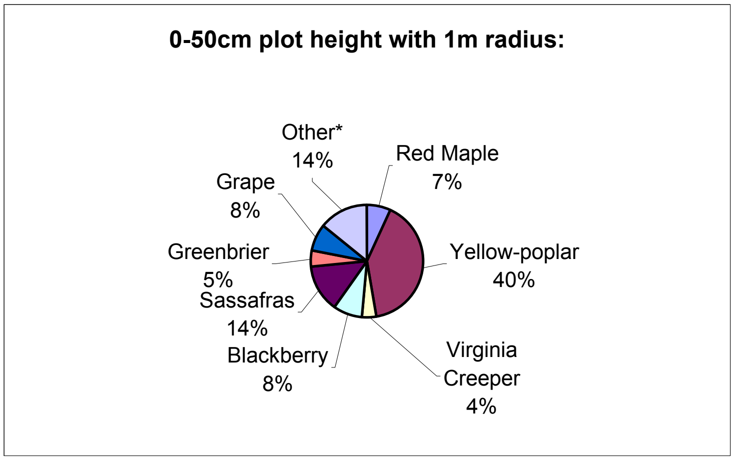


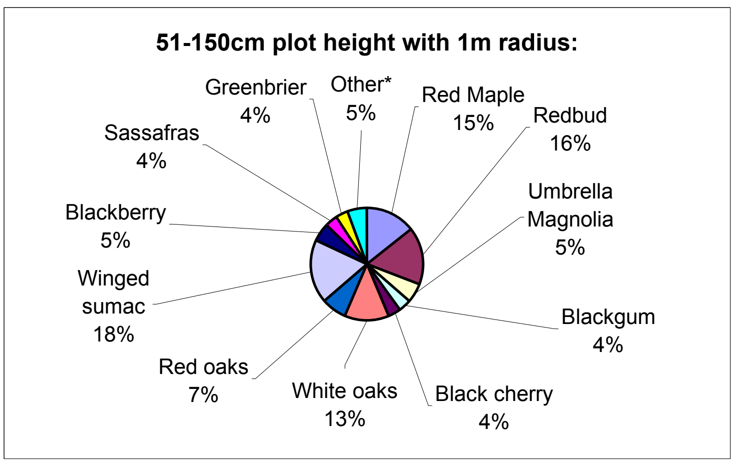
Appendix 16. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the 25% BAR treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

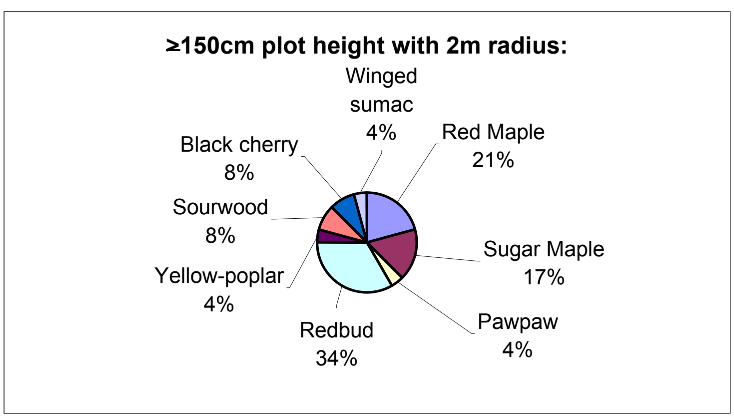




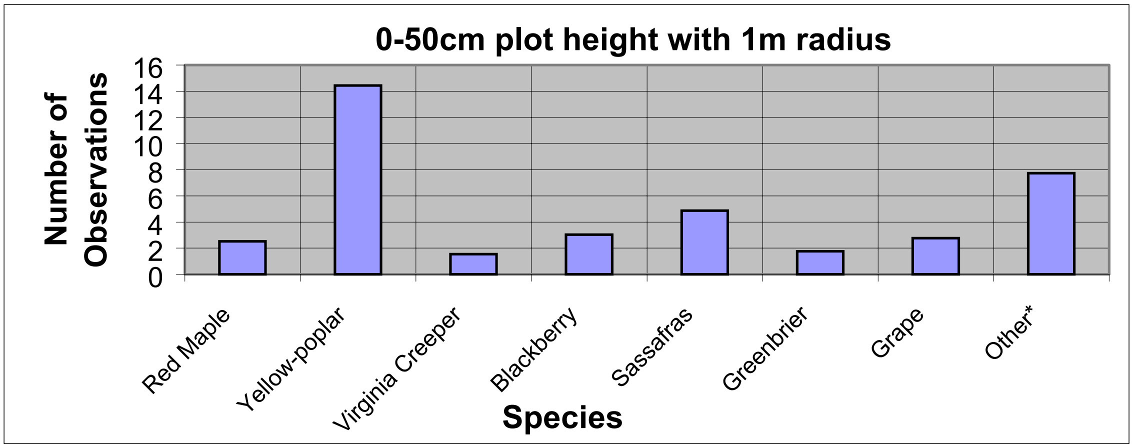
Appendix 17. Percent relative densities for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of the 10 randomly selected NRO seedlings within the 12.5% BAR treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

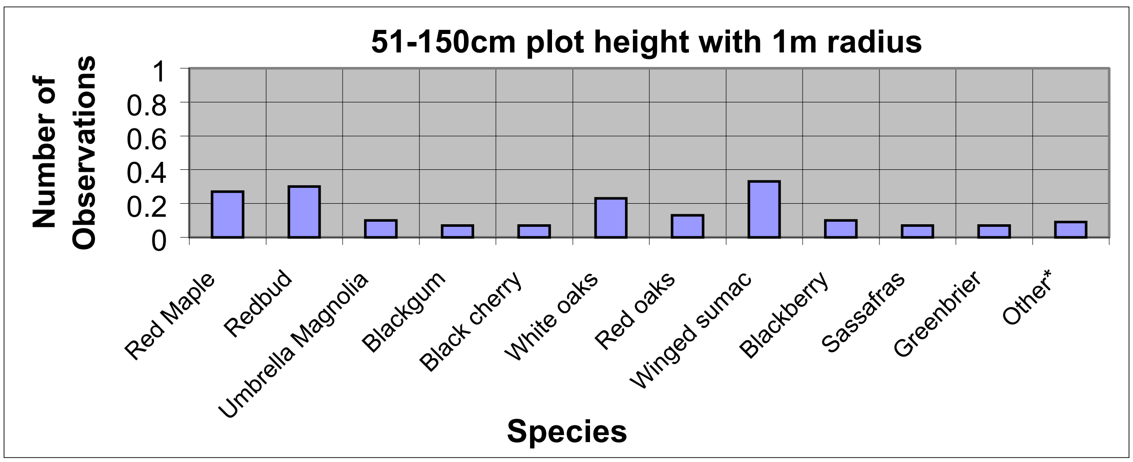


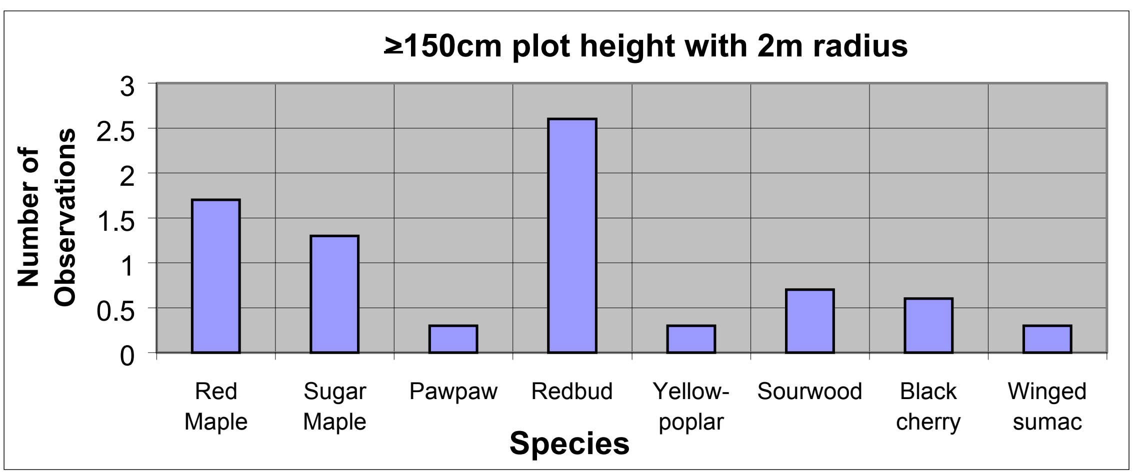




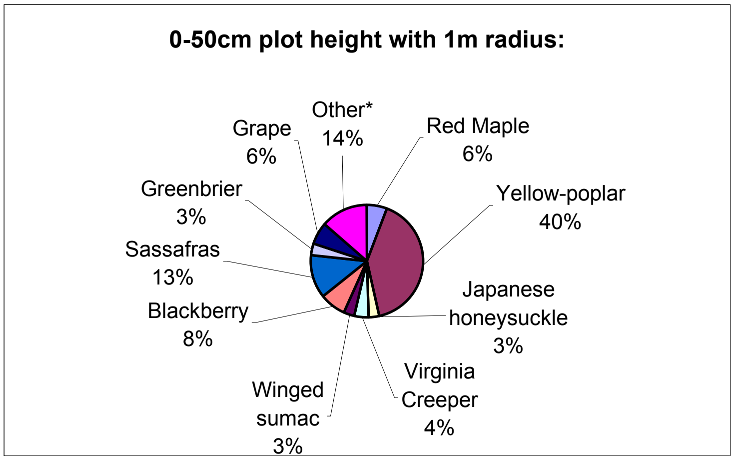
Appendix 18. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the 12.5% BAR treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

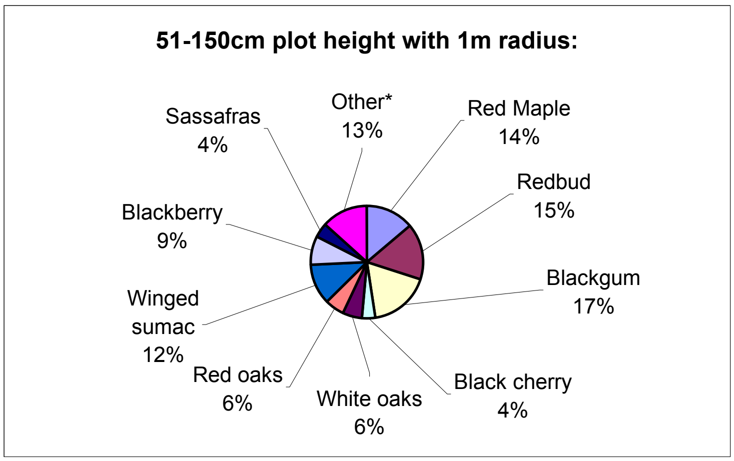


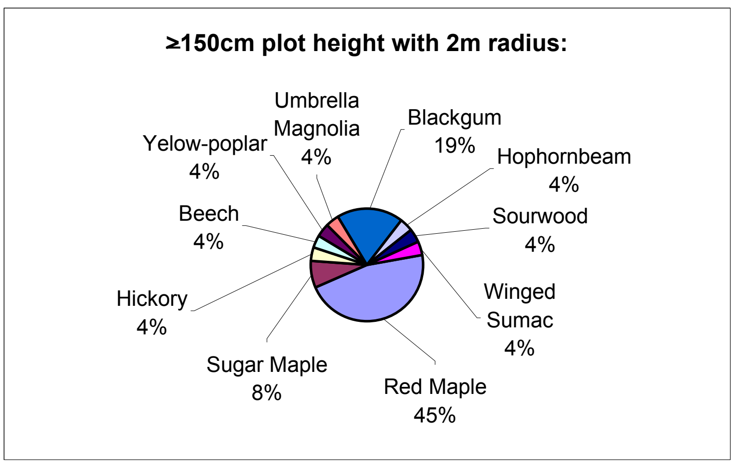




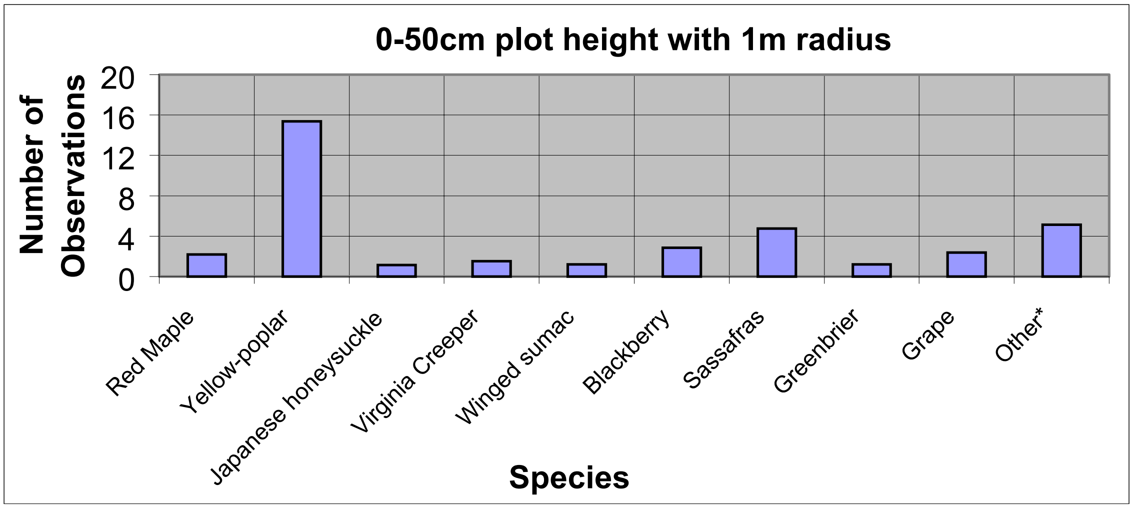
Appendix 19. Percent relative densities for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of the 10 randomly selected NRO seedlings within the CCC treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

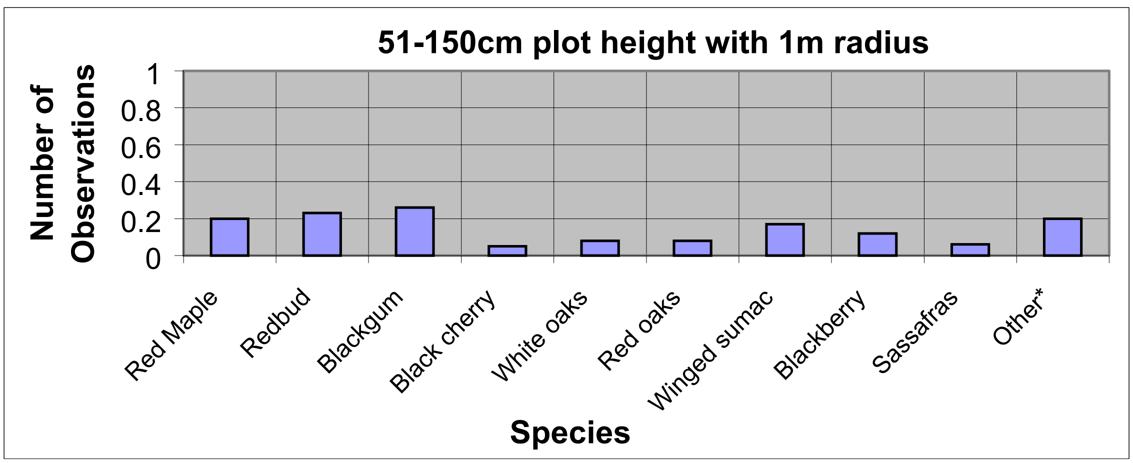


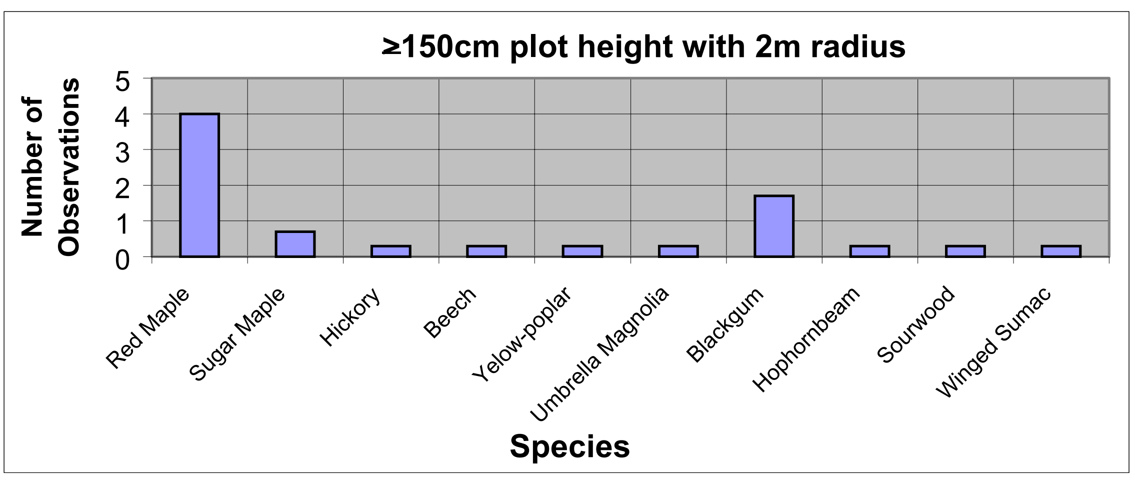




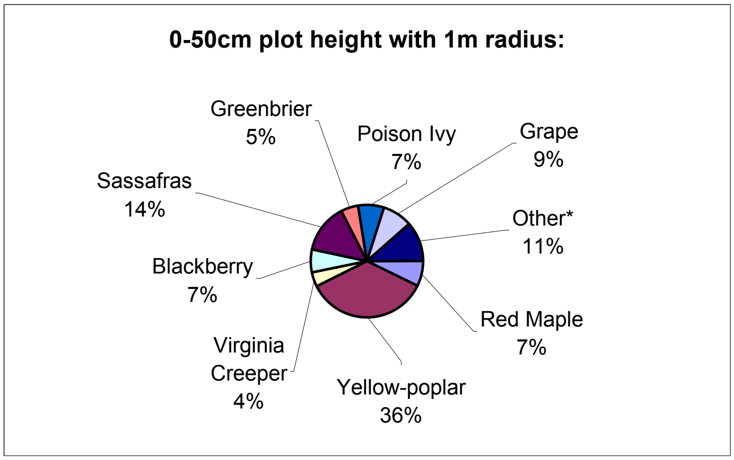
Appendix 20. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the CCC treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

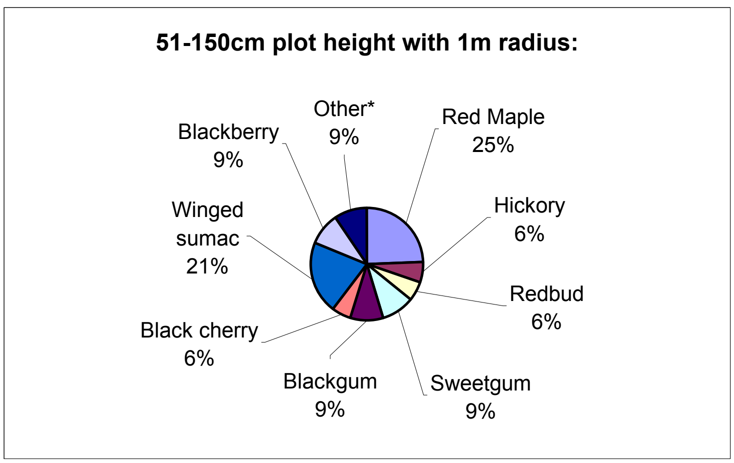


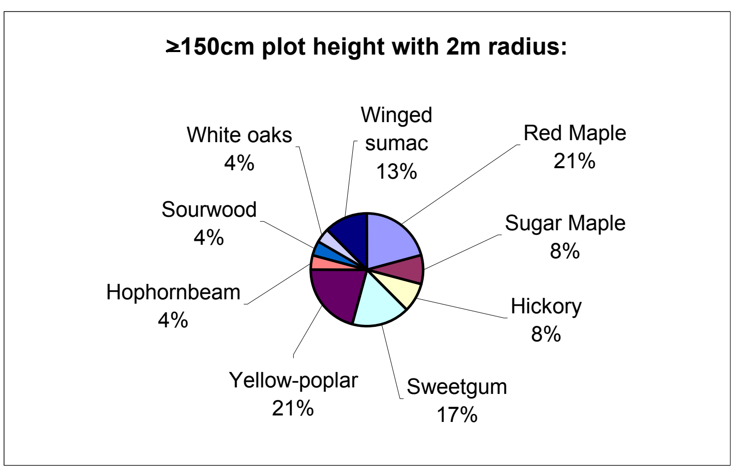




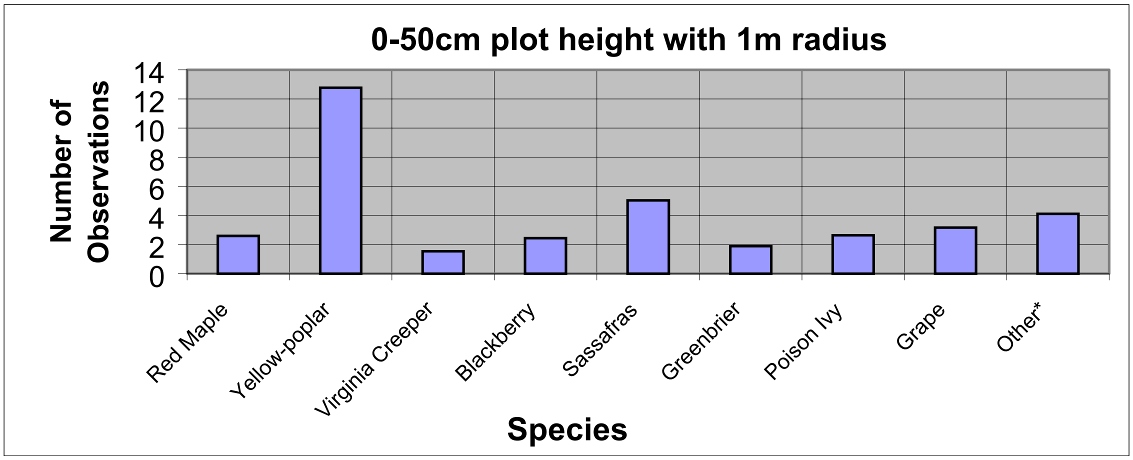
Appendix 21. Percent relative densities for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of the 10 randomly selected NRO seedlings within the SCC treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

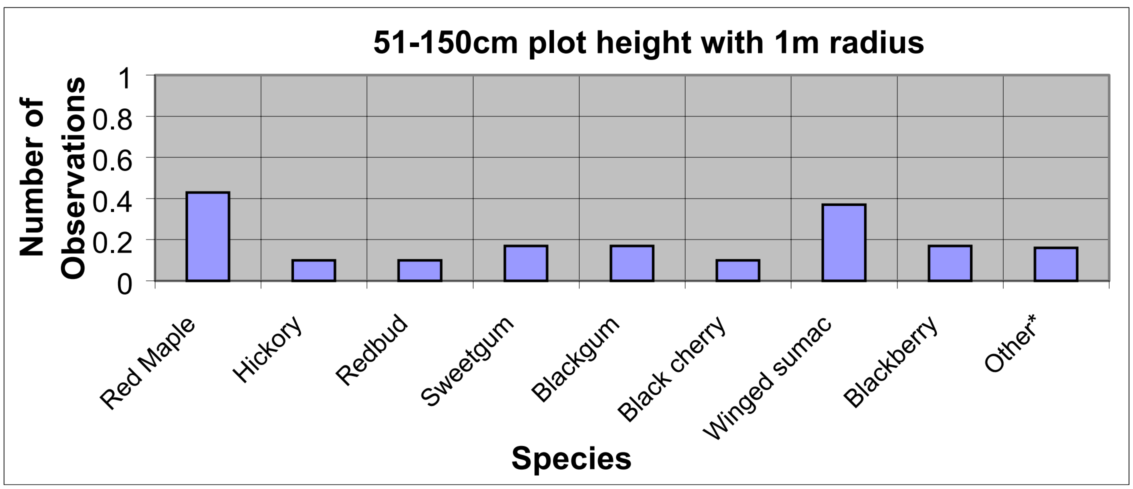


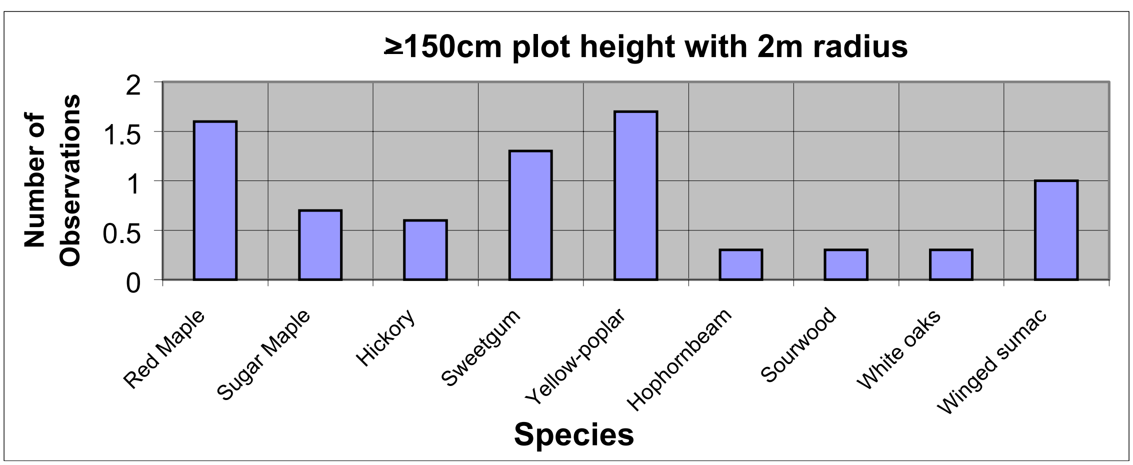




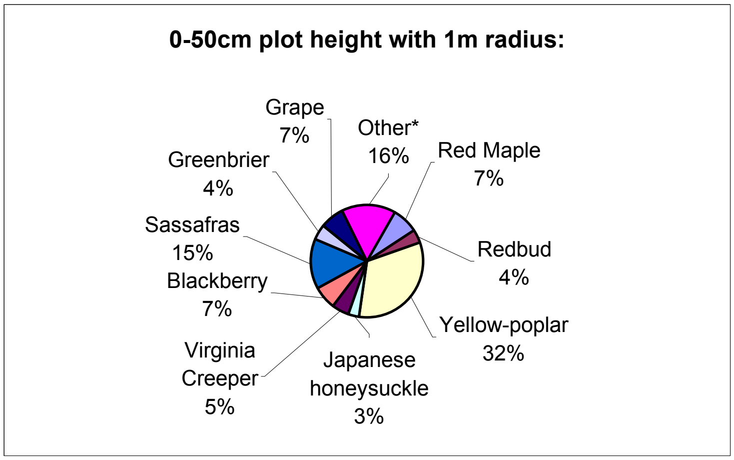
Appendix 22. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within the SCC treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

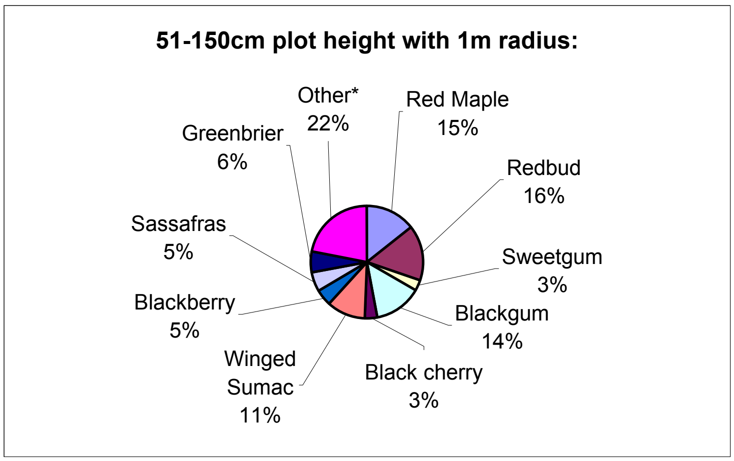


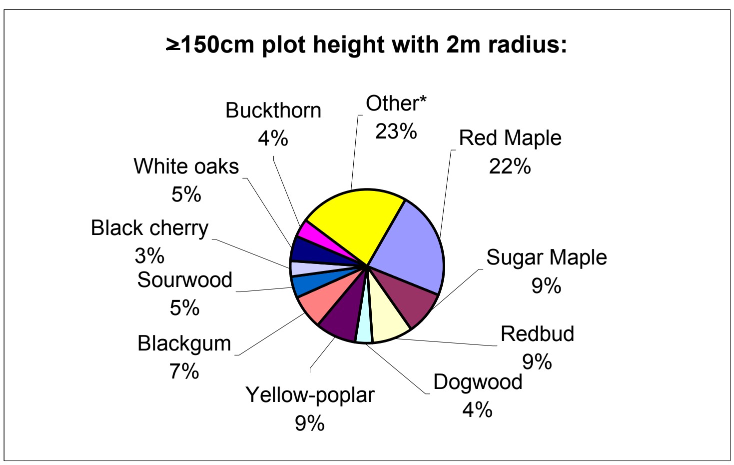




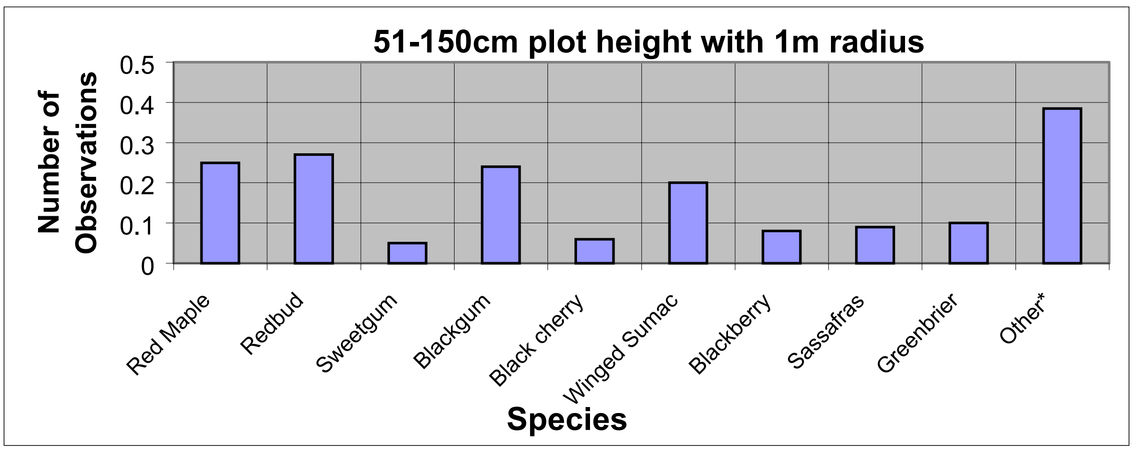
Appendix 23. Percent relative densities for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of the 10 randomly selected NRO seedlings within all six treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

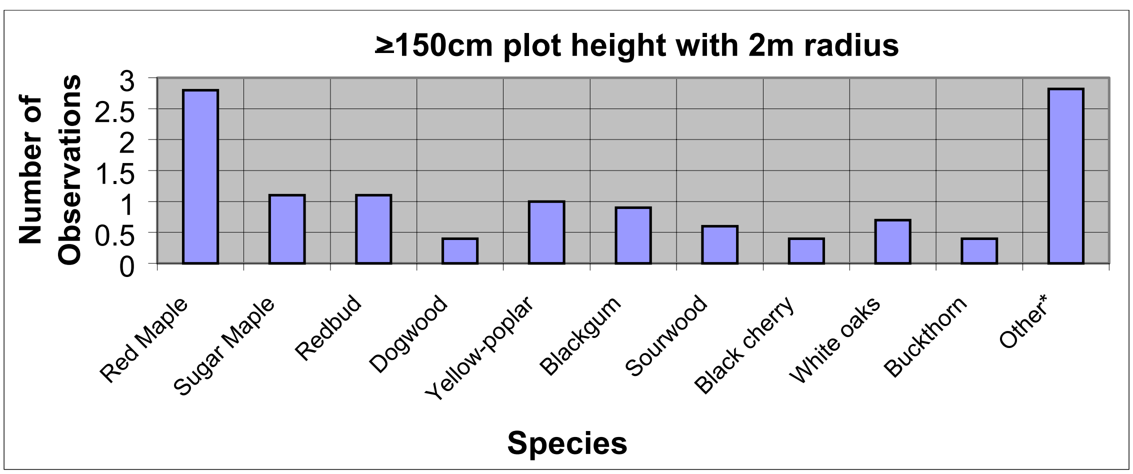






Appendix 24. Mean number of woody competitors for the three size classes (0-50 cm, 51-150 cm and ≥150 cm) by species of 10 randomly selected NRO seedlings within all six treatments for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Other* = <3% occurrence)

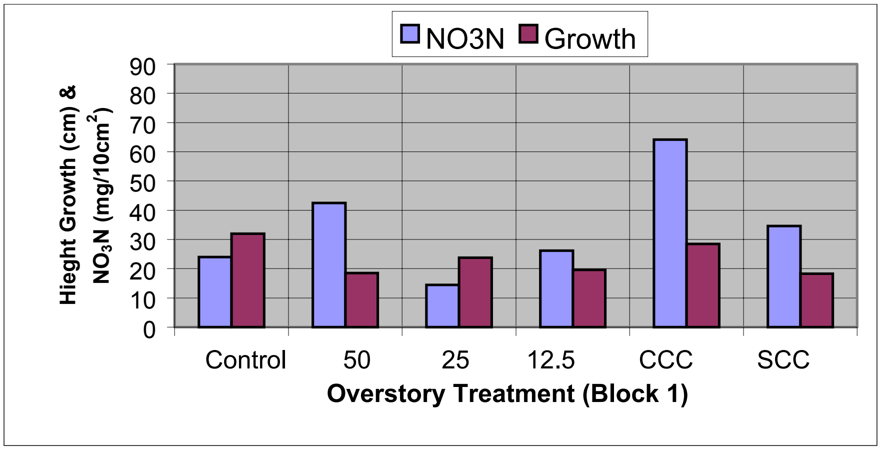


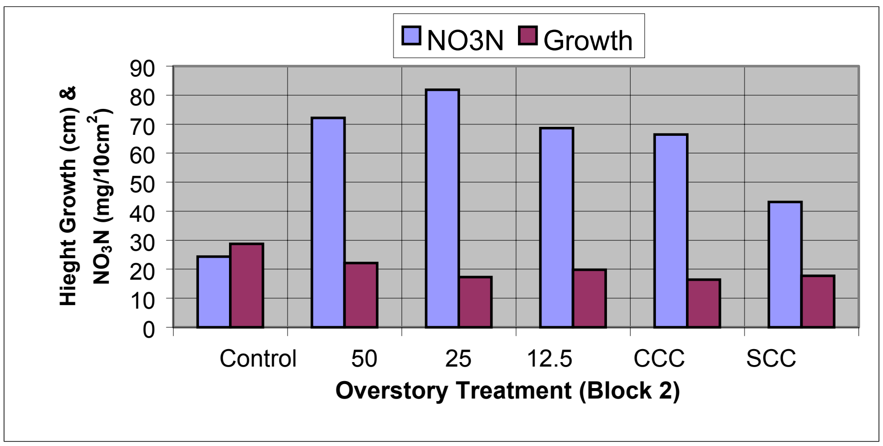


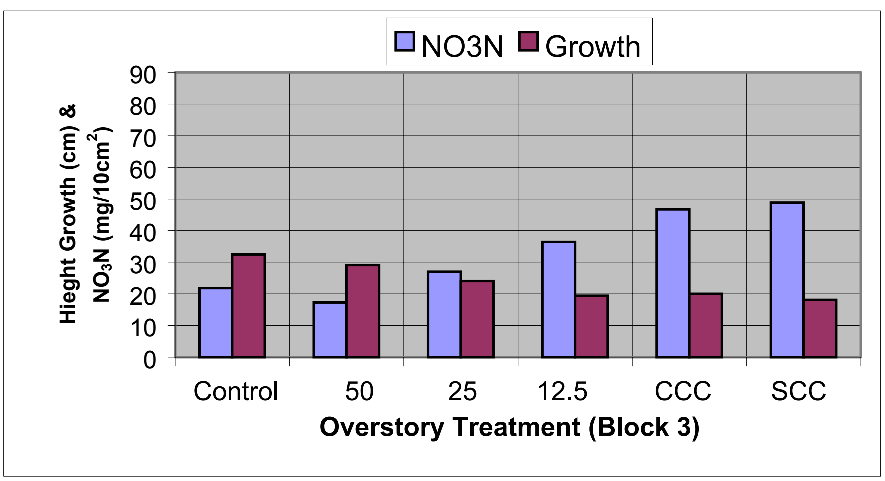
Appendix 25. Family code numbers and their origin for the 18 genetic families used for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee. (Mother tree for genetic family 1 is an open-pollinated progeny from a Tennessee Valley Authority select tree and genetic family 10 is a quarter sib of family 15.)

Family Code	Genetic Family	Growth	N	SE	Origin
4-14-2459	1	29.20	59	1.97	Claiborne, TN
8-19-584	2	27.98	60	1.97	Claiborne, TN
2-16-528	3	27.59	60	1.95	Morgan, TN
4-6-509	4	26.93	60	1.96	Anderson, TN
6-21-500-2	5	26.38	59	1.97	Union, TN
6-11-553	6	25.01	60	1.98	Campbell, KY
2-7-200	7	24.89	61	1.96	Limestone, AL
4-13-705	8	22.73	60	1.96	Anderson, TN
1-21-554	9	20.38	59	2	Morgan, TN
2-10-540	10	19.97	59	2.4	Union, TN
4-6-405	11	19.95	60	1.96	Pickett, TN
5-12-632	12	19.74	59	1.99	Henderson, TN
1-1-905	13	19.53	60	1.97	Henderson, TN
5-2-582	14	19.51	60	1.95	Claiborne, TN
3-35-540	15	19.47	57	1.99	Union, TN
2-29-565	16	19.33	60	1.96	Grundy, TN
2-1-555	17	18.07	55	2.02	Morgan, TN
2-20-323	18	17.05	59	1.97	Trigg, KY

Appendix 26. Level of NO_3^- N received within each treatment and height growth per treatment of planted NRO seedlings by replicate block for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.







Appendix 27. Raw PAR values ($u$mol m^{-2} s^{-1}) received by planted NRO seedlings by treatment, block, time period, and month for the oak seedling study at the Oak Ridge Forestry Experiment Station, Tennessee.

Block 1					**Block 2**					**Block 3**					
Morning	May	June	July	August	Morning	May	June	July	August	Morning	May	June	July	August	Average
Control	22	31	19	6	Control	63	112	76	52	Control	33	39	26	22	42
50% BAR	111	416	385	282	50% BAR	125	525	479	375	50% BAR	125	422	353	126	310
25% BAR	358	797	645	131	25% BAR	237	904	754	662	25% BAR	443	928	814	230	575
12.5% BAR	567	1013	1008	256	12.5% BAR	607	839	741	598	12.5% BAR	650	926	830	688	727
CCC	287	598	535	337	CCC	671	1517	1393	464	CCC	553	794	925	633	726
SCC	861	1096	814	771	SCC	966	1073	948	991	SCC	889	1289	1306	1100	1009
														Total Average:	565
Noon	May	June	July	August	Noon	May	June	July	August	Noon	May	June	July	August	
Control	29	41	29	17	Control	91	75	78	18	Control	103	69	39	67	55
50% BAR	477	613	422	440	50% BAR	265	891	667	741	50% BAR	318	896	890	585	600
25% BAR	867	1404	1285	1084	25% BAR	402	1224	1095	1122	25% BAR	1132	1348	1264	751	1081
12.5% BAR	983	1449	1463	775	12.5% BAR	503	1434	1210	1160	12.5% BAR	770	1703	1372	1156	1165
CCC	1162	1319	918	920	CCC	1554	1823	1783	1198	CCC	1153	1543	719	1335	1286
SCC	1443	1589	1182	1061	SCC	926	1449	1451	1433	SCC	1563	1591	1158	1408	1355
														Total Average:	924
Afternoon	May	June	July	August	Afternoon	May	June	July	August	Afternoon	May	June	July	August	
Control	38	45	34	9	Control	55	32	36	48	Control	61	70	4	56	41
50% BAR	306	661	98	498	50% BAR	386	589	318	595	50% BAR	180	382	402	106	377
25% BAR	819	1241	1131	269	25% BAR	348	783	527	804	25% BAR	735	1013	984	195	738
12.5% BAR	789	1075	1020	300	12.5% BAR	231	1096	700	1093	12.5% BAR	873	1237	134	1214	814
CCC	545	909	530	875	CCC	641	1259	1154	406	CCC	767	1288	111	1259	812
SCC	1069	1089	665	926	SCC	276	951	578	1007	SCC	1204	1026	634	1126	879
														Total Average:	610

Vita

Brian Andrew Barwatt was born in northern Virginia on September 16, 1977. He was raised in Centreville, Virginia and graduated from Centreville High School in 1995. Brian then attended Virginia Polytechnic Institute and State University where he earned the Bachelor of Science degree in Forest Resource Management in May of 2000. In 2001, he joined Americorps NCCC before accepting a position as a Graduate Research Assistant in the Department of Forestry, Wildlife, and Fisheries at the University of Tennessee, Knoxville in August of 2002. Brian plans to travel to Alaska and northwestern Canada this fall to pursue his climbing and mountaineering hobbies before joining the Peace Corps in 2005.