Five-year survival and growth of northern red oak (*Quercus rubra* L.)
seedlings in upland hardwood stands in south central Iowa

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ABSTRACT

A major concern in the management of *Quercus rubra* is the difficulty in regenerating stands that have developed dense understories of shade tolerant species. A study was conducted at two locations in south central Iowa to determine the impact over a five year period of using root graded seedlings, understory control, tree shelters, and overstory reduction on establishing underplanted, 1-0, *Quercus rubra* bare root stock. Relationships between growth or mortality, and photosynthetically active radiation, red to far red light ratio, basal area, average stand diameter, number of trees/hectare, percent stocking, and various combinations of these variables were tested. Shelters and root grading had the greatest impact on survival and growth of the underplanted seedlings. Annual survival and growth of non-sheltered seedlings was greater than sheltered seedlings after three growing seasons. However, By the end of the fifth growing season non-sheltered seedlings had averaged 221 percent greater growth and 75 percent greater survival than sheltered seedlings. Underplanted seedlings with five or more permanent, first-order, lateral roots had 93 percent greater growth at the McNay site and 407 percent at the Stephens sites, respectively, compared to seedlings with fewer, first-order, lateral roots. R-square relationships between growth or mortality, and photosynthetically active radiation, red to far red light ratio, basal area, average stand diameter, number of trees/hectare, percent stocking, and various combinations ranged from 0.00 to 0.66. Spraying and mechanical clearing of the understory prior to underplanting helped underplanted seedlings maintaining a competitive position in the understory. Based on the literature and the results of this study resource managers should: (i) reduce overstory stocking to approximately 60 percent; (ii) use herbicide or

mechanical methods to reduce understory competition; (iii) plant bare root stock with five or more permanent, first-order, lateral roots; and (iv) remove the remaining overstory when the underplanted *Quercus rubra* seedlings are 1.5 m in height in order to aid in the regeneration of *Quercus rubra* in south central Iowa.

INTRODUCTION

Quercus rubra L. is a hardwood species highly prized for lumber, veneer, wildlife habitat, and aesthetics (Dickson, 1991; Isebrands and Dickson, 1994). *Quercus rubra* is widely distributed over the eastern half of North America (Braun, 1950). In the United States it grows from Minnesota south to eastern Nebraska and Oklahoma; and east to Arkansas, southern Alabama, Georgia, and North Carolina. In Canada, *Quercus rubra* grows from Cape Breton Island, Nova Scotia, Prince Edward Island, New Brunswick, and the Gaspè Peninsula of Quebec, to Ontario (Sander, 1990).

A major concern in the management of *Quercus rubra* is the difficulty in regenerating new stands to replace those that are harvested (Holt and Fisher, 1979; Lorimer, 1989; Isebrands and Dickson, 1994). The difficulty in regenerating *Quercus rubra* stands is because many of the *Quercus* forests in parts of the Eastern and Central United States have developed dense understories of shade tolerant species (Schlesinger, 1976; Ehrenfeld, 1980; Coder, 1985). Thus, as *Quercus rubra* stands are harvested, they gradually convert to *Acer saccharum* Marsh., *Tilia americana* L., *Ulmus americana* L., and *Fraxinus americana* L. because there is little or no advanced *Quercus rubra* reproduction (Sander, 1977; Dickson, 1991).

If no artificial regeneration is used, the percentage of *Quercus rubra* in the succeeding rotation is directly related to the amount of *Quercus rubra* reproduction present before final harvesting takes place. While stump sprouts can be anticipated, the ability of *Quercus* to sprout decreases with age. Only 30% of *Quercus rubra* stumps are expected to sprout after they reach 43 cm in diameter (Sander, 1977). Therefore, seedlings must be established in order to regenerate the new stand. This reproduction must be established over a period of time, either by natural or artificial regeneration, before the mature overstory trees are harvested (Carvell, 1979).

Sander, et al. (1984) demonstrated in the Missouri Ozarks that *Quercus rubra* seedlings must be at least 1.5 m in height or 2.5 cm in ground-line diameter to have the potential for reaching dominance in a new stand. Therefore, to successfully establish an adequate *Quercus rubra* component in a future stand, the advance *Quercus rubra* regeneration must be at least 1.5 m in height or 2.5 cm in ground-line diameter at the time of overstory removal. It may take 10 to 20 years before an adequate amount of *Quercus* regeneration reaches these minimum size criteria before the overstory can be removed (Sander, 1977). Such sluggish growth in *Quercus rubra* seedlings, which allows them to be overtopped by the competition at an early age, appears to be the primary reason for *Quercus rubra* regeneration failures (Johnson and Jacobs, 1988; Kolb and Steiner, 1989; Lorimer, 1989).

Research conducted by Sander in the 1960s and 1970s developed the guidelines for establishing *Quercus rubra* regeneration. These guidelines state that 175 *Quercus rubra* seedlings/hectare at 1.5 m in height are needed to establish a pole stand containing 30% *Quercus rubra* (Lorimer, 1989). It has become apparent that very few stands located on average or good sites could even come close to Sander's guidelines for *Quercus rubra* regeneration (Lorimer, 1989).

Current research is focusing on finding ways to successfully establish *Quercus rubra* regeneration, either by stimulating the development of vigorous, natural *Quercus* seedlings or on finding successful means of artificial *Quercus* regeneration. Researchers are focusing on herbicide control of competition, removal of understory and overstory vegetation, planting improved nursery stock, planting *Quercus* seed, using tree shelters, and combinations of these methods to successfully establish *Quercus rubra* regeneration (Johnson, et al., 1989; Kolb, et al., 1989; Schultz and Thompson, 1991; Teclaw and Isebrands, 1991; Buckley, et al., 1995).

This study focused on the establishment of underplanted, 1-0, *Quercus rubra* seedlings during their first five growing seasons. The study focused on the impact that overstory and understory density, seedling root systems, and tree shelters had on establishing underplanted, 1-0, *Quercus rubra* seedlings.

LITERATURE REVIEW

Quercus rubra Seedling Growth

Quercus rubra seedlings have the potential to grow rapidly due to their ability to have multiple flushes under optimal conditions, but when stressed, as is typical in the field, *Quercus rubra* tends to have conservative shoot growth and concentrates more on root growth (Johnson, 1982; Kolb and Steiner, 1990). When *Quercus rubra* has a growth flush, it goes through four distinct phases; bud swell, linear stem growth, linear leaf growth, and leaves fully expanded (Dickson, 1991). During the lag phase, when leaves are fully expanded, *Quercus rubra* allocates current photosynthates to lower shoot and root growth, but some of the current photosynthate is stored in the tap root for the next flush of growth and is not allocated for new root growth (Dickson, 1991; Struve and Joly, 1992; Isebrands, et al., 1994a).

When working with artificial *Quercus rubra* regeneration, seedlings go through a period of transplant shock. Transplant shock is the period between transplanting and the resumption of vigorous growth, which is caused by the loss of roots during lifting from the nursery bed and phenological development (Struve and Joly, 1992).

Bud break of transplanted *Quercus rubra* precedes first root regeneration, and as the number of days increases between bud break and first root regeneration, transplant shock symptoms become more severe (Johnson, et al., 1984). The first growth flush of transplanted *Quercus rubra* seedlings occurs before significant amounts of roots are regenerated (Johnson, et al., 1984; Struve and Joly, 1992). Thus, transplanted *Quercus rubra* seedlings must meet their water and nutrient requirements during establishment with greatly reduced root surface area. The demand for water in newly transplanted *Quercus rubra* seedlings is often offset by reduction in leaf expansion, in order to maintain favorable limits of whole-plant water balance until root growth resumes (Larson and Whitmore, 1970; Farmer, 1975; Struve and Joly, 1992). To meet nutrient requirements during the first growth flush, *Quercus rubra* seedlings use stored carbohydrates from root and shoot reserves (Dickson, 1991; Struve and Joly, 1992).

Light, Stand Density, and *Quercus* Establishment

Environmental factors ranging from the amount of light reaching the understory to soil moisture have a combined effect on the survival, growth, and abundance of forest regeneration (Shirley, 1929a; Pearson, 1930; Carvell and Tryon, 1961). The amount of light reaching the understory is the most important and easiest environmental factor to influence and therefore is often the most manipulated (Shirley, 1929b; Pearcy, 1988; Hannah, 1991).

In summer, a continuous hardwood canopy forest can screen out 90 percent or more of the visible light, expressed as a percentage of light in the open (Reifsnyder and Lull, 1965). The understory light environment that is often present under the continuous hardwood canopy forest is characterized by a very low level of diffused light that is punctuated by intense lightflecks lasting from a few seconds to 15 or more minutes (Pearcy, 1988; Le Gouallec, et al., 1990). As much as 70 percent of the total daily photon irradiance levels reaching the vegetation present in the understory is in the form of lightflecks (Reifsnyder and Lull, 1965; Pearcy, 1988).

Understory vegetation does not need continuous light for carbon gain to occur. The induction occurring during a series of lightflecks results in higher carbon gain from lightflecks later in the series. Depending on the frequency and duration of the lightflecks and the interval of the intervening low-light periods, the carbon gain of a plant in response to a lightfleck is a consequence of the limitations imposed by the induction state plus the enhancement due to post-illumination carbon dioxide (CO_2) fixation (Pearcy, 1988).

Quercus regeneration can best be established on sites that have been disturbed and in which some or all of the forest canopy is removed in order to allow more light to reach the forest floor (Johnson, 1981; Hannah, 1991; Teclaw and Isebrands, 1991). What researchers have not agreed on is the optimal range of light level needed to establish *Quercus rubra* regeneration. Sander (1977) recommends establishing *Quercus* regeneration by using the shelterwood system in which stands are 60 percent stocked. Johnson (1981) and Johnson, et al. (1989) have reported that *Quercus* can be successfully regenerated in clearcuts. Hannah (1991) reports that hardwoods in the northeast regenerate best under a shelterwood with 40 to 80 percent crown cover. Teclaw and Isebrands (1991) report that 25 to 50 percent crown cover may be a good alternative to the more traditional management scheme of 70 percent crown cover with overstory removal at a later date.

This indecisiveness among researchers indicates that further research is needed to develop guidelines on the amount of light needed to establish *Quercus rubra* regeneration. One of the problems with determining the amount of light needed to establish *Quercus rubra* regeneration is the method which is used to measure light. Most woodland and forest managers use a proxy for light; such as basal area, crown cover, stand density, or stem density, since light measuring equipment is expensive. Most of the proxies for light are inaccurate because they are subjective in nature (i. e., crown cover) or are not well enough correlated with photosynthetically active radiation levels.

To help eliminate problems of using proxies and the cost of expensive light measuring equipment, D. T. C. Friend (1961) published a simple method that he recommended for measuring intergrated light values in the field. The method involved using light-sensitive diazo paper that was calibrated against a standard light measuring device. Research by Bardon, et al. (1995) indicates that Friend's method is a poor predictor of intergrated photosynthetic photon flux density (PPFD) and that the diazo paper actually slowly records irradiance. Therefore, the diazo paper method should not be used to measure intergrated PPFD's in the field.

Plant growth is affected by irradiance levels. In early studies of light and plant growth, it has been shown that dry weight of plants increases with increases in irradiance (Shirley, 1929a and b). Research has also shown that certain irradiance levels are favorable for regeneration of desirable species (Wellner, 1948).

When tolerance of forest trees is considered in the establishment and management of desired species, managers need a simple, inexpensive field method for estimating irradiance levels. One method for estimating irradiance levels beneath a canopy is to relate it to a measure of stand density (Wellner, 1948). One measure of stand density is the summation of diameters at breast height per area, which is simply the addition of diameters at breast height per hectare. Wellner (1948) has shown that a relationship exists between stand density and irradiance level and that two out of three estimates obtained were within 10 percent of the actual irradiance levels. The principal use of the method is to determine cutting level to obtain a desired irradiance level (Wellner, 1948).

Other management tools that are not directly based on relationships between irradiance and measures of stand density have been developed in order to assist in the establishment of stands (Gingrich, 1967; McGill, et al., 1991). The current oak management guide recommends thinning stands back to 60% stocking in order to establish *Quercus rubra* regeneration (Sander, 1977). The stocking chart used in the Oak Management Guide (Sander, 1977) was developed by Gingrich (1967) and has been widely used in evaluating stocking and density criteria in upland hardwood stands to determine the adequacy of a given stand density to meet specific management objectives. Those who use the stocking chart only have to measure basal area and number of trees/acre in order to determine the level of stocking. The stocking chart has three levels of stocking. A-level stocking represents a normal condition of maximum stocking (100 %) for undisturbed stands of upland hardwoods of average structure. B-level is the lower limit of stocking (55-58 % of A-level) for full-site occupancy based on the tree area ratio for open grown trees. Optimum stocking and growth for a given objective or product ranges between the A-B range of full stocking. C-level is the lower limit of stocking for a stand to reach B-level in ten years (Gingrich, 1967).

Red to Far Red Light Ratio

Plants respond to proximity of neighboring plants with plastic morphological and physiological changes (Ballaré, et al., 1994). Some of these responses are changes in growth rates that are caused by differences in environmental resource allocations imposed by neighboring plants. Others have developed to determine the proximity of their neighbors. The driving force of one such system is phytochrome. Phytochrome is a pigment that is used by the plant in sensing red to far red light ratio changes in the spectral composition of back scattered light. By sensing such changes in the red to far red light ratio the plant can detect the proximity of the neighboring plants and respond with morphological changes before being shaded by their neighbors (Ballaré, et al., 1994). One such morphological change is increased stem elongation. The increase in stem elongation is most pronounced in shade avoiding species (Kendrick and Frankland, 1983; Smith and Whitelam, 1987). The smaller the ratio of red to far red light the more stem elongation takes place (Kendrick and Frankland, 1983; Smith and Whitelam, 1987; Kimmins, 1987).

Ballaré, et al. (1994) looked at red to far red light ratio and plant response to neighboring plants. Ballaré, et al. found that tobacco plants that over express a phytochrome A gene display little or no morphological response to reduced red/far red ratio and tobacco plants that did not over express the phytochrome A gene had a marked increase in stem elongation. Ballaré, et al. (1994) concluded that tobacco plants that have reduced photomorphogenic responsivity are less capable of responding morphologically to the proximity of other plants.

Quercus rubra Regeneration Methods

Recommended regeneration methods for satisfying the light requirements of *Quercus rubra* are clearcutting, shelterwood, and group selection; with clearcutting and shelterwood recommended the most. Group selection, which consists of recommended openings between 0.2 ha and 0.8 ha, is only recommended if considering other management goals besides timber production (Jacobs and Wray, 1992).

The choice of regeneration method depends on the potential of the existing stand to regenerate itself. The potential to regenerate depends on such factors as size and number of advance reproduction and stumps capable of sprouting (Sander, 1977; Johnson and Sander, 1987; Jacobs and Wray, 1992). If the stand has a high potential to regenerate itself (i.e., large numbers of advance regeneration stems and stumps capable of sprouting) then clearcutting or group selection would be recommended. If the stand is deemed inadequate to regenerate itself, then the shelterwood method is recommended (Sander, 1977; Jacobs and Wray, 1992).

In cases where stands are lacking adequate components of *Quercus rubra*, either in quantity or quality, advanced reproduction of *Quercus rubra* can be enhanced by i.e. (i) using the shelterwood method and underplanting, (ii) using group selection and interplanting, or (iii) clearcutting and interplanting. A review of the literature has shown that no one concise and consistently successful method has been developed for regenerating *Quercus rubra* throughout its range (Marquis, et al., 1976; Loftis, 1983; Johnson, 1981; Johnson, et al., 1989; Potter, 1991; Schultz and Thompson, 1991).

Improved nursery stock

Schultz and Thompson (1991) have focused on developing high quality *Quercus* seedlings for successful artificial regeneration in the Central States. Much of their research has focused on nursery practices and plantation establishment. Schultz and Thompson (1990) have demonstrated that undercut seedlings tend to have larger numbers of permanent first-order lateral roots and are smaller in height and in diameter than seedlings that are not undercut. The larger number of permanent first-order lateral roots, smaller height, and smaller diameter produce a better balanced undercut seedling that is capable of faster growth and better survival. Schultz and Thompson (1991) have demonstrated that *Quercus rubra* seedlings with six or more permanent first-order lateral roots greater than 1 mm in diameter will perform best in growth and survival when outplanted. Research by Teclaw and Isebrands (1993b), which is consistent with research by Schultz and Thompson (1991), demonstrated that seedlings with larger root systems can be used in regeneration plantings in the Lake States, USA.

Tree shelters

British foresters in the 1980's began utilizing translucent plastic tubular tree shelters to protect outplanted seedlings from browse damage. After several years of observation, foresters found sheltered seedlings exhibited greater growth than non-sheltered seedlings. A reduction in damage due to deer browse was considered to be a contributing factor, but it was also theorized that the shelters provided enhanced growing conditions, similar to those found in a greenhouse (Potter, 1991).

The British findings have prompted further research on the application and effects of tree shelters in the United States. Lantagne, et al. (1990), Zastrow and Marty (1991), and Minter, et al. (1992) have studied the effect of tree shelters on *Quercus rubra* seedlings planted in harvested forest openings. Lantange, et al. (1990) concluded that tree shelters used in a Michigan clearcut promoted height growth by improving micro-environments of *Quercus rubra* seedlings and reallocating growth from branches and stem diameter to shoot elongation for sheltered seedlings. Zastrow and Marty (1991) concluded that tree shelters promoted height growth and survival by improving micro-environments of *Quercus rubra* seedlings. Minter, et al. (1992) concluded that tree shelters promote increased height growth by increasing relative humidity, reducing plant transpiration losses, and increasing levels of CO_2. This height growth comes at the expense of diameter growth.

Clearcutting

Johnson, et al. (1989) have shown that clearcutting with herbicide control of competition may be the key to regenerating *Quercus rubra* in southwestern Wisconsin. They reported a case in southwest Wisconsin in which the understory of a mature stand was treated with 2,4,5-T in the two years prior to clearcutting. The second herbicide treatment coincided with a good acorn crop. By age 11, *Quercus rubra* accounted for about half the trees/ha and about a third the basal area. The average diameter at breast height (dbh) was 3.6 cm, with an average *Quercus rubra* dbh of three centimeters.

Based on the results of the clearcut, Johnson, et al. (1989) challenged two widely accepted tenets of *Quercus* management: (i) that advanced *Quercus* reproduction must be present before final harvest and (ii) that *Quercus* reproduction requires a long development period.

Success with clearcutting and natural regeneration is not always consistent (Johnson, et al., 1989). Loftis (1985) reported that a clearcutting and preherbicide treatment case in the southern Appalachian region failed. Ten years after the clearcut and preherbicide treatment, only 18 *Quercus rubra* trees/ha were present compared to 165 yellow poplar trees/ha and 155 trees/ha of other species.

Results with planting *Quercus rubra* seedlings in clearcuts have also been inconsistent. Johnson (1976) found very low success rates of interplanted *Quercus rubra* seedlings. After eight years, only 6-25% of the *Quercus rubra* interplanted were successful at reaching a given relative height. The relative height is the average height (adjusted for site) of *Quercus rubra* stump sprouts at age eight (Johnson, 1976). Teclaw and Isebrands (1993b) found that 1-0 *Quercus rubra* seedlings planted in clearcuts in the Lake States had less height growth on average then did 1-0 *Quercus rubra* seedlings underplanted in a shelterwood of 25% crown cover after three years.

Shelterwood treatments

Johnson, et al. (1989) reported on two successful cases of *Quercus rubra* regeneration using the shelterwood system. The first shelterwood case consisted of three shelterwood cuts in one stand; all three cuts were made from below. The three shelterwood cuts (stand age 84, 94 and 100) reduced the basal area from 28.2 sq m/ha at age 84 to 23.8 sq m/ha at age 100. Eleven years after the mature overstory was removed, *Quercus rubra* accounted for about a third of the trees/ha and about a quarter of the basal area. The average stand diameter at breast height was 5.3 cm, with an average *Quercus rubra* diameter at breast height of 4.6 cm.

The second shelterwood case involved an initial cut at stand age 91; basal area was reduced from 22 sq m/ha to 14.5 sq m/ha by thinning from below. Seventeen years after the mature overstory was removed, *Quercus rubra* accounted for more than half of the trees/ha and more than half of the basal area. The average stand diameter at breast height was 9.4 cm, with an average *Quercus rubra* diameter at breast height of 9.1 cm.

Teclaw and Isebrands (1991 and 1993ab) focused on developing adequate prescriptions for establishing artificial *Quercus rubra* regeneration in the Lake States. They suggest that underplanting quality nursery stock and overstory reduction are needed to establish artificial *Quercus rubra* regeneration in the Lake States. They have shown that after two years artificial *Quercus rubra* regeneration performed best in height growth when planted under 25% crown closure and no herbicide control of the competing vegetation.

STUDY OBJECTIVE AND HYPOTHESES

The objective of this study was to determine the impact of undercutting, herbicide control of competition, tree shelters, and removal of all non-*Quercus* trees greater than 2.54 cm diameter at breast height on establishment of underplanted, 1-0, *Quercus rubra* bare root stock. To understand what happens to underplanted, 1-0, *Quercus rubra* seedlings during the first five growing seasons in the field, the following hypotheses were tested.

Hypotheses

1. Survival, height growth, and basal diameter growth at ground-line, of underplanted, 1-0, *Quercus rubra* seedlings after five growing seasons are increased by using tree shelters.
2. Increased survival, height growth, and basal diameter growth at ground-line of underplanted, 1-0, *Quercus rubra* seedlings after the first five growing seasons are positively correlated with numbers of permanent, first-order, lateral roots greater than 1 mm in diameter.
3. Survival, height growth, and basal diameter growth at ground-line of underplanted, 1-0, *Quercus rubra* seedlings that were undercut at the nursery are greater than underplanted, 1-0, *Quercus rubra* seedlings that were not undercut at the nursery, after the first five growing seasons.
4. The ratio of red to far red light is reduced inside a white tree shelter compared to outside the tree shelter
5. The red to far red light ratio is reduced by increasing the amount of surrounding vegetation.

6. The amount of photosynthetic active radiation is reduced inside a white tree shelter compared to outside a white tree shelter.
7. An inverse relationship exists between percentage of full sunlight and basal area, making basal area a proxy for percentage of full sunlight.
8. A range of percent full sunlight, ratio of red to far red light, leaf area index, basal area, or percent stocking exists in which underplanted, 1-0, *Quercus rubra* seedlings respond rapidly in height growth, basal diameter growth at ground-line, and increase in survival during the first five growing seasons.
9. A range of combinations of percent full sunlight and the ratio of red to far red light exist in which underplanted, 1-0, *Quercus rubra* seedlings respond rapidly in height growth, basal diameter growth at ground-line, and increase in survival during the first five growing seasons.
10. Combining basal area, average stand diameter at breast height, and number of trees per hectare (5.08 cm or greater in diameter at breast height) will make a stronger proxy for percentage of full sunlight than just basal area.
11. A range of basal area, average stand diameter at breast height, and number of trees per hectare, 5.08 cm or greater in diameter at breast height, exist in which underplanted, 1-0, *Quercus rubra* seedlings respond rapidly in height growth, basal diameter growth at ground-line, and increase in survival during the first five growing seasons.
12. The average total height of underplanted, 1-0, *Quercus rubra* seedlings after the first five growing seasons will be greater than the height of competing vegetation.

STUDY AREA

This study was conducted in two upland, mixed, hardwood stands of 2.3 hectares each, located in Lucas County in south central Iowa. The stands are located on the McNay Research Farm at 40° 57' N and 93° 26' W and the Lucas Unit of the Stephens State Forest at 40° 57' N and 93° 30' W. The McNay site has a history of grazing until approximately 20 years ago. The Stephens sites has been managed by the Forestry Division of the Iowa Department of Natural Resources for approximately 40 years.

The average monthly amount of precipitation and the monthly amount of precipitation for 1991 through 1995 in Lucas County are presented in Table 1. The average temperature of Lucas County is approximately 50 ^{o}F; ranging from an avareage annual maximum temperature of approximately 97 ^{o}F to an average annual minimum temperature of approximately -11 ^{o}F. The normal seasonal cooling degree days (base = 65 ^{o}F) for Lucas County is 848 degree days. The 1991 to 1995 actual seasonal cooling degree days for Lucas County are presented in Table 2. On average the five years of the study were wetter and cooler than normal. However, 1994 was substantially drier than normal and followed an exceptionally wet year.

An initial inventory of both the McNay and Stephens stands were conducted in order to characterize the sites (Bardon, 1992). The initial inventories consisted of nine prism plots (Husch, et al., 1982) and nine mil-acre plots on the McNay site and 11 prism plots and 11 mil-acre plots on the Stephens site. The data collected, for *Quercus* and non-*Quercus*, from the prism plots included total basal area, species, diameter at breast height, and total height for each tree. Total number of seedlings by species was collected in the mil-acre plots.

Table 1. Average and 1991 (establishment year) through 1995 monthly and total amount of precipitation (cm) for Lucas county, Iowa based on data collected by Iowa Department of Agriculture

		Precipitation (cm)				
Month	Average	1991	1992	1993	1994	1995
January	2.67	2.01	1.88	3.10	1.85	1.45
February	2.82	0.53	4.65	2.29	3.96	1.37
March	6.25	10.26	3.91	7.67	0.89	7.47
April	9.25	22.2	15.62	8.13	7.52	11.89
May	10.06	10.24	3.40	14.89	5.21	23.04
June	12.29	6.63	1.60	8.86	12.29	8.56
July	9.75	5.99	26.34	44.55	5.82	9.04
August	10.18	5.84	4.88	21.03	3.96	4.95
September	11.28	3.23	31.88	9.98	6.15	6.58
October	6.58	9.60	0.89	2.77	4.01	3.05
November	4.42	10.08	11.05	2.18	6.93	4.83
December	2.87	3.78	3.89	1.19	3.56	1.24
Total	88.42	90.73	109.98	126.64	62.15	83.47

McNay Site

Based on the initial inventory, the average site index (base age = 50) (Husch, et al., 1982) for the McNay site was 20 m (SD = 6) with an average stocking level of 21.5 m^2/ha (SD = 3). The stand was considered fully stocked, with a 100% stocking level for the McNay site. Fully stocked indicates the range of stocking where trees can fully utilize the site. The stocking levels are based on stocking guides developed by Gingrich (1971). After cutting all non-*Quercus* trees, the average stocking level was 14.1 m^2/ha (SD = 2.3). By cutting out all non-*Quercus* trees, the stocking level was reduced to 48% for the McNay site.

Table 2. Establishment year (1991) through 1995 monthly and sum of seasonal cooling degree days for Lucas county, Iowa based on data collected by Iowa Department of Agriculture.

	Cooling degree days[a]				
	1991	1992	1993	1994	1995
January	0	0	0	0	0
February	0	0	0	0	0
March	4	0	0	0	0
April	13	1	0	14	0
May	134	46	19	29	1
June	231	83	150	206	148
July	298	190	255	203	301
August	246	102	280	208	383
September	151	58	24	79	52
October	9	6	12	18	4
November	0	0	0	0	0
December	0	0	0	0	0
Total	1086	486	740	757	889

[a]Seasonal norm is 848 degree days. Base = 65°F

Table 3 lists the major tree species, before and after cutting all non-*Quercus* trees 2.54 cm and greater in dbh, on the McNay site by average number of trees/ha, average basal area, average dbh, and percent composition. The McNay site was regenerating to: *Ulmus* species (280 seedlings /ha, SD = 130), *Quercus alba* L. (90 seedlings/ha, SD = 50), *Ostrya virginiana* (Mill.) K. Koch (50 seedlings/ha, SD = 30), and *Quercus rubra*, *Celtis occidentalis* L., and *Zanthoxylum americanum* Mill. (40 seedlings/ha, SD = 20). Figure 1 presents a distribution of average number of trees/hectare by 5 cm diameter class for

Quercus trees left on the McNay site and non-*Quercus* trees that were removed from the McNay site. Figure 2 presents a distribution of average basal area (m^2/ha) by 5 cm diameter class for *Quercus* trees left on the McNay site and non-*Quercus* trees that were removed from the McNay site.

Stephens Site

Based on the initial inventory, the average site index (base age = 50) for the Stephens site was 20 m (SD = 6) with an average stocking level of 19.2 m^2/ha (SD = 1.4). The stand was considered fully stocked, with a 75% stocking level for the Stephens site. After cutting all non-*Quercus* trees, the average stocking level was 15.9 m^2/ha (SD = 1.7), a reduction of 15% in the average stocking level for the Stephens site.

Table 3. Major tree species, before and after cutting all non-*Quercus* 2.54 cm and greater in diameter at breast height (dbh), on the McNay site by average dbh (cm), average number of trees/hectare, average basal area (m^2/ha) (BA), and percent composition (Comp) (Bardon, 1992)

	Before Cutting				After Cutting			
Species	dbh	trees /ha	BA	% Comp	dbh	trees /ha	BA	% Comp
Ulmus species	8	79	2.3	30				
Ostrya virginiana (Mill.) K. Koch	5	62	0.8	24				
Celtis occidentalis L.	5	41	0.5	16				
Carya species	7	31	0.8	12				
Gleditsia triacanthos L.	16	17	2.0	7				
Quercus alba L.	46	13	13.8	5	46	13	13.8	87
Maclura pomifera (Raf.) Schneid.	10	10	0.5	4				
Quercus rubra L.	15	2	0.3	1	15	2	0.3	13
Juglans nigra L.	46	1	0.5	1				
Total		256	21.5	100		15	14.1	100
SE of the Mean		64.7	1.7			3.5	2.3	

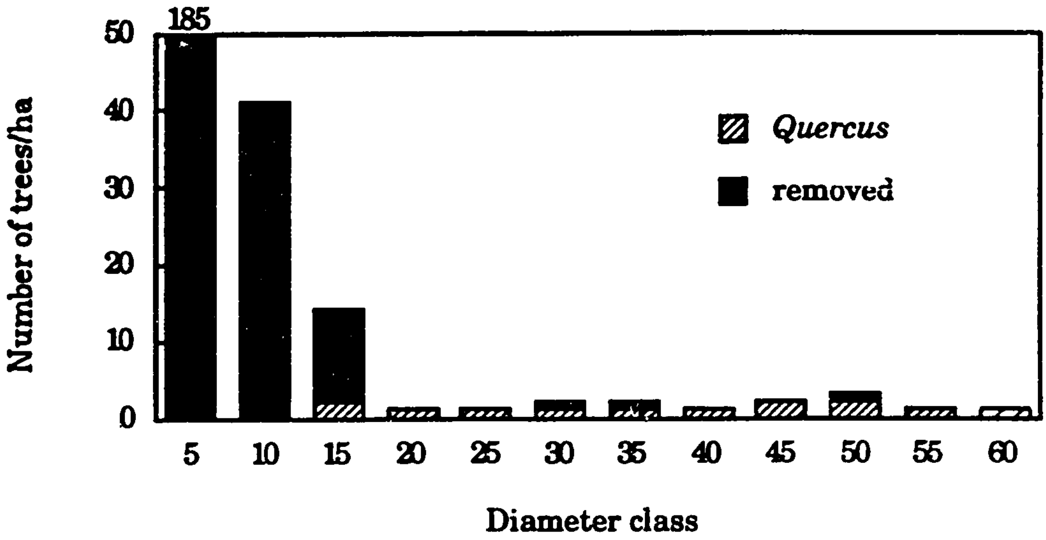

Figure 1. Average number of trees/hectare by 5 cm diameter class for *Quercus* trees left on the McNay site and non-*Quercus* trees removed from the McNay site (Bardon, 1992)

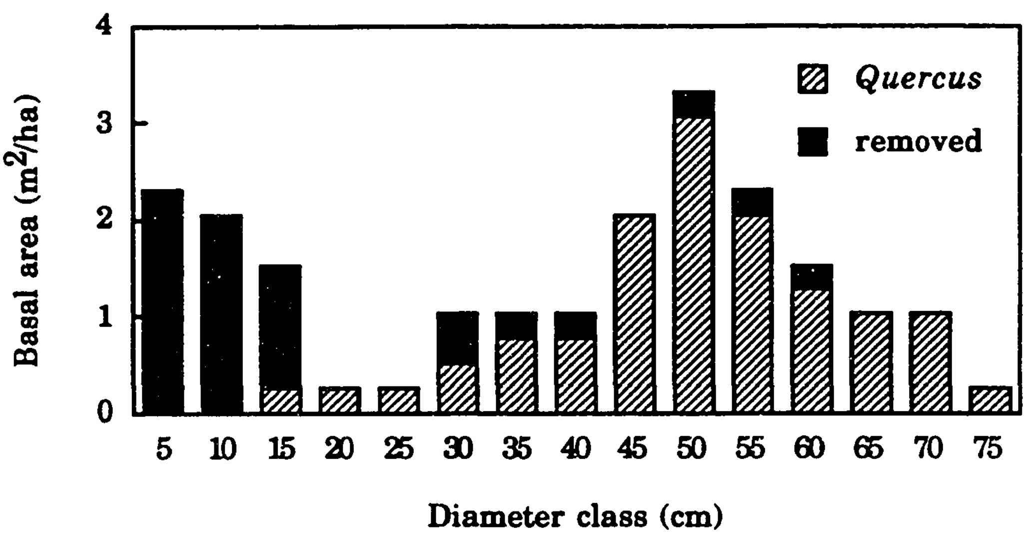

Figure 2. Average basal area (m^2/ha) by 5 cm diameter class for *Quercus* trees left on the McNay site and non-*Quercus* trees removed from the McNay site (Bardon, 1992)

The major tree species, before and after cutting all non-*Quercus* trees 2.54 cm and greater in dbh, on the Stephens site by average dbh, average number of trees/ha, average basal area (m^2/ha), and percent composition are presented in Table 4. The stand was regenerating to: *Cornus* specie (360 seedlings/ha, SD = 170), *Ulmus* species (200 seedlings/ha, SD = 40), *Quercus alba* L. (150 seedlings/ha, SD = 30), *Quercus rubra* . (90 seedlings/ha, SD = 30), *Carya* species and *Prunus serotina* Ehrh. (20 seedlings/ha, SD = 6), and *Celtis occidentalis* L. (9 seedlings/ha, SD = 3). Figure 3 presents a distribution of average number of trees/ha by 5 cm diameter class for *Quercus* trees left on the Stephens site and non-*Quercus* trees that were removed from the Stephens site. Figure 4 presents a distribution of average basal area (m^2/ha) by 5 cm diameter class for *Quercus* trees left on the Stephens site and non-*Quercus* trees that were removed from the Stephens site.

Soil information presented is based on an interum report of the soil survey that is in the process of being completed for Lucas county, Iowa (Fenton, 1992)

The McNay site soil types are approximately 90 percent Gara loam and 10 percent Armstrong loam formed in glacial till on uplands under natural prairie and deciduous trees. The soils have slow to moderate permeability, 15 to 20 cm/m of available water capacity, and approximately 2.5 to 3.5 percent surface layer organic matter. The depths to the low and high water tables are not as deep for the Armstrong loam, approximately 91.4 cm and 30.5 cm respectively. A management concern based on the soils is slight seedling mortality for the Gara loam and severe seedling mortality for the Armstrong loam soil.

Table 4. Major tree species, before and after cutting all non-*Quercus* trees 2.54 cm and greater in diameter at breast height (dbh), on the Stephens site by average dbh, average number of trees/hectare, average basal area (m^2/ha) (BA), and percent composition (Comp) (Bardon, 1992)

	Before Cutting				After Cutting			
Species	dbh	trees /ha	BA	% Comp	dbh	trees /ha	BA	% Comp
Quercus alba L.	26	31	9.6	32	26	31	9.6	67
Carya species	15	25	2.7	27				
Prunus serotina Ehrh.	6	19	0.4	20				
Quercus rubra L.	29	15	6.3	17	29	15	6.3	33
Ulmus species	10	4	0.2	4				
Total		95	19.2	100		46	15.9	100
SE of the Mean		19	1.4			7	1.7	

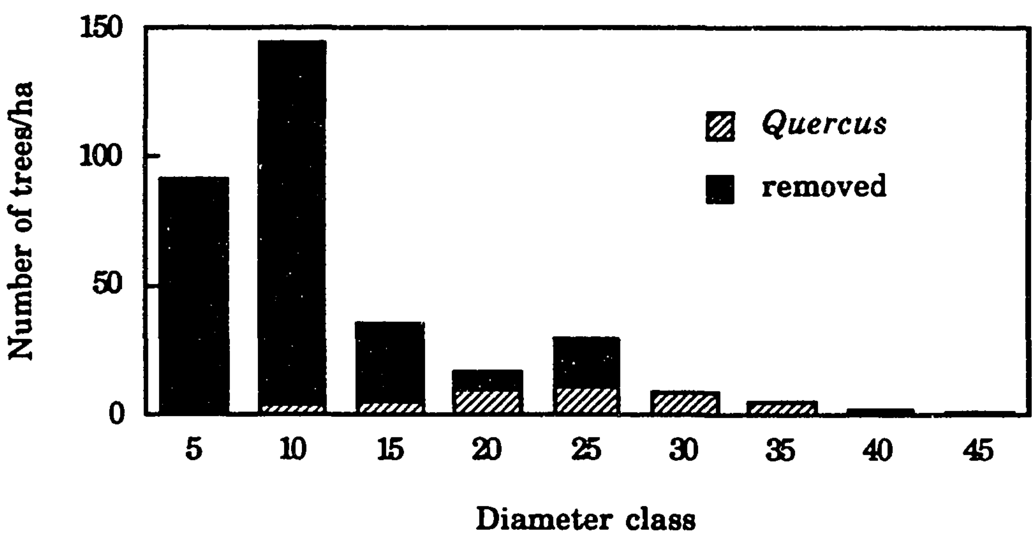

Figure 3. Average number of trees/hectare by 5 cm diameter class for *Quercus* trees left on and non-*Quercus* trees removed from the Stephens site (Bardon, 1992)

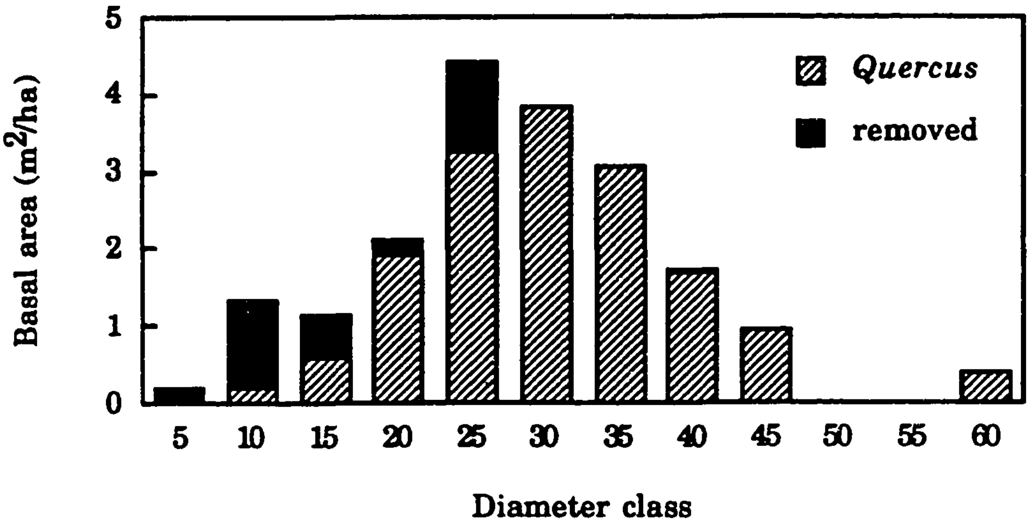

Figure 4. Average basal area (m^2/ha) by 5 cm diameter class for *Quercus* trees left on and non-*Quercus* trees removed from the Stephens site (Bardon, 1992)

The Stephens site soil types are approximately 45 percent Welter silt loam, 45 percent Lindley loam, and 10 percent Keswick loam formed in glacial till and loess on uplands under deciduous trees. The soils have slow to moderate permeability, 10-20 cm/m of available water capacity, and approximately 1.5 to 3.5 percent surface layer organic matter. The depths to the low and high water tables are relatively deep for the Lindley loam, approximately 182.9 cm for both The depths to the low and high water tables are moderately deep for the Welter silt loam, approximately 121.9 cm and 61 cm respectively. The depths to the low and high water tables are not as deep for the Keswick loam, 91.4 cm and 30.5 cm respectively. A management concern based on these soils is severe seedling mortality for the Welter silt loam and slight seedling mortality for the Lindley and Keswick loam soils.

MATERIALS AND METHODS

Square blocks, 46 m on each side, were laid out in August, 1990 at both sites (Figure 5). After the blocks were laid out, seven blocks at the McNay site and eight blocks at the Stephens site were randomly allocated to one of two whole-block treatments: i) cut and remove all non-*Quercus* trees and ii) spray the understory with herbicide before removing all non-*Quercus* trees. The sprayed blocks received a foliar application of glyphosate herbicide at a rate of 0.5 l/ha using a backpack sprayer, in August 1990. The herbicide was applied to kill all material less than 2.5 cm dbh. In the cutting treatment blocks, all non-*Quercus* trees with diameters greater than 2.5 cm dbh were cut during the winter of 1990-1991 using a chainsaw; the stumps of those trees were treated with picloram to prevent resprouting. The cut trees were removed from the site, during the winter of 1990-1991, by hand carrying and dragging the trees to a chipper located on the site. The trees were chipped into a wagon and the chips were then hauled from the site.

During the spring of 1991, treatments of underplanting undercut seedlings and underplanting seedlings that were not undercut were randomly assigned to one of four sub-plots (15.2 x 15.2 m each) in each block (Figure 6). These sub-plots were established in each block (Figure 5) to compare undercut and not undercut seedlings. The outer 7.6 m in each block was a buffer strip, had the same stand characteristics, and received the same whole-plot treatment as the block.

All 1-0 *Quercus rubra* seedlings used in this study were provided by the Department of Natural Resources state nursery in Ames, Iowa. The undercut seedlings were undercut at a depth of 12.7-15.24 cm in early August, 1990. All seedlings were lifted in early April, 1991.

Before underplanting, the undercut and not undercut seedlings were graded by the number of permanent, first-order, lateral roots greater than 1 mm in basal diameter at the tap root. The seedlings were separated into the following root number classes: 0-4, 5-9, and 10 or more permanent, first-order, lateral roots greater than 1 mm. Permanent, first-order, lateral root greater than 1 mm that originated from the callus wound of undercut seedlings were also included in meeting the separation criteria.

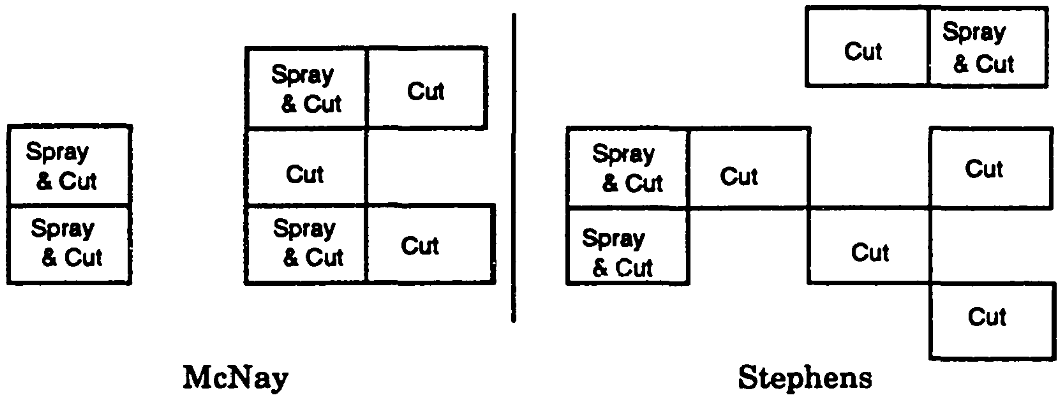

Figure 5. Block layout for the McNay and Stephens sites (Bardon, 1992)

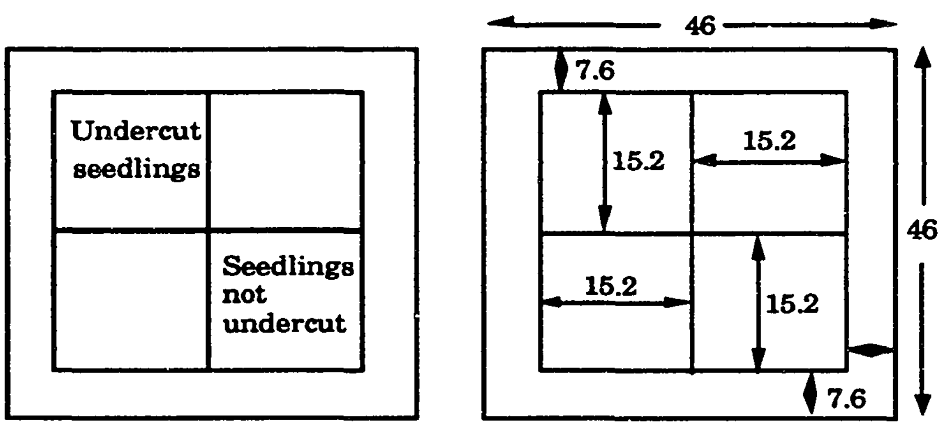

Figure 6. Sub-plot layout of underplanted, 1-0, *Quercus rubra* seedlings and plot dimensions in meters (Bardon, 1992)

As the seedlings were being graded, they were assigned a color coded numbered tag. The tags provided a way to keep track of the seedlings. The tags were placed loosely around the lower stem of the seedlings. Initial height of each seedling was measured from the root collar to the tip of the terminal bud on the main leader and initial basal diameter was measured just above the root collar.

In each area to be underplanted with *Quercus rubra* seedlings (Figure 6), ten seedlings in each of the root number classes were hand planted using a two-man, gas powered auger. The auger bit used was 20.5 cm in diameter.

The underplanted seedlings were planted in 3 rows, with 10 seedlings per row at a spacing of 1.2 m between seedlings and 3 m between rows. Each root number class was planted in a randomly assigned row. The spacing between rows and seedlings was based on the size of the area that was underplanted. Sometimes, stumps and trees present on the sites affected seedling placement.

Once the seedlings were underplanted, white tree shelters that are approximately 122 cm tall were randomly assigned to the first five seedlings or the second five seedlings in each row. The shelters were placed on the seedlings at the time of planting and were placed according to the directions provided with the shelters. Tubex brand of tree shelters were used based on their availability, no endorsement of this brand is implied by the author.

Mil-acre plots were used to observe competition. A mil-acre plot was established at 3.8, 7.6, and 11.4 m along a transect in the middle of each plot. The mil-acre plots coincide with the middle planting row in each underplanted seedling treatment. The center of each mil-acre plot was permanently marked with a PVC stake. In each mil-acre plot the species and height of each individual woody plant was recorded annually.

To observe overstory impact, prism plots were established at each of the underplanted seedlings in April and May, 1994. At each of the underplanted seedlings, a 10-factor prism was used to determine the basal area that corresponded with each underplanted seedling. For each tree counted in the prism plot, diameter at breast height was recorded.

A test to assess differences in red to far red light ratio inside and outside a white tree shelter was performed on June 6, 1995 from 1346h to 1446h as a basis for an experiment in the field starting June 12, 1995. An SKR 1800 two channel light sensor (Skye-Probetech, Perkasie, PA) was used to measure the ratio of red to far red light.

Ten replications were measured of the red to far red light ratio inside and outside of a white tree shelter, under three different canopy covers (open, partial cover, and complete cover). Each replication consisted of four readings, with the sensor held horizontal, measured inside the tree shelter and four readings measured outside the tree shelter at the four cardinal directions; 0 degrees (north), 90 degrees (east), 180 degrees (south), and 270 degrees (west).

To observe understory impact, red to far red light ratios were measured on June 12, 13, 15, and 23, 1995 at all 1-0 underplanted seedlings on the McNay site and the Stephens site using the SKR 1800 two channel light sensor. The sensor was held horizontal for all measurements. The light ratio was measured at the four cardinal directions at the top of the crown (last known height if the seedling was dead) of each seedling. The sensing surface was pointed to the four cardinal directions. For the seedlings with tree shelters, the light ratio was measured inside the tree shelter. The light ratio was measured from two hours before solar noon till two hours after solar noon.

Photosynthetic active radiation (PAR) was measured twice at the McNay site and twice at the Stephens site. The first readings were taken on June 19-23, 28-30 and July 2-3, 1995 at the McNay site and the Stephens site. The second measurement period occurred August 17-18, 21-22, 24, 28-31, and September 1, 1995.

A LI-COR 190SA quantum sensor with a LI-COR 1000 data logger (LI-COR, Lincoln, NE) were placed in full sunlight and at the top of the crown (last known height if the seedling was dead) of 120 underplanted 1-0 red oak seedlings that had 10 or more permanent, first-order, lateral roots at the time of planting; 60 seedlings on the McNay site and 60 seedlings on the Stephens site. The 60 *Quercus rubra* seedlings were divided into 30 seedlings that were not undercut in the nursery; 15 with tree shelters and 15 without tree shelters, and 30 seedlings that were undercut in the nursery; 15 with tree shelters and 15 without tree shelters. The quantum sensor was attached to the south side of a PVC pipe or bamboo stake with a clamp and leveled. PAR was measured from two hours before solar noon till two hours after solar noon at each of the 120 seedlings. Readings were taken every second and then averaged for the one minute period. The one minute average was then recorded by the LI-COR 1000 data logger. In order to measure PAR at all 120 seedlings, 12 different seedlings were measured each day during the two measurement periods. Seedlings were selected to provide representation throughout the range of overstory basal areas (4.6 to 23.0 m^2/ha). Full sunlight readings measured in the open were collected according to the U.S. Forest Service guidelines (Isebrands, et al., 1994b). Percent full sunlight was calculated based on the proportion of the total amount of sunlight measured at the seedling and the total amount of sunlight measured in the open.

PAR readings were measured to develop a relationship between PAR measured outside a tree shelter and PAR measured inside a tree shelter. PAR readings were measured twice; from 0615h to 2130h central daylight time (CDT) on July 14, 1995 and from 0900h to 2045h CDT on August 11, 1995, inside and outside a white tree shelter. The tree shelter was set up in a clearing approximately 0.3 ha in size. Two LI-COR 190SA quantum sensors with a LI-COR 1000 data logger were used to measure PAR inside and outside a white tree shelter. Readings were taken once every second then averaged over a minute time period. The average for the one minute period was then recorded by the LI-COR 1000 data logger. One sensor was placed inside a shelter at approximately 25 cm from the bottom. The second sensor was placed approximately 1 m south of the shelter and at approximately the same height as the sensor inside the shelter.

A Sunfleck PAR Ceptometer, model SF-80 (Decagon Devices, Inc., Pullman, WA) was used to determine overstory leaf area index (LAI) at all 1-0 *Quercus rubra* seedlings underplanted on the McNay site and the Stephens site. The ceptometer measures PAR which was used to determine the LAI. Separate ceptometer measurements were also performed on the 120 seedlings being measured with the LI-COR 190SA quantum sensor on the same day each seedling was measured with the LI-COR sensor. To take a measurement with the ceptometer, the ceptometer was held level at approximately 1.5 m high. The ceptometer was then rotated clock wise for 360 degrees. The ceptometer records the average PAR along the bar every second. A minimum of 30 readings were averaged per sweep. Sweeps were measured from two hours before solar noon till two hours after solar noon.

Statistical analyses were done using analysis of variance, Pearson's correlation analysis, regression analysis, response surface techniques, and multivariate analysis (SAS Institute Inc., 1988).

The following definitions are presented to understand how data were analyzed. Annual height growth, basal diameter growth, and mortality for 1991 are based on all 900 underplanted seedlings. Annual growth for 1991 is the difference in total height or total basal diameter measured at the end of the 1991 growing season and the initial height and initial basal diameter. The initial height of each seedling is the distance from the terminal bud to the root collar at the time the seedling was lifted and root graded. Initial basal diameter is the diameter of the seedling measured just above the root collar at the time the seedling was lifted and root graded. Percent mortality is based on the number of seedlings dead at the end of the 1991 growing season. A seedling was dead at the end of the 1991 growing season if the seedling had zero live height at the end of the 1991 and 1992 growing seasons. Annual growth, mortality, and dieback for 1992 through 1995 are for seedlings that were alive at the end of the pervious growing season. For example, if a seedling had zero live height at the end of 1991 and 1992 growing seasons it was considered dead and was not used in calculating growth, mortality, or dieback in 1992. Total height growth is the difference between the total height of the seedling at the end of 1995 and the initial height of the seedling at the time of lifting from the nursery. Total basal diameter growth is the difference between the diameter at the ground-level in 1995 and the initial diameter of the seedling at the time of lifting from the nursery. Total mortality is the percentage of the original 900 underplanted seedlings dead after five growing seasons.

The results presented are based on data collected on August 6-8, September 10-12 and 24-26, 1991; September 14, 24-25, and 28-29; October 8-9, 1992; September 4-6 and 9, 1993; September 4-5, 17-18, and 23-24, 1994; June 19-23, and 28-30; and July 2-3; August 17-18, 21-22, 24, and 28-31; and September 1, 11-13, and 26-28, 1995.

RESULTS

Underplanted Seedling Performance

Analysis of the data indicated that there are statistical differences in the various seedling treatments that impact growth, mortality, and dieback for underplanted seedlings at the McNay and Stephens sites. These statistical differences in the various seedling treatments did not occur in the same growing season or simultaneously at both locations (Table 5), indicating that these differences are not truly biologically significant. Therefore, the results of the analysis will not be presented.

Tree shelters appear to be the exception to the above, but only for growth and mortality. Shelters altered annual height growth (Figure 7A and Figure 8A), annual basal diameter growth (Figure 7B and Figure 8B) and annual mortality (Figure 7C, Figure 8C, and Table 6) for all five growing seasons. To help make it easier to interpret figure 7C and 8C, percent mortality is based on the number of live seedlings at the beginning of each growing season. Also, the number of seedlings that died each year can be seen in Table 6. The analysis of variance of the tree shelter treatment on annual height growth, annual basal diameter growth, and annual mortality are presented in Tables 7-36.

From 1991 to 1993 sheltered seedlings grew as much or more in height growth than non-sheltered seedlings at the McNay and Stephens sites. By the end of the 1993 growing season, sheltered seedlings at the McNay and Stephens sites had 110 percent and 243 percent greater growth respectively compared to non-sheltered seedlings. In 1994 and 1995, non-sheltered seedlings grew as much or more in height growth than sheltered seedlings at the McNay and Stephens sites. By the end of the 1995 growing season,

Table 5. Summary of annual and total treatment effects on height growth (h), basal diameter growth (c), mortality (m), and dieback (d) for the McNay and Stephens sites. Dieback was measured annually from 1992 through 1995. S=spray, T=undercut, R=root class, SH=treeshelter

	1991			1992				1993				1994				1995				total			
	h	c	m	h	c	m	d	h	c	m	d	h	c	m	d	h	c	m	d	h	c	m	d
McNay																							
S																							
T																							
TxS																							
R	a			b	a		a	a		b									a	a	a		
RxS				a	a		a		a											b	ba		
RxT				b	a		a										b						
RxTxS																							
SH	b	a		b	b		b	b		a		b	b		b	b	b		b	b	b		
SHxS				a			b	a							a		a	a			a		
SHxT	a			a																			
SHxSxT							a		a														
SHxR				a																	a		
SHxRxS																							
SHxTxR		a																					
SHxTxRxS																							
Stephens																							
S											a		b							a	a	a	
T		b																			a		
TxS																							
R	b													a					b				
RxS				a	a	a	a							a			a	a					
RxT	a							a	b						a					ba			a
RxTxS												b	a				a					a	
SH	a		a	a			a	a		b		b	b	b	b	b	b	b			b	b	b
SHxS							b					a			a					b		a	
SHxT												a	b	b			a				a		b
SHxSxT																							
SHxR																							
SHxRxS													b										
SHxTxR																							
SHxTxRxS										b			b	b				b					

[a]significant at the 0.05 level
[b]significant at the 0.01 level

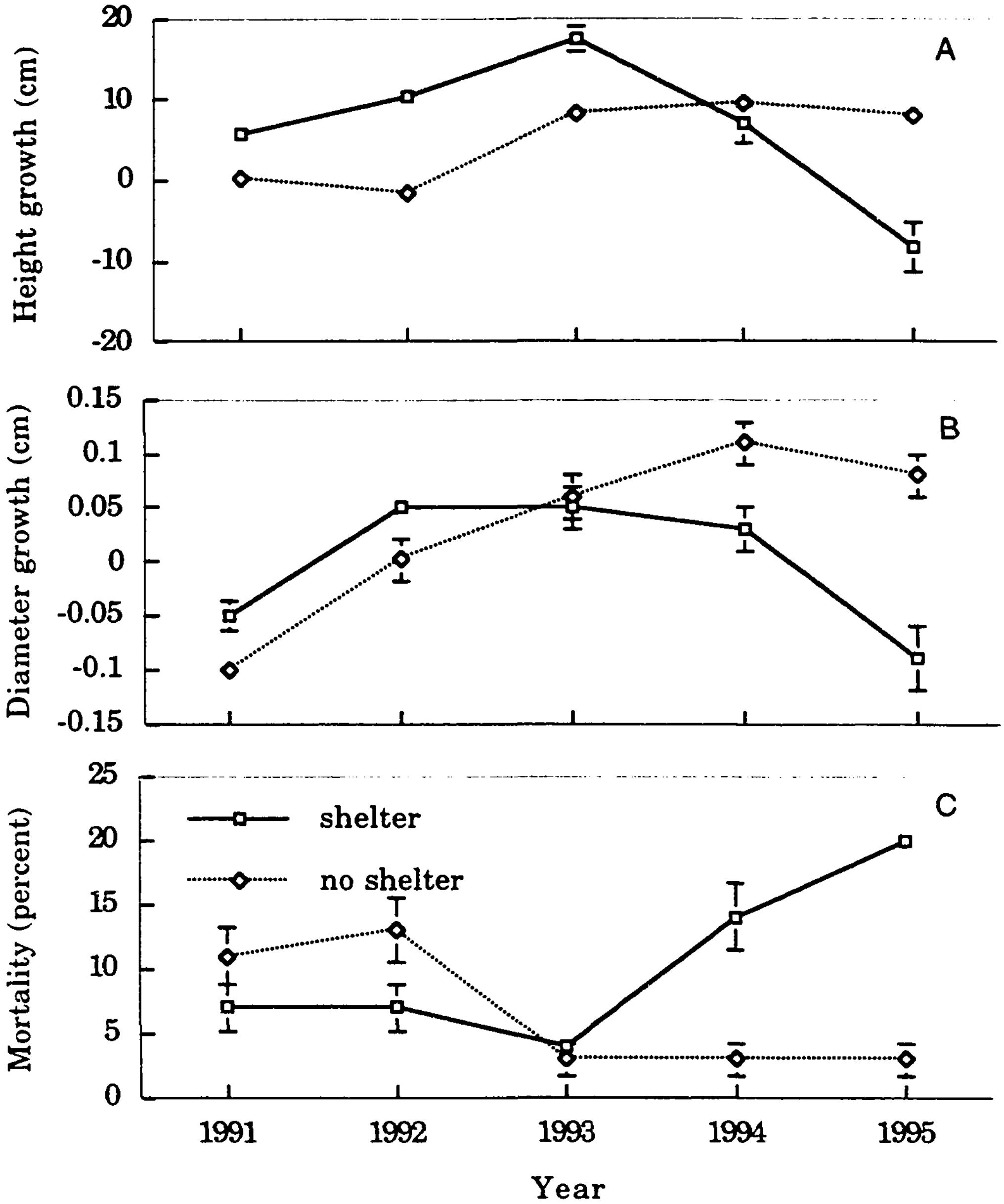

Figure 7. Annual hieght growth, basal diameter growth, and mortality for underplanted, sheltered and non-sheltered *Quercus rubra* L. seedlings at the McNay site

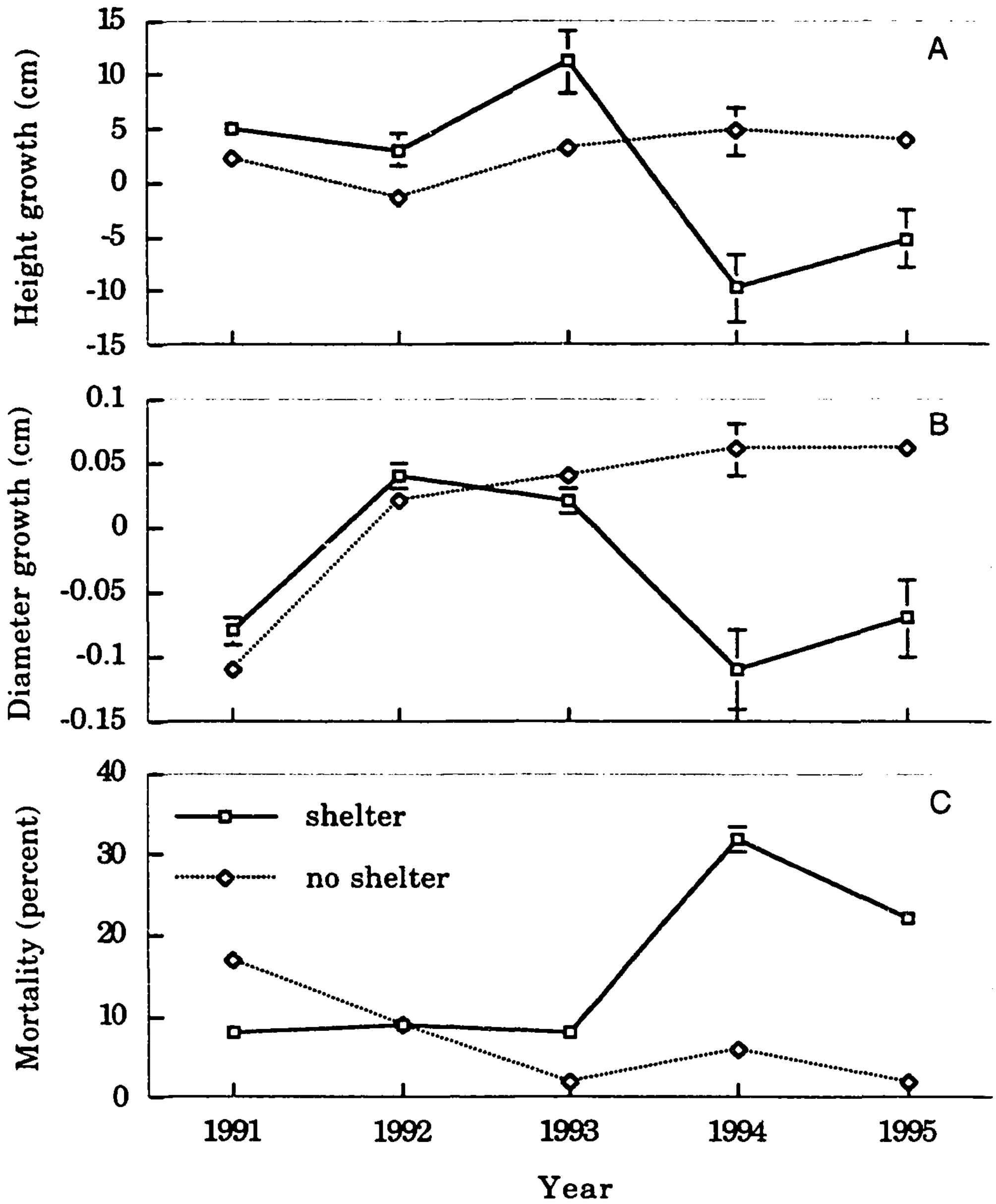

Figure 8. Annual height growth, basal diameter growth, and mortality for underplanted, sheltered and non-sheltered *Quercus rubra* L. seedlings at the Stephens site

Table 6. Number of underplanted *Quercus rubra* seedlings that died annually for the McNay and Stephens site, separated by shelter.

	Year				
	1991	1992	1993	1994	1995
McNay					
Shelter	15	13	8	25	32
Non-shelter	24	24	5	4	4
Stephens					
Shelter	20	20	15	60	30
Non-shelter	40	19	4	10	4

Table 7. Anova of 1991 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	3185.9	3185.9	31.61**
SxSH	1	194.8	194.8	1.93
TxSH	1	414.1	414.1	4.11*
TxSxSH	1	69.8	69.8	0.69
RxSH	2	435.6	217.8	2.16
RxSxSH	2	160.1	80.1	0.79
RxTxSH	2	567.7	283.9	2.82
RxTxSxSH	2	122.3	61.2	0.61
BxRxTxSH(S)	30	3023.7	100.8	

* significant at the 0.05 level
** significant at the 0.01 level

Table 8. Anova of 1991 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	833.2	833.2	4.62*
SxSH	1	5.3	5.3	0.03
TxSH	1	218.4	218.4	1.21
TxSxSH	1	200.7	200.7	1.11
RxSH	2	113.2	56.6	0.31
RxSxSH	2	180.9	90.5	0.50
RxTxSH	2	256.0	128.0	0.71
RxTxSxSH	2	181.7	90.9	0.50
BxRxTxSH(S)	36	6492.9	180.4	

* significant at the 0.05 level
** significant at the 0.01 level

Table 9. Anova of 1991 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.20	0.20	5.77*
SxSH	1	0.05	0.05	1.30
TxSH	1	0.00	0.00	0.01
TxSxSH	1	0.10	0.10	2.83
RxSH	2	0.06	0.03	0.83
RxSxSH	2	0.00	0.00	0.04
RxTxSH	2	0.16	0.08	2.23
RxTxSxSH	2	0.09	0.04	1.21
BxRxTxSH(S)	30	1.06	0.04	

* significant at the 0.05 level
** significant at the 0.01 level

Table 10. Anova of 1991 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.12	0.12	2.33
SxSH	1	0.05	0.05	1.00
TxSH	1	0.00	0.00	0.04
TxSxSH	1	0.03	0.03	0.53
RxSH	2	0.03	0.02	0.34
RxSxSH	2	0.03	0.01	0.26
RxTxSH	2	0.15	0.07	1.40
RxTxSxSH	2	0.06	0.03	0.57
BxRxTxSH(S)	36	1.86	0.05	

* significant at the 0.05 level
** significant at the 0.01 level

Table 11. Anova of 1991 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.20	0.20	3.16
SxSH	1	0.00	0.00	0.00
TxSH	1	0.07	0.07	1.13
TxSxSH	1	0.24	0.24	3.79
RxSH	2	0.31	0.16	2.51
RxSxSH	2	0.05	0.02	0.38
RxTxSH	2	0.46	0.23	3.66x
RxTxSxSH	2	0.08	0.04	0.67
BxRxTxSH(S)	30	1.87	0.06	

* significant at the 0.05 level
** significant at the 0.01 level

Table 12. Anova of 1991 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.65	0.65	5.82*
SxSH	1	0.11	0.11	0.98
TxSH	1	0.15	0.15	1.36
TxSxSH	1	0.38	0.38	3.38
RxSH	2	0.36	0.18	1.60
RxSxSH	2	0.23	0.11	1.02
RxTxSH	2	0.15	0.07	0.66
RxTxSxSH	2	0.39	0.19	1.75
BxRxTxSH(S)	36	4.00	0.11	

* significant at the 0.05 level
** significant at the 0.01 level

Table 13. Anova of 1992 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	12988.9	12988.9	45.75**
SxSH	1	1159.6	1159.6	4.08
TxSH	1	1480.8	1480.8	5.22*
TxSxSH	1	924.5	924.5	3.26
RxSH	2	2257.5	1128.7	3.98*
RxSxSH	2	224.3	112.2	0.40
RxTxSH	2	161.4	80.7	0.28
RxTxSxSH	2	124.8	62.4	0.22
BxRxTxSH(S)	30	8516.7	283.9	

* significant at the 0.05 level
** significant at the 0.01 level

Table 14. Anova of 1992 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	2878.3	2878.3	5.50*
SxSH	1	1488.5	1488.5	2.85
TxSH	1	18.1	18.1	0.03
TxSxSH	1	60.8	60.8	0.12
RxSH	2	1203.9	601.9	1.15
RxSxSH	2	51.9	25.9	0.05
RxTxSH	2	662.3	331.2	0.63
RxTxSxSH	2	700.7	350.4	0.67
BxRxTxSH(S)	36	18827.9	522.9	

* significant at the 0.05 level
** significant at the 0.01 level

Table 15. Anova of 1992 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.22	0.22	7.05*
SxSH	1	0.07	0.07	2.21
TxSH	1	0.06	0.06	1.76
TxSxSH	1	0.01	0.01	0.53
RxSH	2	0.16	0.08	2.48
RxSxSH	2	0.01	0.00	0.11
RxTxSH	2	0.00	0.00	0.05
RxTxSxSH	2	0.09	0.05	1.55
BxRxTxSH(S)	30	0.94	0.03	

* significant at the 0.05 level
** significant at the 0.01 level

Table 16. Anova of 1992 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.12	0.12	1.77
SxSH	1	0.04	0.04	0.64
TxSH	1	0.01	0.01	0.17
TxSxSH	1	0.09	0.09	1.38
RxSH	2	0.10	0.05	0.80
RxSxSH	2	0.06	0.03	0.44
RxTxSH	2	0.30	0.15	2.30
RxTxSxSH	2	0.22	0.11	1.66
BxRxTxSH(S)	36	2.37	0.07	

* significant at the 0.05 level
** significant at the 0.01 level

Table 17. Anova of 1992 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.34	0.34	3.82
SxSH	1	0.20	0.20	2.27
TxSH	1	0.32	0.32	3.53
TxSxSH	1	0.04	0.04	0.47
RxSH	2	0.45	0.22	2.49
RxSxSH	2	0.09	0.05	0.53
RxTxSH	2	0.16	0.08	0.88
RxTxSxSH	2	0.20	0.10	1.14
BxRxTxSH(S)	30	2.69	0.09	

* significant at the 0.05 level
** significant at the 0.01 level

Table 18. Anova of 1992 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.02	0.02	0.11
SxSH	1	0.18	0.18	1.21
TxSH	1	0.06	0.06	0.39
TxSxSH	1	0.09	0.09	0.65
RxSH	2	0.12	0.07	0.42
RxSxSH	2	0.09	0.05	0.31
RxTxSH	2	0.11	0.06	0.38
RxTxSxSH	2	0.27	0.14	0.92
BxRxTxSH(S)	36	5.23	0.15	

* significant at the 0.05 level
** significant at the 0.01 level

Table 19. Anova of 1993 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	6570.3	6570.3	27.69**
SxSH	1	922.9	922.9	3.89
TxSH	1	339.9	339.9	1.43
TxSxSH	1	259.9	259.9	1.10
RxSH	2	924.9	462.5	1.95
RxSxSH	2	412.1	206.0	0.87
RxTxSH	2	539.0	269.5	1.14
RxTxSxSH	2	87.28	43.6	0.18
BxRxTxSH(S)	30	7119.3	237.3	

* significant at the 0.05 level
** significant at the 0.01 level

Table 20. Anova of 1993 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	4189.9	4189.9	4.64*
SxSH	1	1026.8	1026.8	1.14
TxSH	1	113.6	113.6	0.13
TxSxSH	1	698.4	698.4	0.77
RxSH	2	911.3	455.7	0.50
RxSxSH	2	35.7	17.9	0.02
RxTxSH	2	4889.9	2444.9	2.71
RxTxSxSH	2	805.5	402.7	0.45
BxRxTxSH(S)	36	32496.2	902.7	

* significant at the 0.05 level
** significant at the 0.01 level

Table 21. Anova of 1993 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.00	0.00	0.00
SxSH	1	0.00	0.00	0.12
TxSH	1	0.08	0.08	2.66
TxSxSH	1	0.15	0.15	4.93*
RxSH	2	0.10	0.05	1.74
RxSxSH	2	0.11	0.06	1.74
RxTxSH	2	0.17	0.08	2.81
RxTxSxSH	2	0.03	0.02	0.53
BxRxTxSH(S)	30	0.91	0.03	

* significant at the 0.05 level
** significant at the 0.01 level

Table 22. **Anova of 1993 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block**

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.05	0.05	2.17
SxSH	1	0.00	0.00	0.02
TxSH	1	0.00	0.00	0.00
TxSxSH	1	0.04	0.04	1.53
RxSH	2	0.01	0.01	0.28
RxSxSH	2	0.11	0.06	2.16
RxTxSH	2	0.02	0.01	0.47
RxTxSxSH	2	0.35	0.17	7.15**
BxRxTxSH(S)	36	0.88	0.02	

* significant at the 0.05 level
** significant at the 0.01 level

Table 23. **Anova of 1993 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block**

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.00	0.00	0.03
SxSH	1	0.01	0.01	0.48
TxSH	1	0.02	0.02	0.61
TxSxSH	1	0.05	0.05	2.09
RxSH	2	0.07	0.03	1.35
RxSxSH	2	0.03	0.01	0.51
RxTxSH	2	0.00	0.00	0.06
RxTxSxSH	2	0.03	0.02	0.58
BxRxTxSH(S)	30	0.78	0.03	

* significant at the 0.05 level
** significant at the 0.01 level

Table 24. Anova of 1993 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.30	0.30	8.01**
SxSH	1	0.05	0.05	1.26
TxSH	1	0.02	0.02	0.53
TxSxSH	1	0.03	0.03	0.85
RxSH	2	0.03	0.01	0.35
RxSxSH	2	0.17	0.08	2.19
RxTxSH	2	0.12	0.06	1.63
RxTxSxSH	2	0.06	0.03	0.85
BxRxTxSH(S)	36	1.38	0.04	

* significant at the 0.05 level
** significant at the 0.01 level

Table 25. Anova of 1994 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	156.4	156.4	0.30
SxSH	1	384.8	384.8	0.74
TxSH	1	131.7	131.7	0.25
TxSxSH	1	737.4	737.4	1.43
RxSH	2	527.7	263.9	0.51
RxSxSH	2	67.9	33.9	0.07
RxTxSH	2	338.1	169.1	0.33
RxTxSxSH	2	1164.8	582.4	1.13
BxRxTxSH(S)	29	14980.6	516.6	

* significant at the 0.05 level
** significant at the 0.01 level

Table 26. Anova of 1994 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	13223.9	13223.9	26.13**
SxSH	1	2899.7	2899.7	5.73*
TxSH	1	3095.2	3095.2	6.12*
TxSxSH	1	84.3	84.3	0.17
RxSH	2	821.9	410.9	0.81
RxSxSH	2	2961.9	1480.9	2.93
RxTxSH	2	136.7	68.4	0.14
RxTxSxSH	2	6171.1	3085.5	6.10**
BxRxTxSH(S)	36	18220.5	506.1	

* significant at the 0.05 level
** significant at the 0.01 level

Table 27. Anova of 1994 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.51	0.51	7.22**
SxSH	1	0.00	0.00	0.05
TxSH	1	0.00	0.00	0.01
TxSxSH	1	0.09	0.09	1.20
RxSH	2	0.16	0.08	1.11
RxSxSH	2	0.28	0.14	2.00
RxTxSH	2	0.32	0.16	2.28
RxTxSxSH	2	0.26	0.13	1.82
BxRxTxSH(S)	29	2.06	0.07	

* significant at the 0.05 level
** significant at the 0.01 level

Table 28. Anova of 1994 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	2.20	2.20	41.40**
SxSH	1	0.14	0.14	2.75
TxSH	1	0.48	0.48	8.97**
TxSxSH	1	0.04	0.04	0.77
RxSH	2	0.01	0.01	0.09
RxSxSH	2	0.51	0.26	4.84*
RxTxSH	2	0.13	0.06	1.21
RxTxSxSH	2	0.24	0.12	2.28
BxRxTxSH(S)	36	1.92	0.05	

* significant at the 0.05 level
** significant at the 0.01 level

Table 29. Anova of 1994 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	0.83	0.83	10.03**
SxSH	1	0.06	0.06	0.75
TxSH	1	0.00	0.00	0.01
TxSxSH	1	0.00	0.00	0.00
RxSH	2	0.00	0.00	0.02
RxSxSH	2	0.17	0.09	1.02
RxTxSH	2	0.14	0.07	0.82
RxTxSxSH	2	0.31	0.15	1.85
BxRxTxSH(S)	29	2.41	0.08	

* significant at the 0.05 level
** significant at the 0.01 level

Table 30. Anova of 1994 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	5.94	5.94	58.94**
SxSH	1	0.31	0.31	3.09
TxSH	1	0.84	0.84	8.31**
TxSxSH	1	0.00	0.00	0.04
RxSH	2	0.25	0.13	1.27
RxSxSH	2	0.53	0.27	2.66
RxTxSH	2	0.52	0.26	2.59
RxTxSxSH	2	1.34	0.67	6.66**
BxRxTxSH(S)	36	3.63	0.10	

* significant at the 0.05 level
** significant at the 0.01 level

Table 31. Anova of 1995 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	17576.8	17576.8	17.62**
SxSH	1	671.9	671.9	0.67
TxSH	1	188.3	188.3	0.19
TxSxSH	1	0.05	0.05	0.00
RxSH	2	1695.4	847.7	0.85
RxSxSH	2	492.4	246.2	0.25
RxTxSH	2	1354.7	677.3	0.68
RxTxSxSH	2	833.6	416.8	0.42
BxRxTxSH(S)	29	28932.7	997.7	

* significant at the 0.05 level
** significant at the 0.01 level

Table 32. Anova of 1995 growing season height growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	5957.1	5957.1	9.20**
SxSH	1	72.6	72.6	0.11
TxSH	1	684.4	684.4	1.06
TxSxSH	1	636.2	636.2	0.98
RxSH	2	771.8	385.8	0.60
RxSxSH	2	897.2	448.6	0.69
RxTxSH	2	962.1	481.1	0.74
RxTxSxSH	2	2029.6	1014.8	1.57
BxRxTxSH(S)	33	21379.2	647.9	

* significant at the 0.05 level
** significant at the 0.01 level

Table 33. Anova of 1995 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	1.86	1.86	17.55**
SxSH	1	0.57	0.57	5.39*
TxSH	1	0.09	0.09	0.88
TxSxSH	1	0.05	0.05	0.50
RxSH	2	0.32	0.16	1.50
RxSxSH	2	0.08	0.04	0.40
RxTxSH	2	0.03	0.01	0.14
RxTxSxSH	2	0.26	0.13	1.20
BxRxTxSH(S)	29	3.08	0.11	

* significant at the 0.05 level
** significant at the 0.01 level

Table 34. Anova of 1995 growing season basal diameter growth of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	1.33	1.33	12.68**
SxSH	1	0.08	0.08	0.78
TxSH	1	0.51	0.51	4.90*
TxSxSH	1	0.17	0.17	1.61
RxSH	2	0.01	0.00	0.04
RxSxSH	2	0.57	0.29	2.73
RxTxSH	2	0.24	0.12	1.14
RxTxSxSH	2	0.16	0.08	0.77
BxRxTxSH(S)	33	3.46	0.10	

* significant at the 0.05 level
** significant at the 0.01 level

Table 35. Anova of 1995 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the McNay site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	2.25	2.25	31.83**
SxSH	1	0.35	0.35	4.91*
TxSH	1	0.03	0.03	0.36
TxSxSH	1	0.07	0.07	1.05
RxSH	2	0.43	0.22	3.04
RxSxSH	2	0.07	0.04	0.54
RxTxSH	2	0.28	0.14	1.97
RxTxSxSH	2	0.04	0.02	0.30
BxRxTxSH(S)	29	2.05	0.07	

* significant at the 0.05 level
** significant at the 0.01 level

Table 36. Anova of 1995 growing season mortality of 1-0 *Quercus rubra* seedlings underplanted at the Stephens site. SH=tree shelter, S=spray, T=undercut, R=rootclass, and B=block

Source	DF	Type III SS	Mean Square	F Value
SH	1	2.51	2.51	19.99**
SxSH	1	0.29	0.29	2.38
TxSH	1	0.24	0.24	1.94
TxSxSH	1	0.00	0.00	0.00
RxSH	2	0.08	0.04	0.32
RxSxSH	2	0.33	0.17	1.33
RxTxSH	2	0.53	0.26	2.12
RxTxSxSH	2	1.38	0.69	5.51**
BxRxTxSH(S)	33	4.13	0.13	

* significant at the 0.05 level
** significant at the 0.01 level

sheltered seedlings had died back approximately five to eight centimeters, with the non-sheltered seedlings having 205 percent and 236 percent greater growth at the McNay and Stephens sites respectively.

In 1991 basal diameter growth was negative on both the McNay and Stephens sites because it was not possible to measure basal diameter growth at the root collar, as it was measured during the grading process at the State Nursery. In most cases, the root collar was planted just below ground-line. The actual values measured for basal diameter growth in 1991 are irrelevant. The fact that sheltered seedlings had less shrinkage than non-sheltered seedlings is what is significant. During the first two growing seasons, sheltered seedlings, grew more in basal diameter than non-sheltered seedlings at the McNay and Stephens sites (Figure 7B and Figure 8B). By the end of the 1993 growing season there was no statistical difference in basal diameter growth between sheltered and non-sheltered seedlings on the McNay or Stephens sites, but the trend was for non-sheltered seedlings to grow more (17 percent more in basal diameter compared to sheltered seedlings at the McNay site and 50 percent more in basal diameter compared to sheltered seedlings at the Stephens site). During the last two growing seasons (1994-1995) non-sheltered seedlings had 212 percent and 217 percent greater basal diameter growth than sheltered seedlings for both the McNay and Stephens sites, respectively (Figure 7B and Figure 8B).

From 1991 to 1992 sheltered seedlings had less mortality or as much mortality as the non-sheltered seedlings at the McNay and Stephens sites (Figure 7C, Figure 8C, and Table 6). The 1993 growing season seemed to be the turning point in performance of sheltered and non-sheltered seedlings. At the end of the 1993 growing season there was no statistical difference in mortality between the sheltered and non-sheltered seedlings on the McNay site (Figure 7C). At the end of the 1993 growing season on the Stephens site, sheltered seedlings had approximately 300 percent greater mortality than non-sheltered seedlings (Figure 8C). By the end of the 1995 growing season, sheltered seedlings had 900 percent and 1000 percent greater mortality than non-sheltered seedlings at the McNay or Stephens sites, respectively (Figure 7C and Figure 8C).

Total height and total mortality are being analyzed since height and mortality are the criteria most often used when judging the success of *Quercus rubra* seedlings in future stands. Analysis of total height of all live seedlings annually shows that by the end of five growing seasons there is no statistical differences in sheltered and non-sheltered seedlings at the McNay or Stephens sites (Table 37) based on Student's t-test. Within the first two growing seasons, *Quercus rubra* seedlings have significant differences in mortality between sheltered and non-sheltered seedlings, with non-sheltered seedlings having greater mortality than sheltered seedlings. By the fourth or fifth growing seasons, sheltered *Quercus rubra* seedlings have significantly greater mortality than the non-sheltered seedlings. By the end of the fifth growing season overall mortality of sheltered seedlings were 40 percent for the McNay site and 55 percent for the Stephens site. Values for the non-sheltered seedlings were 26 percent for the McNay site and 28 percent for the Stephens site (Table 37).

Separating the underplanted *Quercus rubra* seedlings by root class significantly affected total height growth after the first five growing seasons both at the McNay (Pr>f=0.04) and Stephens sites(Pr>f= 0.01) (Table 38), but did not affect total basal diameter growth or total mortality. *Quercus rubra* seedlings, at the McNay site, in root class 10 or more grew approximately three percent more than seedlings in root class 5-9 and approximately 99 percent more than seedlings in root class 0-4. *Quercus rubra* seedlings in root class 5-9, at the McNay site, grew approximately 93 percent more than seedlings in root class 0-4. *Quercus rubra* seedlings, at the Stephens site, in root class 10 or more grew approximately 111 percent more than seedlings in root class 5-9 and approximately 969 percent more than seedlings in root class 0-4. *Quercus rubra* seedlings in root class 5-9, at the Stephens site, grew approximately 407 percent more than seedlings in root class 0-4.

Table 37. Initial height (cm), annual total height (cm) of all live seedlings, and total mortality (%) by year of 1-0, underplanted, *Quercus rubra* seedlings at the McNay and Stephens sites

	Total Height (cm)		Total Mortality (%)	
	Shelter	No Shelter	Shelter	No Shelter
McNay	n=42	n=42	n=42	n=42
initial height	20.5 (5.1)[a]	21.8 (5.8)		
1991	28.1 (6.8)	24.9 (5.8)	7 (11)	11 (17)
1992	40.6 (16.1)	25.9 (6.3)**	12 (14)	22 (22)**
1993	60.7 (28.8)	35.6 (9.8)**	16 (17)	24 (24)
1994	78.5 (38.6)	44.9 (15.7)**	27 (21)	26 (25)
1995	71.1 (44.2)	53.2 (21.3)	40 (21)	26 (24)**
Stephens	n=48	n=48	n=48	n=48
initial height	22.3 (7.7)	21.6 (6.1)		
1991	29.8 (10.1)	28.1 (7.8)	8 (17)	17 (23)*
1992	35.5 (11.8)	29.7 (7.4)*	18 (22)	25 (27)
1993	47.3 (27.9)	32.9 (8.1)**	23 (25)	26 (27)
1994	50.9 (30.7)	38.4 (10.1)*	47 (28)	28 (27)**
1995	44.4 (35.4)	41.7 (13.3)	55 (30)	28 (28)**

[a] standard deviation in parentheses
* significant at the 0.05 level
** significant at the 0.01 level

Table 38. Total height growth (cm) by root class after the first five growing seasons for 1-0 *Quercus rubra* L. seedlings underplanted at the McNay and Stephens sites

	Total Height Growth (cm)	
Root Class	McNay[a]	Stephens
0-4	14.9 (0.32)[b]	1.5 (0.24)
5-9	28.9 (0.35)	7.5 (0.23)
10 or More	29.9 (0.36)	15.8 (0.22)

a sample size is 140 and 160 for the McNay and Stephens sites, respectively
b standard error in parentheses

Red to Far Red Light Ratio Pretest

Pretest results show the tree shelter is screening out red light; reducing the ratio of red to far red light by approximately six percent (Table 39). The ratio of red to far red light decreased by approximately 52 percent as the amount of canopy cover increased (Table 40). The canopy is filtering out more red light than far red light; reducing the red to far red light ratio. The red to far red light ratio measured on the south and west was approximately 48 percent and 39 percent larger than the red to far red light ratio measured on the north and east respectively (Table 41). This is not surprising because the study was conducted from 1346h to 1446h during which time the sun was west and south of the pre-test study site. The red to far red light ratio measured outside a tree shelter at the four cardinal directions was significantly larger than the red to far red light ratio measured inside the tree shelter at the four cardinal directions (Table 42). The shelter seems to be filtering out red light, as indicated by the differences in the proportions inside the shelter and outside the shelter. The amount of canopy cover and the direction in which the ratio was measured impacts the ratio of red to far red light. Red to far red light ratios were larger if in the open and measured on the south and west sides. The canopy filters out more red light than far red light and the north and east directions reduced the amount of direct red light reaching the sensor; lowering the ratio of red to far red light (Table 43). Results were statistically different between the ratio of red to far red light measured inside a tree shelter and outside a tree shelter, as the amount of canopy cover increased from none to completely covered, at the four cardinal directions, inside and outside the tree shelter at the four cardinal directions, and under the various canopies and at the four cardinal directions (Table 44).

Table 39. Pretest results of the ratio of red to far red light measured inside and outside a white plastic tree shelter

	Red to Far Red ratio	std error
Shelter	0.48	0.01
No shelter	0.51	0.01

Table 40. Pretest results of the ratio of red to far red light measured under no canopy, partial canopy, and complete canopy cover.

Canopy Cover	Red to Far Red ratio	std error
No canopy	0.64	0.01
Partial canopy	0.55	0.01
Complete canopy	0.31	0.01

Table 41. Pretest results of the ratio of red to far red light measured at north, east, south, and west

Cardinal Directions	Red to Far Red ratio	std error
Nnorth	0.34	0.02
East	0.38	0.02
South	0.65	0.02
West	0.62	0.02

Table 42. Pretest results of the ratio of red to far red light measured north, east, south, and west inside and outside a white tree shelter

Shelter	Cardinal Directions	Red to Far Red ratio	std error
Shelter	north	0.31	0.02
Shelter	east	0.31	0.02
Shelter	south	0.70	0.02
Shelter	west	0.62	0.02
No shelter	north	0.39	0.02
No shelter	east	0.45	0.02
No shelter	south	0.59	0.02
No shelter	west	0.62	0.02

Table 43. Pretest results of the ratio of red to far red light measured at the four cardinal directions and beneath no cover, partial cover, and complete canopy cover

Canopy Cover	Cardinal Directions	Red to Far Red ratio	std error
No cover	north	0.47	0.03
No cover	east	0.45	0.03
No cover	south	0.78	0.03
No cover	west	0.84	0.03
Partial cover	north	0.32	0.03
Partial cover	east	0.46	0.03
Partial cover	south	0.74	0.03
Partial cover	west	0.69	0.03
Complete cover	north	0.26	0.03
Complete cover	east	0.24	0.03
Complete cover	south	0.42	0.03
Complete cover	west	0.32	0.03

Table 44. ANOVA of the pretest of the ratio of red to far red light measured at the four cardinal directions inside and outside a white plastic tree shelter under no cover, partial cover, and complete canopy cover.

Source	DF	Type III SS	Mean Square	F Value
Shelter	1	0.06	0.059	4.59*
Canopy	2	4.65	2.327	182.08**
Shelter*Canopy	2	0.07	0.033	2.60
Direct	3	4.27	1.424	111.47**
Shelter*Direct	3	0.52	0.172	13.45**
Canopy*Direct	6	0.94	0.157	12.25**
Shelter*Canopy*Direct	6	0.12	0.020	1.58
Error	216	2.76	0.012	

* significant at the 0.05 level
** significant at the 0.01 level

White Tree Shelters and Photosynthetic Active Radiation

Linear regression was used to determine the relationship between the amount of photosynthetic active radiation (PAR) ($\mu mol \cdot m^{-2} \cdot s^{-1}$) measured inside a white tree shelter and measured outside a white tree shelter (Figure 9 and Table 45). The relationship is statistically significant (Pr > F=0.0001) with a coefficient of variation equal to 30.47 and a R-squared equal to 0.73. The pattern appear to be curvilinear (Figure 9), therefore, the data was transformed exponentially by adding the term "PAR outside a white shelter-squared" (Table 46). The relationship based on adding the exponential component is statistically significant (Pr > F=0.0001), the coefficient of variation dropped to 12.29, and the R-square is 0.96. The equation used for predicting PAR inside a white tree shelter is:

PAR inside a white tree shelter = 1.203*PAR outside a white tree shelter -0.0004 * (PAR outside a white tree shelter)^2 - 31.553 [1]

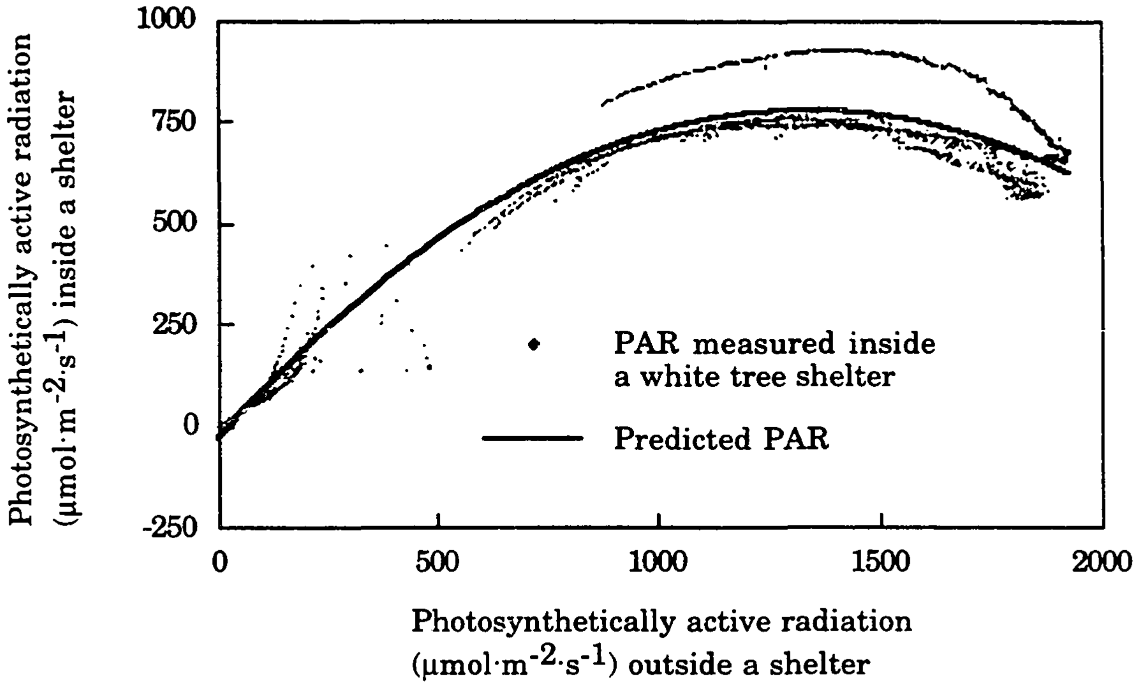

Figure 9. Photosyntheticlly active radiation ($\mu mol \cdot m^{-2} \cdot s^{-1}$) (PAR) inside a white tree shelter verses PAR measured in the open. Plot of predicted PAR values for inside a shelter is from the equation PAR inside a white tree shelter = 1.203*PAR outside a white tree shelter -0.0004 * (PAR outside a white tree shelter)^2 - 31.553. R^2=0.96

Table 45. Regression analysis for developing a relationship between PAR measured inside a white tree shelter and PAR measured outside a white tree shelter.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	109430228	109430228	4337.17	0.0001
Error	1618	40823462	25231		
Corrected total	1619	150253690			

R-Square	C.V.	Root MSE	Inside PAR Mean
0.728303	30.47	158.84	521.25

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Outside PAR	1	109430228	109430228	4337.17	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
Intercept	126.584	17.64	0.0001	7.176
Outside PAR	0.372	65.86	0.0001	0.006

Table 46. Regression analysis for developing a relationship between PAR measured inside a white tree shelter and PAR measured outside a white tree shelter. The relationship has an exponential component, PAR measured outside a white tree shelter squared.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	143621625	71810813	17508.59	0.0001
Error	1617	6632064	4101		
Corrected total	1619	150253690			

R-Square	C.V.	Root MSE	Inside PAR Mean
0.955861	12.28	64.04	521.25

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Outside PAR	1	109430228	109430228	26680.78	0.0001
Outside PAR^2	1	34191397	34191397	8336.39	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Outside PAR	1	67476252.6	67476252.6	16451.76	0.0001
Outside PAR^2	1	34191397.2	34191397.2	8336.39	0.0001

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
Intercept	-31.553	-9.36	0.0001	3.372
Outside PAR	1.203	128.26	0.0001	0.009
Outside PAR^2	-0.0004	-91.30	0.0001	0.000005

The variation in the PAR measured inside the tree shelter is related to the variation in the atmosphere, the angle of the sun, and in the plastic used to create the shelter. The slight curvature downward from approximately 1400 to 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Figure 9) is probably related to the angle at which the light hits the shelter and is reflected away and due to the fact the shelter is made of corrugated plastic. The smaller the sun's zenith angle the more light is reflected away by the shelter.

Figure 10 shows the percentage of PAR inside the white tree shelter verses the PAR outside the white tree shelter. The percentage of PAR inside the tree shelter is not a constant percentage of the PAR outside the shelter. This is due to the same reasons for the variation in the PAR measured inside the shelter.

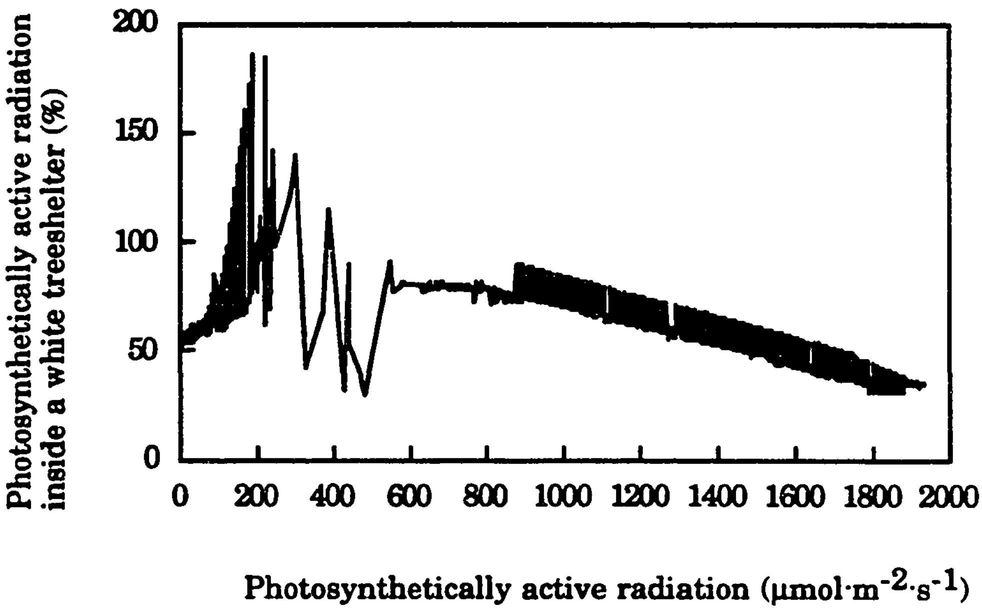

Figure 10. Percent of photosynthetic active radiation ($\mu mol \cdot m^{-2} \cdot s^{-1}$) (PAR) inside a white tree shelter verses PAR measured in the open.

Photosynthetic Active Radiation and Stand Density

Regression analyses were performed to develop relationships between percent full sunlight measured outside the tree shelter and averaged over mid and late summer measurement periods and basal area, average stand diameter at breast height, number of trees per hectare, or various combinations of these measures of stand densities. The same regression analyses as above were performed between overstory leaf area index (LAI) and the different measures of stand densities. Even though there were significant differences in the regression models (Table 47), the R-squares, less than or equal to 0.40, were unacceptable and therefore, none of the models will be used to predict percent full sunlight or LAI. Since none of the models are acceptable the results of the analyses will not be presented.

Further analyses were performed using response surface techniques to develop relationships between percent full sunlight measured outside the tree shelter and averaged over mid-summer and late-summer measurement periods with, basal area and average stand diameter at breast height, basal area and number of trees per hectare, or basal area and average stand diameter at breast height and number of trees per hectare. The R-squares were less than or equal to 0.42 and the lack of fit test for each model was statistically significant at the 0.01 level (Table 48). Even though stationary points indicate optimums they should not be considered since the lack of fit test for each model was significant (Table 48). Stationary points can be maximum optimum (max), no optimum (saddle), or minimum optimum (min).

Table 47. R-squares and F values for regressions between percent full sunlight or overstory leaf area index and various combinations of stand densities. The measures of stand density are basal area, average stand diameter, and number of trees/hectare. Full sunlight was measured outside the tree shelter and averaged over mid- and late-summer measurement periods

Variable	R-squared	F-value
Percent full sunlight		
Basal Area	0.28	45.68**
Avg. Stand Diameter	0.01	0.82
Trees/Hectare	0.04	5.39*
Basal Area & Avg. Stand Diameter	0.28	22.80**
Basal Area & Trees/Hectare	0.31	26.00**
Basal Area & Avg. Stand Diameter & Trees/Hectare	0.33	18.66**
Leaf Area Index		
Basal Area	0.28	344.90**
Average Stand diameter	0.22	256.97**
Trees/Hectare	0.11	109.76**
Basal Area & Avg. Stand Diameter	0.28	292.54**
Basal Area & Trees/Hectare	0.29	344.89**
Basal Area & Avg. Stand Diameter & Trees/Hectare	0.40	202.08**

* significant at the 0.05 level
** significant at the 0.01 level

Table 48. R-squares and F values for response surfaces between percent full sunlight and various combinations of stand density. The measure of stand densities are basal area, average stand diameter, and number of trees/hectare. Full sunlight was measured outside the tree shelter and averaged over mid- and late- summer measurement periods,

Variable	R-squared	Stationary Point
Percent full sunlight		
Basal Area & Avg. Stand Diameter	0.36	max**
Basal Area & Trees/Hectare	0.34	max**
Basal Area & Avg. Stand Diameter & Trees/Hectare	0.42	saddle**

* lack of fit significant at the 0.05 level
** lack of fit significant at the 0.01 level

Growth, Mortality, and Light

Regression analysis, by shelter, was used to develop a relationship between percent full sunlight measured outside the shelter and averaged over mid and late summer measurement periods and total height growth, total basal diameter growth, and total mortality at the end of the first five growing seasons. Because of low R-squares percent full sunlight is unacceptable as a predictor for total height growth, total basal diameter growth, or mortality (Table 49).

Table 49. R-square and F values for regression analyses, separated by shelter, between percent full sunlight and total height growth, total basal diameter growth, and total mortality after the first five growing seasons for 1-0 underplanted *Quercus rubra* seedlings with 10 or more permanent, first-order, lateral roots greater than 1 mm. Percent full sunlight was measured outside the tree shelter and averaged over mid- and late- summer measurement periods

Variable	R-squared	F-value
Percent full sunlight		
Shelter		
Total height growth	0.48	54.51**
Total basal diameter growth	0.37	35.59**
Total mortality	0.15	4.56*
Non-shelter		
Total height growth	0.04	2.46
Total basal diameter growth	0.08	4.82*
Total mortality	0.06	1.46

* significant at the 0.05 level
** significant at the 0.01 level

Regression analysis, by shelter, was used to develop a relationship between overstory LAI averaged over mid- and late- summer measurement periods and total height growth, total basal diameter growth, and total mortality at the end of the first five growing seasons. Because of low R-squares LAI is unacceptable as a predictor for total height growth, total basal diameter growth, or total mortality (Table 50).

Table 50. R-square and F values for regressions between overstory leaf area index and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings with 10 or more permanent, first-order, lateral roots, separated by shelter. The overstory leaf area index was averaged over mid- and late- summer measurement periods

Variable	R-squared	F-value
Leaf area index		
Shelter		
Total height growth	0.28	23.21**
Total basal diameter growth	0.19	14.10**
Total mortality	0.16	5.53*
Non-shelter		
Total height growth	0.004	0.23
Total basal diameter growth	0.002	0.12
Total mortality	0.13	3.56

* significant at the 0.05 level
** significant at the 0.01 level

Pearson correlation coefficients were used to determine which independent variables would be used in regression analysis with total height growth, total basal diameter growth, and total mortality. Unadjusted PAR and LAI were observed independently of all other independent variables used in Pearson correlation analysis because these two variables, separately, are often used to describe light conditions within a stand. The independent variables used in the correlation analysis were adjusted percent full sunlight measured during the period from the end of June to the beginning of July, adjusted percent full sunlight measured during the period from the end of August to the beginning of September, adjusted percent full sunlight averaged between the June and August measurement periods, minimum red to far red light ratios, maximum red to far red light ratios, average of the red to far red light ratios, LAI measured in the June measuring period, LAI measured in the August measuring period, and LAI averaged between the June and August measuring periods.

The independent variables determined to be used in the regression analyses with total height growth, total basal diameter growth, and total mortality were adjusted percent full sunlight averaged between the June and August measurement periods, maximum red to far red light ratio, and average ratios of red to far red light (Table 51). Independent variables were selected based on R^2 values for sheltered seedlings becuase of their higher R-squares.

Table 51. Pearson's correlation coefficients between total height growth, total basal diameter growth, or total mortality and maximum red to far red light ratio (r/fr), minimum r/fr, average r/fr, adjusted percent full sunlight (pfs), average pfs, overstory leaf area index (LAI), and average LAI, separated by shelter. The average r/fr was measured at the four cardinal directions. The pfs and LAI were measured from the end of June to early July, and from the end of August to early September. Averaged pfs and averaged LAI are between the early and late summer measurement periods

	Sheltered			Non-sheltered		
Independent Variable	Height Growth	Caliper Growth	Mortality	Height Growth	Caliper Growth	Mortality
Average pfs	0.76**	0.65**	-0.34**	0.20	0.28*	-0.15
August pfs	0.73**	0.63**	-0.33**	0.15	0.17	-0.03
June pfs	0.72**	0.62**	-0.36**	0.20	0.31*	-0.21
Maximum r/fr	0.74**	0.60**	-0.43**	0.30*	0.30*	-0.17
Average r/fr	0.58**	0.46**	-0.30*	0.31*	0.35**	-0.20
Minimum r/fr	0.16	0.12	-0.09	0.23	0.27*	-0.16
Average LAI	-0.53**	-0.44**	0.29*	-0.06	-0.05	0.09
June LAI	-0.48**	-0.40**	0.29*	-0.03	-0.04	0.12
August LAI	-0.42**	-0.35**	0.19	-0.08	-0.04	0.11

* significant at the 0.05 level
** significant at the 0.01 level

Regression analysis was used to determine the relationship between total height growth, total basal diameter growth or total mortality, separated by shelter, and the independent variables of adjusted percent full sunlight, maximum red to far red light ratio, the average red to far red light ratio, or combinations of the independent variables. The combinations are adjusted percent full sunlight and maximum red to far red light ratio and adjusted percent full sunlight and average red to far red light ratio. Because of low R-squares adjusted percent full sunlight, maximum red to far red light, and average red to far red light ratio and the combinations of these independent variables are poor predictors of total height growth, total basal diameter growth, or total mortality (Table 52).

Further tests using response surface techniques were used to see if any of the combinations of average adjusted percent full sunlight and maximum red to far red light ratio or adjusted percent full sunlight and average red to far red light ratio could be used to predict total height growth, total basal diameter growth, or total mortality after the first five growing seasons. None of the response surfaces had an R-square greater than 0.66 (Table 53), with R-squares for sheltered seedlings being larger than R-squares for non-sheltered seedlings for total height growth and total basal diameter growth after the first five years. Response surfaces for total mortality after the first five growing seasons had R-square values of 0.21 and less and were not statistically significant (Table 53). Response surface results for total height growth and total basal diameter growth after the first five growing seasons often showed that non-sheltered seedling models that resulted in stationary points as saddle points (no optimum) or maximum points (maximum optimum) would end up with

Table 52. R-square and F values for regressions between maximum red to far red light ratio (r/fr) or average r/fr and total height growth, total basal diameter growth, and total mortality for 1-0, underplanted, *Quercus rubra* seedlings with 10 or more permanent, first-order, lateral roots, separated by shelter

Variable	R-squared	F-value
Adjusted percent full sunlight		
Shelter		
Total height growth	0.58	83.00**
Total basal diameter growth	0.42	44.45**
Total mortality	0.28	5.44*
Non-shelter		
Total height growth	0.04	2.40
Total basal diameter growth	0.08	4.68*
Total mortality	0.06	1.46
Maximum red to far red light ratio		
Shelter		
Total height growth	0.54	71.27**
Total basal diameter growth	0.36	33.30**
Total mortality	0.34	11.73**
Non-shelter		
Total height growth	0.09	5.52*
Total basal diameter growth	0.09	5.70*
Total mortality	0.09	2.16
Average red to far red light ratio		
Shelter		
Total height growth	0.34	30.60**
Total basal diameter growth	0.21	15.94**
Total mortality	0.09	2.31
Non-shelter		
Total height growth	0.09	5.84*
Total basal diameter growth	0.12	7.70**
Total mortality	0.09	2.17

* significant at the 0.05 level

** significant at the 0.01 level

Table 53. R-square and F values for response surfaces between adjusted percent full sunlight (pfs) and maximum red to far red light ratio (r/fr), or pfs and average r/fr and total height growth, total basal diameter growth, and total mortality for 1-0, underplanted, *Quercus rubra* seedlings with 10 or more permanent, first-order, lateral roots, separated by shelter,

Variable	R-squared ,	F-value
Adjusted percent full sunlight & maximum red to far red light ratio		
Shelter		
Total height growth	0.66	22.12**
Total basal diameter growth	0.47	9.95**
Total mortality	0.19	1.06
Non-shelter		
Total height growth	0.16	1.95
Total basal diameter growth	0.18	2.27
Total mortality	0.21	1.69
Adjusted percent full sunlight & average red to far red light ratio		
Shelter		
Total height growth	0.62	18.24**
Total basal diameter growth	0.47	10.04**
Total mortality	0.15	1.94
Non-shelter		
Total height growth	0.13	1.61
Total basal diameter growth	0.18	2.29
Total mortality	0.11	1.25

* significant at the 0.05 level
** significant at the 0.01 level

stationary points as a minimum (minimum optimum) if seedlings were protected by shelters (Table 54). Response surface results for total mortality after the first five growing seasons often showed that non-sheltered seedlings models that resulted in stationary points as saddle points or minimum points would end up with stationary points as a maximum if seedlings were protected by shelters (Table 54). These changes in optimum points indicate that shelters may be having an adverse effect on growth and survival.

Table 54. Response surfaces stationary points that changed between non-sheltered and sheltered seedlings, by root class. adjsun = average percent full sunlight, rfr max = maximum ratio of red to far red light, rfravg = average ratio of red to far red light

Model	Non-Shelter stationary point	shelter stationary point
Height growth=adjsun, rfr max	saddle	saddle**
Caliper growth=adjsun, rfr max	saddle*	saddle**
Mortality=adjsun, rfr max	saddle	maximum
Height growth=adjsun, rfravg	saddle*	maximum**
Caliper growth=adjsun, rfravg	saddle**	saddle
Mortality=adjsun, rfr avg	saddle	minimum*

* linear model significant at the 0.05 level
** linear model significant at the 0.01 level

Growth, Mortality, and Stand Density

Pearson correlation coefficients were used to determine which independent variables would be used in regression analysis with total height growth, total basal diameter growth and total mortality. The independent variables used in the correlation analysis were basal area, average stand diameter, quadratic mean diameter, and number of trees/hectare. All of these variables except quadratic mean diameter were determined to be useful in regression analysis (Table 55). Since there seems to be no difference in average stand diameter values and quadratic mean values, average stand diameter was chosen as the independent variable.

Regression analysis was used to determine the relationship between the dependent variables, separated by root class and shelter, and the independent variables of basal area, average stand diameter, number of trees per hectare, and combinations of the independent variables. The combinations are basal area and average stand diameter, basal area and number of trees per hectare, and basal area, average stand diameter, and number of trees per hectare.

The regression analysis, separated by shelter treatment, determined that none of the independent variables or combinations of independent variables were significantly related to total height growth, total basal diameter growth, or total mortality (Table 56 to 62). R-squares ranged from 0.00 to 0.20.

Table 55. Pearson Correlation coefficients between total height growth, total basal diameter growth (total diameter growth), or total mortality and basal area, number of trees /hectare, average stand diameter, and quadratic mean diameter, separated by shelter and number of permanent, first-order, lateral roots

	Basal Area	Average Stand Diameter	Quadratic Mean Diameter	Trees per Hectare
Shelter				
0-4 roots				
Total height growth	-0.28**	0.17*	0.17*	0.02
Total diameter growth	-0.18*	0.07	0.07	0.06
Total mortality	-0.04	-0.03	0.03	-0.08
5-9 roots				
Total height growth	-0.36**	0.27**	0.26**	-0.27**
Total diameter growth	-0.29**	0.20*	0.20*	-0.21**
Total mortality	0.06	-0.20*	-0.21*	0.17
10 + roots				
Total height growth	-0.37**	0.30**	0.31**	-0.24**
Total diameter growth	-0.28**	0.22**	0.22**	-0.19*
Total mortality	0.13	-0.12	-0.13	0.14
No shelter				
0-4 roots				
Total height growth	-0.27**	0.07	0.08	-0.07
Total diameter growth	-0.26**	-0.02	-0.01	-0.04
Total mortality	0.04	0.10	0.10	-0.05
5-9 roots				
Total height growth	-0.25**	0.38**	0.39**	-0.18*
Total diameter growth	-0.25**	0.30**	0.30**	-0.18*
Total mortality	0.04	-0.14	-0.15	0.05
10 + roots				
Total height growth	-0.20*	0.11	0.11	-0.20**
Total diameter growth	-0.09	0.06	0.08	-0.15
Total mortality	-0.03	0.05	0.08	0.05

* significant at the 0.05 level
** significant at the 0.01 level

Table 56. R-square and F values for regressions between basal area and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth & Basal area		
Shelter		
Root class 0-4	0.07	12.8**
Root class 5-9	0.13	22.76**
Root Class 10 or More	0.14	23.86**
Non-shelter		
Root class 0-4	0.07	11.78**
Root class 5-9	0.06	9.83**
Root Class 10 or More	0.04	6.20**
Total basal diameter growth & Basal area		
Shelter		
Root class 0-4	0.03	4.74*
Root class 5-9	0.08	13.57**
Root Class 10 or More	0.08	12.69**
Non-shelter		
Root class 0-4	0.07	10.76**
Root class 5-9	0.06	9.56**
Root Class 10 or More	0.01	1.28
Total mortality & Basal area		
Shelter		
Root class 0-4	0.001	0.13
Root class 5-9	0.00	0.32
Root Class 10 or More	0.02	1.86
Non-shelter		
Root class 0-4	0.002	0.15
Root class 5-9	0.00	0.19
Root Class 10 or More	0.001	0.14

* significant at the 0.05 level

** significant at the 0.01 level

Table 57. R-square and F values for regressions between average stand diameter (Avg. stand diam.) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth & Avg. stand diam.		
Shelter		
Root class 0-4	0.03	4.32*
Root class 5-9	0.07	11.29**
Root Class 10 or More	0.09	14.87**
Non-shelter		
Root class 0-4	0.01	0.77
Root class 5-9	0.15	25.60**
Root Class 10 or More	0.01	1.69
Total basal diameter growth & Avg. stand diam.		
Shelter		
Root class 0-4	0.005	0.73
Root class 5-9	0.04	6.27**
Root Class 10 or More	0.05	7.63**
Non-shelter		
Root class 0-4	0.00	0.04
Root class 5-9	0.09	14.28**
Root Class 10 or More	0.003	0.50
Total mortality & Avg. stand diam.		
Shelter		
Root class 0-4	0.001	0.11
Root class 5-9	0.04	4.49*
Root Class 10 or More	0.01	1.46
Non-shelter		
Root class 0-4	0.01	1.17
Root class 5-9	0.02	1.91
Root Class 10 or More	0.002	0.21

* significant at the 0.05 level
** significant at the 0.01 level

Table 58. R-square and F values for regressions between number of trees per hectare (Trees/ha) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth & Trees/ha		
Shelter		
Root class 0-4	0.000	0.07
Root class 5-9	0.07	11.40**
Root Class 10 or More	0.06	9.36**
Non-shelter		
Root class 0-4	0.01	0.82
Root class 5-9	0.03	5.16*
Root Class 10 or More	0.04	6.49**
Total basal diameter growth & Trees/ha		
Shelter		
Root class 0-4	0.004	0.56
Root class 5-9	0.05	7.01**
Root Class 10 or More	0.04	5.51*
Non-shelter		
Root class 0-4	0.001	0.19
Root class 5-9	0.03	5.23*
Root Class 10 or More	0.02	3.18
Total mortality & Trees/ha		
Shelter		
Root class 0-4	0.01	0.74
Root class 5-9	0.03	2.88
Root Class 10 or More	0.02	2.02
Non-shelter		
Root class 0-4	0.002	0.25
Root class 5-9	0.002	0.22
Root Class 10 or More	0.004	0.42

* significant at the 0.05 level
** significant at the 0.01 level

Table 59. R-square and F values for regressions between basal area and average stand diameter at breast height (avg. stand diam.) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth - Basal area & Avg. stand diam.		
Shelter		
Root class 0-4	0.09	7.12**
Root class 5-9	0.15	13.23**
Root Class 10 or More	0.19	17.74**
Non-shelter		
Root class 0-4	0.07	5.85**
Root class 5-9	0.17	14.99**
Root Class 10 or More	0.04	3.43
Total basal diameter growth - Basal area & Avg. stand diam.		
Shelter		
Root class 0-4	0.03	2.39
Root class 5-9	0.09	7.62**
Root Class 10 or More	0.11	8.92**
Non-shelter		
Root class 0-4	0.08	6.04**
Root class 5-9	0.12	9.74**
Root Class 10 or More	0.01	0.75
Total mortality - Basal area & avg. stand diam.		
Shelter		
Root class 0-4	0.002	0.10
Root class 5-9	0.04	2.22
Root Class 10 or More	0.03	1.45
Non-shelter		
Root class 0-4	0.02	0.78
Root class 5-9	0.02	0.95
Root Class 10 or More	0.002	0.16

* significant at the 0.05 level
** significant at the 0.01 level

Table 60. R-square and F values for regressions between basal area and number of trees/hectare (Trees/ha) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth - Basal area &Trees/ha		
Shelter		
Root class 0-4	0.09	7.28**
Root class 5-9	0.14	12.02**
Root Class 10 or More	0.16	14.00**
Non-shelter		
Root class 0-4	0.07	5.85**
Root class 5-9	0.07	5.85**
Root Class 10 or More	0.07	5.15**
Total basal diameter growth - Basal area &Trees/ha		
Shelter		
Root class 0-4	0.04	3.38*
Root class 5-9	0.09	7.15**
Root Class 10 or More	0.09	7.47**
Non-shelter		
Root class 0-4	0.07	5.51**
Root class 5-9	0.07	5.76**
Root Class 10 or More	0.02	1.83
Total mortality - Basal area &Trees/ha		
Shelter		
Root class 0-4	0.01	0.38
Root class 5-9	0.03	1.50
Root Class 10 or More	0.03	1.53
Non-shelter		
Root class 0-4	0.01	0.27
Root class 5-9	0.003	0.16
Root Class 10 or More	0.01	0.33

* significant at the 0.05 level
** significant at the 0.01 level

Table 61. R-square and F values for regressions between average stand diameter (avg. stand diam.), and number of trees/hectare (Trees/ha) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth - Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.08	6.76**
Root class 5-9	0.08	6.64**
Root Class 10 or More	0.09	7.41**
Non-shelter		
Root class 0-4	0.01	0.49
Root class 5-9	0.16	14.51**
Root Class 10 or More	0.05	3.79*
Total basal diameter growth - Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.04	2.86
Root class 5-9	0.05	3.88*
Root Class 10 or More	0.05	3.86*
Non-shelter		
Root class 0-4	0.004	0.26
Root class 5-9	0.09	7.24**
Root Class 10 or More	0.03	2.16
Total mortality - Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.01	0.48
Root class 5-9	0.04	2.30
Root Class 10 or More	0.02	1.02
Non-shelter		
Root class 0-4	0.01	0.60
Root class 5-9	0.03	1.29
Root Class 10 or More	0.02	1.27

* significant at the 0.05 level
** significant at the 0.01 level

Table 62. R-square and F values for regressions between basal area, average stand diameter (avg. stand diam.), and number of trees/hectare (Trees/ha) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth - Basal area & Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.16	9.04**
Root class 5-9	0.15	8.77**
Root Class 10 or More	0.20	11.96**
Non-shelter		
Root class 0-4	0.07	3.88**
Root class 5-9	0.20	11.89**
Root Class 10 or More	0.07	3.82**
Total basal diameter growth - Basal area & Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.07	3.69**
Root class 5-9	0.09	5.05**
Root Class 10 or More	0.11	5.94**
Non-shelter		
Root class 0-4	0.08	4.00**
Root class 5-9	0.12	6.80**
Root Class 10 or More	0.03	1.61
Total mortality - Basal area & Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.01	0.32
Root class 5-9	0.04	1.54
Root Class 10 or More	0.03	1.04
Non-shelter		
Root class 0-4	0.02	0.52
Root class 5-9	0.03	0.87
Root Class 10 or More	0.03	0.96

* significant at the 0.05 level
** significant at the 0.01 level

Further tests using response surface techniques were used to see if any of the combinations of basal area and number of trees per hectare, basal area and average stand diameter at breast height, average stand diameter at breast height and number of trees per hectare, or basal area, average stand diameter at breast height, and number of trees per hectare could be used to predict total height growth, total basal diameter growth, or total mortality after the first five growing seasons. None of the response surfaces had an R-square greater than 0.26 (Tables 63 through 66). Response surface results for total height growth and total basal diameter growth after the first five growing seasons often showed that non-sheltered seedling models that resulted in no optimum response (saddle) or maximum response (maximum) would end up with a stationary point as a minimum response if seedlings were protected by tree shelters (Tables 67 and 68). Response surface results for total mortality after the first five growing seasons often showed that non-sheltered seedling models that resulted in no optimum response or minimum response would end up with a stationary point as a maximum response if seedlings were protected by shelters (Table 69).

Growth, Mortality, and Stocking

Regression analysis, by root class and shelter, was used to develop a relationship between total height growth, total basal diameter growth, or total mortality of underplanted *Quercus rubra* seedlings and percent overstory stocking. Results (Table 70) indicate there is very poor correlation between total height growth, total basal diameter growth, or total mortality and percent overstory stocking. R-squares ranged from 0.00 to 0.06.

Table 63. **R-square and F values for response surfaces between basal area and average stand diameter (avg. stand diam.) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class**

Variable	R-squared	F-value
Total height growth - Basal area & Avg. stand diam.		
Shelter		
Root class 0-4	0.21	7.61**
Root class 5-9	0.23	8.71**
Root Class 10 or More	0.22	7.91**
Non-shelter		
Root class 0-4	0.11	3.52**
Root class 5-9	0.22	7.94**
Root Class 10 or More	0.06	1.89
Total basal diameter growth - Basal area & Avg. stand diam.		
Shelter		
Root class 0-4	0.12	3.94**
Root class 5-9	0.21	7.59**
Root Class 10 or More	0.14	4.62**
Non-shelter		
Root class 0-4	0.14	4.77**
Root class 5-9	0.14	4.63**
Root Class 10 or More	0.02	0.66
Total mortality - Basal area & avg. stand diam.		
Shelter		
Root class 0-4	0.04	0.76
Root class 5-9	0.11	2.52*
Root Class 10 or More	0.04	0.72
Non-shelter		
Root class 0-4	0.04	0.71
Root class 5-9	0.06	1.06
Root Class 10 or More	0.03	0.65

* significant at the 0.05 level
** significant at the 0.01 level

Table 64. R-square and F values for response surfaces between basal area and number of trees/hectare (Trees/ha) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth - Basal area &Trees/ha		
Shelter		
Root class 0-4	0.16	5.46**
Root class 5-9	0.23	8.49**
Root Class 10 or More	0.20	7.08**
Non-shelter		
Root class 0-4	0.11	3.47**
Root class 5-9	0.10	3.32**
Root Class 10 or More	0.08	2.65*
Total basal diameter growth - Basal area &Trees/ha		
Shelter		
Root class 0-4	0.10	3.31**
Root class 5-9	0.21	7.61**
Root Class 10 or More	0.13	4.18**
Non-shelter		
Root class 0-4	0.12	4.02**
Root class 5-9	0.09	2.90*
Root Class 10 or More	0.04	1.10
Total mortality - Basal area &Trees/ha		
Shelter		
Root class 0-4	0.02	0.51
Root class 5-9	0.10	3.18**
Root Class 10 or More	0.03	0.82
Non-shelter		
Root class 0-4	0.02	0.44
Root class 5-9	0.02	0.45
Root Class 10 or More	0.04	1.16

* significant at the 0.05 level
** significant at the 0.01 level

Table 65. R-square and F values for response surfaces between average stand diameter (avg. stand diam.) and number of trees/hectare (Trees/ha) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class

Variable	R-squared	F-value
Total height growth - Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.18	6.52**
Root class 5-9	0.17	5.98**
Root Class 10 or More	0.23	8.68**
Non-shelter		
Root class 0-4	0.07	2.28*
Root class 5-9	0.22	8.21**
Root Class 10 or More	0.08	2.44*
Total basal diameter growth - Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.10	3.12**
Root class 5-9	0.12	3.91**
Root Class 10 or More	0.16	5.47**
Non-shelter		
Root class 0-4	0.08	2.59*
Root class 5-9	0.13	4.46**
Root Class 10 or More	0.04	1.30
Total mortality - Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.02	0.54
Root class 5-9	0.06	1.91
Root Class 10 or More	0.04	1.09
Non-shelter		
Root class 0-4	0.04	1.27
Root class 5-9	0.02	0.50
Root Class 10 or More	0.04	1.07

* significant at the 0.05 level
** significant at the 0.01 level

Table 66. **R-square and F values for response surfaces between basal area, average stand diameter (avg. stand diam.), and number of trees/hectare (Trees/ha) and height growth, basal diameter growth, and mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by shelter and root class**

Variable	R-squared	F-value
Total height growth - Basal area & Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.21	4.21**
Root class 5-9	0.25	5.27**
Root Class 10 or More	0.26	5.56**
Non-shelter		
Root class 0-4	0.11	1.99*
Root class 5-9	0.31	6.92**
Root Class 10 or More	0.09	1.57
Total basal diameter growth - Basal area & Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.13	2.29*
Root class 5-9	0.23	4.70**
Root Class 10 or More	0.18	3.40**
Non-shelter		
Root class 0-4	0.16	2.90**
Root class 5-9	0.21	4.11**
Root Class 10 or More	0.05	0.84
Total mortality - Basal area & Avg. stand diam. & Trees/ha		
Shelter		
Root class 0-4	0.04	0.69
Root class 5-9	0.15	2.64**
Root Class 10 or More		
Non-shelter		
Root class 0-4	0.06	1.00
Root class 5-9	0.09	1.58
Root Class 10 or More	0.07	1.20

* significant at the 0.05 level
** significant at the 0.01 level

Table 67. **Response surface results for total height growth by root class and shelter. Ht=total height growth, BA=basal area, AD=average stand diameter at breast height, and TRHA=number of trees/hectare**

Model	Root class	Non-shelter stationary point	Shelter stationary point
Ht growth=AD TRHA	0	saddle#	saddle**##
Ht growth=AD TRHA	5	saddle**#	saddle**
Ht growth=AD TRHA	10	saddle*	minimum**##
Ht growth=BA AD	0	saddle**	minimum**##^^
Ht growth=BA AD	5	saddle**#	minimum**##
Ht growth=BA AD	10	maximum*	minimum**
Ht growth=BA AD TRHA	0	saddle*	saddle**
Ht growth=BA AD TRHA	5	saddle**^^	saddle**##
Ht growth=BA AD TRHA	10	saddle*	saddle**
Ht growth=BA TRHA	0	saddle*	minimum**##
Ht growth=BA TRHA	5	saddle**+	minimum**##
Ht growth=BA TRHA	10	maximum**	minimum**

* linear model significant at the 0.05 level

** linear model significant at the 0.01 level

\# quadratic model significant at the 0.05 level

\## quadratic model significant at the 0.01 level

^^ crossproduct model significant at the 0.01 level

\+ lack of fit test significant at the 0.05 level

Table 68. Response surface results for total basal diameter growth by root class and shelter. Cal=basal diameter, BA=basal area, AD=average stand diameter at breast height, and TRHA=number of trees/hectare

Model	Root class	Non-shelter stationary point	Shelter stationary point
Cal growth=AD TRHA	0	saddle#^	saddle*#
Cal growth=AD TRHA	5	saddle**#	saddle*##
Cal growth=AD TRHA	10	saddle	minimum*##+
Cal growth=BA AD	0	saddle**##	saddle#^^
Cal growth=BA AD	5	minimum**	saddle**##
Cal growth=BA AD	10	saddle	minimum**
Cal growth=BA AD TRHA	0	saddle**#	saddle*
Cal growth=BA AD TRHA	5	saddle**^^	saddle**##
Cal growth=BA AD TRHA	10	saddle	saddle**#
Cal growth=BA TRHA	0	saddle**#	saddle*^
Cal growth=BA TRHA	5	saddle**	minimum*#
Cal growth=BA TRHA	10	saddle	minimum**^

* linear model significant at the 0.05 level

** linear model significant at the 0.01 level

\# quadratic model significant at the 0.05 level

\##quadratic model significant at the 0.01 level

^ crossproduct model significant at the 0.05 level

^^ crossproduct model significant at the 0.01 level

+ lack of fit test significant at the 0.05 level

++ lack of fit test significant at the 0.01 level

Table 69. Response surface results for mortality by root class and shelter. BA=basal area, AD=average stand diameter, and TRHA=number of trees/hectare

Model	Root class	Non-shelter stationary point	Shelter stationary point
Mortality=AD TRHA	0	saddle	saddle
Mortality=AD TRHA*	5	maximum	saddle
Mortality=AD TRHA	10	minimum	maximum
Mortality=BA AD	0	saddle	maximum
Mortality=BA AD	5	maximum	saddle
Mortality=BA AD	10	saddle	saddle
Mortality=BA AD TRHA	0	saddle	saddle
Mortality=BA AD TRHA	5	saddle^	saddle#^
Mortality=BA AD TRHA	10	saddle	saddle
Mortality=BA TRHA	0	saddle	saddle
Mortality=BA TRHA	5	saddle	maximum##
Mortality=BA TRHA	10	saddle	saddle

quadratic model significant at the 0.05 level
##quadratic model significant at the 0.01 level
^ crossproduct model significant at the 0.05 level

Table 70. R-square and F values for regressions between percent overstory stocking and height growth, basal diameter growth, or mortality after five growing seasons for 1-0, underplanted, *Quercus rubra* seedlings, separated by root class and shelter

Variable	R-squared	F-value
<u>Height Growth and Percent Overstory Stocking</u>		
<u>Shelter</u>		
Root class 0-4	0.02	2.73
Root class 5-9	0.05	7.88**
Root Class 10 or More	0.06	8.96**
<u>Non-shelter</u>		
Root class 0-4	0.03	4.99*
Root class 5-9	0.01	1.06
Root Class 10 or More	0.04	5.95
<u>Basal Diameter Growth and Percent Overstory Stocking</u>		
<u>Shelter</u>		
Root class 0-4	0.01	0.90
Root class 5-9	0.03	4.93*
Root Class 10 or More	0.03	5.24*
<u>Non-shelter</u>		
Root class 0-4	0.04	5.45*
Root class 5-9	0.01	1.30
Root Class 10 or More	0.01	0.84
<u>Mortality and Percent Overstory Stocking</u>		
<u>Shelter</u>		
Root class 0-4	0.01	0.95
Root class 5-9	0.00	0.38
Root Class 10 or More	0.00	0.08
<u>Non-shelter</u>		
Root class 0-4	0.00	0.00
Root class 5-9	0.00	0.31
Root Class 10 or More	0.00	0.17

* significant at the 0.05 level
** significant at the 0.01 level

Competition

Total height comparisons were done using general linear model procedures and Dunnett's T tests between the underplanted *Quercus rubra* seedlings and competing woody understory vegetation that was alive at the end of the fifth growing season on the McNay and Stephens sites.

For the McNay sites, the *Quercus rubra* seedlings were as tall as the competition after the first five growing seasons (Table 71). Separating the *Quercus rubra* seedlings by root class, spraying the area with herbicide prior to planting, or using shelters to protect the *Quercus rubra* seedlings had no significant impact on seedling height when compared to the competition at the end of the fifth growing season (Table 72). For Stephens, the competition was taller than the non-sheltered, *Quercus rubra* seedlings at the end of the fifth growing season (Table 73 and 74). Underplanted *Quercus rubra* seedlings were as tall as the competition when the area was sprayed with herbicide prior to planting and shelters were used to protect the *Quercus rubra* seedlings.

Table 71. Comparison of average competing seedlings and *Quercus rubra* seedlings heights (cm) after five growing seasons at the McNay site. The comparison was separated by shelter, herbicide, and root class treatments

	Sample Size	Avg. Height (cm)	Standard Deviation
Sheltered			
Sprayed			
Root class 0-4	8	93.08	42.95
Root class 5-9	8	92.21	49.16
Root class ≥ 10	8	101.60	45.55
Non-sprayed			
Root class 0-4	6	67.41	39.88
Root class 5-9	6	80.71	65.60
Root class ≥ 10	6	67.19	33.25
Non-sheltered			
Sprayed			
Root class 0-4	7	51.30	19.16
Root class 5-9	8	66.43	27.42
Root class ≥ 10	8	59.43	17.19
Non-sprayed			
Root class 0-4	6	46.78	20.94
Root class 5-9	6	49.23	17.12
Root class ≥ 10	6	47.73	17.21
Competition			
Sprayed	8	81.97	25.22
Not sprayed	6	59.5[a]	23.11

* significantly different from competition at the 0.05 level

Table 72. Anova of comparison between average competing seedlings and *Quercus rubra* seedlings heights after five growing seasons for 1-0, *Quercus rubra* seedlings underplanted on the McNay site

Source	df	ss	ms	F
Root Class	3	445.79	148.59	0.05
Root Class * Spray	4	9144.75	2286.19	0.76
Block*Root Class(Spray)	20	59595.03	2979.75	
Non-Shelter	1	2900.63	2900.63	3.85
Non-Shelter*Spray	2	3226.47	1613.23	2.14
Root Class*Non-shelter	2	348.76	174.38	0.23
Root Class*Spray*Non-shelter	2	142.10	71.05	0.09
Block*Root Class*Non-shelter(Spray)	18	15078.17	753.91	
Shelter	1	1709.55	1709.55	0.55
Spray*Shelter	2	7583.33	3791.66	1.21
Root Class*Shelter	2	263.55	131.78	0.04
Root Class*Spray*Shelter	2	915.67	457.83	0.15
Block*Root Class*Shelter(Spray)	20	5662.17	314.56	

Table 73. Comparison of average competing seedlings and *Quercus rubra* seedlings heights (cm) after five growing seasons at the Stephens site. The comparisons are separated by shelter, herbicide, and root class treatments

	Sample Size	Avg. Height (cm)	Standard Deviation
Sheltered			
Sprayed			
Root class 0-4	5	61.65	41.91
Root class 5-9	6	87.00	42.51
Root class ≥ 10	6	84.92	39.46
Non-sprayed			
Root class 0-4	9	33.14*	8.00
Root class 5-9	6	44.13*	16.33
Root class ≥ 10	8	50.37*	18.57
Non-sheltered			
Sprayed			
Root class 0-4	6	42.60*	14.04
Root class 5-9	6	42.61*	7.72
Root class ≥ 10	6	53.59*	13.50
Non-sprayed			
Root class 0-4	10	30.41*	8.86
Root class 5-9	10	40.42*	8.51
Root class ≥ 10	10	50.50*	10.01
Competition			
Sprayed	6	72.58	29.40
Not sprayed	10	76.47	16.99

*significantly different from competition at the 0.05 level

Table 74. Anova of average competing seedlings and *Quercus rubra* seedling heights after five growing seasons for 1-0, *Quercus rubra* seedlings underplanted on the Stephens site

Source	df	ss	ms	F
Root Class	3	12309.11	4103.04	6.65**
Root Class*Spray	4	8828.62	2207.16	3.58*
Block*Root Class(Spray)	24	14798.05	616.59	
Non-Shelter	1	11140.52	11140.52	45.64**
Spray*Non-Shelter	2	438.04	219.02	0.89
Root Class*Non-shelter	2	1982.38	991.19	4.06*
Root Class*Spray*Non-shelter	2	229.33	114.66	0.47
Block*Root Class*Non-shelter(Spray)	24	5857.83	244.07	
Shelter	1	2660.97	2660.97	3.09
Spray*Shelter	2	12560.77	6280.39	7.30**
Root Class *Shelter	2	2389.65	1194.82	1.39
Root Class*Spray*Shelter	2	457.55	228.77	0.27
Block*Root Class*Shelter(Spray)	24	20654.29	860.59	

* significant at the 0.05 level
** significant at the 0.01 level

DISCUSSION

This study focused on the impact seedling root systems, tree shelters, understory competition, and overstory competition have on establishing underplanted, 1-0, *Quercus rubra* seedlings. Results indicate that using tree shelters and root grading had the greatest impact on growth and survival of underplanted *Quercus rubra* seedlings.

Height, Caliper, Mortality, and Tree Shelters

Shelters altered annual height growth, annual basal diameter growth, and annual mortality of underplanted, 1-0, *Quercus rubra* seedlings for all five growing seasons. By the end of the first three growing seasons sheltered seedlings grew 110 percent more (9.3 cm) in height growth than non-sheltered seedlings at the McNay site (Figure 7A) and 243 percent more (7.89) in height growth than non-sheltered seedlings at the Stephens site (Figure 8A). This increase in height growth is due to improved micro-environments with in the shelters (Lantange, et al., 1990; Zastrow and Marty, 1991). Minter, et al., (1992) found that micro-environments with in shelters had increased levels of CO_2 and relative humidity, which reduced plant transpiration losses.

Results from this study proves that the sheltered seedlings due not always maintain rapid height growth until the seedlings are out of the top of the shelter compared to non-sheltered seedlings. In 1994 and 1995 non-sheltered seedlings grew as much or more than sheltered seedlings at the McNay and Stephens site. By the end of 1995 non-sheltered seedlings out grew sheltered seedlings by approximately 205 percent (16.25 cm) in height growth at the McNay site (Figure 7A) and 236 percent (9.18 cm) in height growth at the Stephens site (Figure 8A). If the *Quercus rubra* seedling does not reach the top of the shelter in the first two to three growing seasons, then the non-sheltered seedling out grows the sheltered seedling in height. This increase in height growth is probably due to a fully exposed crown and a more balance root to shoot ratio that can support increased growth. Sheltered seedlings have rapid height growth initially which probably creates an unbalanced shoot to root ratio (Zaczek, 1994). This initial rapid height growth for sheltered seedlings comes at the expense of the root system, which probably results in less height growth in later years. The reduced height growth in the later years is probably due to sheltered seedlings building their root systems in order to have a balanced shoot to root ratio.

By the end of the first three growing seasons, the trend was for non-sheltered seedlings to grow more in basal diameter than sheltered seedlings, 17 percent (0.01 cm) and 50 percent (0.03 cm) more at the McNay site (Figure 7B) and at the Stephens site (Figure 8B) respectively. However, this difference in basal diameter growth was not statistically different. By the last growing seasons (1995), sheltered seedlings, statistically, had less basal diameter growth than non-sheltered seedlings for both the McNay (Figure 7B) and Stephens (Figure 8B) sites. In 1995, non-sheltered seedlings had grown approximately 213 percent (0.17 cm) more than sheltered seedlings in basal diameter growth at the McNay site (Figure 7B) and approximately 217 percent (0.13 cm) more than sheltered seedlings in basal diameter growth at the Stephens site (Figure 8B). The reduced basal diameter growth for sheltered *Quercus rubra* seedlings is probably related to the fact that the sheltered seedlings have less photosynthate available for basal diameter growth and are putting more resources in to trying to maintain and support its height and height growth. In order for the seedling to support its height and height growth, during active shoot growth about 90 percent of the translocated photosynthate is transported upward to the developing leaves and stem (Dickson, 1991; Isebrands, et al., 1994a). During active shoot growth, basal leaves translocate more photosynthate to the lower stem and roots, while the apical leaves are translocating more photosynthate to the developing shoot (Isebrand, et al., 1994a). Because of the shelter restricting the crowns, basal leaves of sheltered seedlings are probably receiving less photosynthetic active radiation than non-sheltered seedlings, and therefore are producing less photosynthate for translocation to the lower stem and roots during active shoot growth compared to non-sheltered seedlings . This could create an unbalanced shoot to root ratio which would have a negative effect on growth and survival.

In 1991 and 1992, sheltered seedlings had less annual mortality or as much annual mortality as the non-sheltered seedlings at the McNay (Figure 7C and Table 6) and Stephens (Figure 8C and Table 6) sites. The 1993 growing season seems to be the turning point in performance of sheltered and non-sheltered seedlings. At the end of the 1993 growing season, there was no statistical difference in annual mortality between the sheltered and non-sheltered seedlings on the McNay site (Figure 7C). Eight out of 186 sheltered and five out of 164 non-sheltered seedlings that were alive at the end of the 1992 growing season had died on the McNay site. At the end of the 1993 growing season, on the Stephens site, sheltered seedlings had approximately 300 percent greater annual mortality than non-sheltered seedlings (Figure 8C). Fifteen out of 199 sheltered and four out of 181 non-sheltered seedlings that were alive at the end of the 1992 growing season had died on the Stephens site. In 1994 and 1995, non-sheltered seedlings had less annual mortality than sheltered seedlings at the McNay (Figure 7C) or Stephens (Figure 8C) sites. By the end of the 1995 growing season, sheltered seedlings had 900 percent and 1000 percent more annual mortality than non-sheltered seedlings at the McNay and Stephens sites, respectively. Thirty two out of 158 sheltered and four out of 158 non-sheltered seedlings that were alive at the end of the 1994 growing season had died on the McNay site. Thirty out of 138 sheltered and four out of 176 non-sheltered seedlings that were alive at the end of the 1994 growing season had died on the Stephens site. After 1993, sheltered seedlings had an increase in the rate of annual mortality, where non-sheltered seedlings had a lower constant rate of annual mortality. Within the first two growing seasons, *Quercus rubra* seedlings had significant differences in total mortality between sheltered and non-sheltered seedlings, with non-sheltered seedlings having greater total mortality than sheltered seedlings (Table 37). By the fourth or fifth growing seasons, sheltered *Quercus rubra* seedlings had significantly greater total mortality than the non-sheltered seedlings. By the end of the fifth growing season, total mortality of sheltered seedlings ranged from 40 to 55 percent compared to non-sheltered seedlings, which ranged from 26 to 28 percent. The seedlings are dying inside the shelter. Review of the literature shows that most studies dealing with survival between sheltered and non-sheltered seedlings have been in large forest openings, e.g. clearcuts, or have been based on two to three years of results. Results from the studies by Teclaw and Isebrands (1991), Ward and Stephens (1995), and Lantange (1995) indicate that sheltered seedlings have greater survival. Ward and Stephens' (1995) results indicate that shelters reduced *Quercus rubra* seedling mortality by 75 percent compared to non-sheltered *Quercus rubra* seedlings. These studies were either done in clearcuts or are based only on two to three years of results. The seedlings protected by shelters in the open are probably receiving enough light that these seedlings are able to put excess photosynthate into height growth and development of an adequate root system. This allows the seedlings to reach the top of the shelter in two to three years. For the short term studies (two to three years) in which the protected seedlings are underplanted, the seedlings are probably relying on their stored carbohydrates in order to support their growth and maintain their existence. The other possibility is that the sheltered seedlings in these short term studies have not yet become enough out of balance in the root to shoot ratio to become fatal. Similar results were found in this study during the first and second growing season. At the end of the 1991 growing season, sheltered seedlings at the McNay site had approximately 36 percent less mortality than non-sheltered seedlings. At the end of the 1992 growing season, sheltered seedlings at the McNay site had approximately 50 percent less mortality than non-sheltered seedlings. Similar results were obtained during the first and second growing seasons at the Stephens site, where sheltered seedlings after the 1991 growing season had approximately 50 percent less mortality than non-sheltered seedlings, and after the 1992 growing season had approximately zero percent less mortality than non-sheltered seedlings.

Response surface results indicate that shelters may be having an adverse impact on total height growth, total basal diameter growth, and total survival. When optimum ranges are explored, *Quercus rubra* seedlings without shelters often had no optimum or maximum optimums, but sheltered seedlings would often have minimum optimums.

This decrease in height growth, basal diameter growth, and increase in mortality for sheltered seedlings are probably related to rapid growth the first two to three growing seasons, possibly reduced leaf surface area exposed to photosynthetic active radiation caused by the shelter constricting the crown, and possibly a reduced root system. The rapid growth the first two to three growing seasons by sheltered seedlings produced a larger seedling that requires larger quantities of photosynthate to maintain itself, as well as, to support continued growth. It is possible that to support its size and continued growth, the seedling is using up more stored carbohydrates than it is storing, therefore, the seedling is experiencing a net loss in stored carbohydrates. The shoot to root ratio is probably also out of balance creating an additional strain on the seedling. By the third growing season the crowns of the sheltered seedlings were constricted by the shelter, which likely reduced the leaf surface area, leading to possibly reduced quantities of photosynthate being produced. For the seedling to support its growth, which is predetermined the previous year (Dickson 1991), the seedlings probably continued to deplete their stored carbohydrates and could not continue to support growth the fourth and fifth growing seasons, and that, in some cases, lead to death. Even though growth is predetermined in *Quercus rubra* seedlings the previous year, the current growing season conditions have an impact on the seedlings needs for meeting the predetermined growth. Moisture is significant in determining how much the cells expand and elongate. During the 1994 growing season precipitation was well below normal (Table 1). The lack of moisture, along with unbalanced shoot to root systems on sheltered seedlings, probably helped contribute to the impact shelters had on annual growth and mortality in 1994. By the third growing season, non-sheltered seedlings probably had larger crowns and a more balanced root to shoot ratio than sheltered seedlings. The larger crown meant larger leaf surface area exposed for capturing photosynthetic active radiation and supporting a larger seedling.

Sheltered seedlings that were alive at the end of the first five growing seasons were approximately 34 percent taller in height than non-sheltered seedlings at the end of 1995, at the McNay site; and were approximately six percent taller in height than non-sheltered seedlings at the end of 1995, at the Stephens site (Table 37). Sheltered seedlings on the McNay and Stephens sites reached maximum heights in 1994, with no statistical differences in total height in 1995. By the end of the fifth growing season sheltered seedlings were approximately 1/3 to 1/2 the height of the 122 cm tall tree shelter. The sheltered seedlings were taller than the non-sheltered seedlings because of the rapid height growth the sheltered seedlings had during the first two to three growing seasons. This rapid growth could not be maintained by the sheltered seedlings because the constricted crowns probably could not produce enough photosynthate. Also if the sheltered seedlings have an unbalanced shoot to root ratio then the large top and any additional height growth could not be supported by the smaller root system. Similar results were found by Walters (1993) after only two years. Walters (1993) found that sheltered *Quercus rubra* seedlings the second year had no significant difference in height between sheltered *Quercus rubra* seedlings and fenced *Quercus rubra* seedlings, with both sheltered and fenced *Quercus rubra* seedlings taller than unprotected *Quercus rubra* seedlings. Walters believes that deer browse is why there is the difference in height between the unprotected and protected *Quercus rubra* seedlings.

Results from this study indicate that tree shelters may not be biologically feasible in the establishment of underplanted, 1-0, *Quercus rubra* seedlings. Tree shelters seem to be detrimental to establishing underplanted *Quercus* *rubra* seedlings after the end of the first three growing seasons. It may be possible to remove the tree shelters after the first three growing seasons if the seedlings do not need the tree shelters for support. This may save those seedlings that would possibly not last until they reached the top of the shelter. Removal of the tree shelter by the third growing season would allow for expansion of seedling crowns; which otherwise would be constricted by the tree shelter. Tree shelters seem to be feasible under specific conditions in which seedlings receive enough light and other resources needed for seedlings to grow out of the shelter within three years. Tree shelters still remain a high cost alternative to establishing *Quercus rubra* stands or plantations where deer browse is so heavy that the use of tree shelters is the only method of establishing *Quercus* regeneration (Bardon, 1992).

Root Class and Seedling Performance

Separating the underplanted *Quercus rubra* seedlings by root class significantly affected total height growth, but not total basal diameter growth or mortality, after the first five growing seasons both at the McNay and Stephens sites. *Quercus rubra* seedlings with five or more permanent, first-order, lateral roots had 93 and 407 percent or greater total height growth at the McNay and Stephens sites, respectively, compared to seedlings with 0-4 permanent, first-order lateral roots. The increased total height growth is because of the large number of permanent, first-order, lateral roots at the time of planting. The permanent, first-order, lateral roots form the basic framework for the new root network (Struve, 1990). The more permanent roots at the time of planting, the greater the potential for growth. This finding is consistent with research done by Schultz and Thompson (1991). Schultz and Thompson have shown that *Quercus rubra* seedlings with six or more permanent, first-order, lateral roots generally have greater height growth than those with fewer permanent, first-order, laterals. This performance was expected because of the larger root system. The larger the root system the better the seedling performs. Research by Teclaw and Isebrands (1993b), which is consistent with research by Schultz and Thompson (1991), demonstrated that seedlings with larger root systems can be used in regeneration plantings on dry mesic sites in the Lake States, USA.

Results from this study, Schultz and Thompson (1991), and Teclaw and Isebrands (1993a) indicate that resource managers need to plant seedlings with at least 5 or more permanent, first-order, lateral roots greater than 1 mm for the seedlings to compete successfully.

Undercutting had no impact on growth or mortality at the end of the first five growing seasons. Similar results were found by Zaczek, et al. (1993) in which undercutting seedlings in the nursery prior to planting had no impact on height growth after three years. It is most likely that separating seedlings into root classes prior to planting removed any effect of undercutting. Undercutting is probably significant at the nursery where the nursery can manipulate a seedling. Schultz and Thompson (1991) have demonstrated that undercut seedlings tend to have larger numbers of permanent first-order lateral roots than seedlings that are not undercut.

Light, Stand Density, Stocking, and Seedling Performance

An inverse relationship does not exist between percentage of full sunlight and basal area or a combination of basal area, average stand diameter at breast height, and number of trees per hectare (5.08 cm or greater in diameter at breast height). The lack of relationships are probably related to the large variation in light under forest canopies. Gatherum (1961) found that variation in measurement of light intensity increased as one moved from a clearcut to increased understory vegetation. This large variation in light among basal area in the current study is probably related to the variation in the amount of understory vegetation and overstory trees. Many of the sensors measuring photosynthetic active radiation were lower than the existing understory vegetation, therefore the sensors were not just measuring light below a mature overstory canopy, but also under an additional layer of vegetation, the understory competition. Another point that probably should have been considered in the design, but was not, is that 15 square meters of basal area at five cm average stand diameter will have a different light regime than 15 square meters of basal area at 38 cm average stand diameter. In order to try and develop a specific relationship between light and basal area, basal area and stand diameter would have to be replicated many more times than was feasible in this study.

Poor relationships were found between growth or mortality, and percent full sunlight, ratio of red to far red light, leaf area index, basal area,average stand diameter, number of trees per hectare, percent stocking, and combinations of the fore-mentioned variables. The lack of response in growth and survival are probably related to the fact that *Quercus rubra* seedlings under stress will allocate photosynthate in excess of respiration to root development (Dickson, 1991). Under less than favorable conditions caused by overstory and understory competition, excessively high rainfall (during 1993 growing season) and lack of rainfall (1994), and transplant shock (1991-1992), *Quercus rubra* seedlings will stop top growth and allocate photosynthate to root growth and storage (Dickson, 1991). Under less than favorable conditions *Quercus* often will only have one growth flush per season (Reich, et al., 1980).

What seems to be occurring is that *Quercus rubra* seedlings build a root system that will support rapid growth once the *Quercus rubra* seedling is released from competition. The lack of multiple flushes in the field and dying back and resprouting are important to the life of *Quercus* species in the drier ecosystems because they facilitate the development of large root systems and large root to shoot ratios, which in turn effect rapid shoot growth once the seedlings are released (Sander, 1971; Johnson, 1979; Reich, et al., 1980). This physiological response is probably related to *Quercus rubra* adapting to growing and surviving on dryer sites as well as sites prone to fire. Other evidence that supports the fact that *Quercus rubra* seedlings are developing their root system at the expense of shoot growth is that *Quercus rubra* seedlings are known to die back and resprout. Merz and Boyce (1956) have shown that seedlings that appear to be from one to five years old based on their stem actually are sprouts that had root systems approximately 40 years old. In an unpublished study 60 *Quercus rubra* natural regeneration plants on the Stephens site had similar results with stems ranging from one to six growth rings and root systems ranging from three to 18 growth rings. It is most likely that growth rings in the study are actually stem and root ages, but since it is possible for *Quercus rubra* to have multiple flushes the values are reported as growth rings.

The level to which the overstory should be reduced depends on the ecosystem being manipulated, but some reduction of the overstory is necessary to establish underplanted *Quercus rubra* seedlings. Depending on the ecosystem, overstory competition should be reduced to levels suggested by Sander (1977), Teclaw and Isebrands (1993a, 1993b), or Johnson (1994).

Understory Competition and Seedling Performance

An integral part of establishing *Quercus rubra* is disturbance. In the past fire was the most frequent form of disturbance that promoted the establishment of *Quercus rubra* regeneration (Van Lear and Watt, 1992; Johnson, 1994; Guyette and Dey, 1995). Fire would burn through a site, often releasing *Quercus rubra* seedlings from competition. This sudden release from competition would correspond to a sudden increase in growth by *Quercus rubra* trees present on the disturbed site (Guyette and Dey, 1995). Since fire is no longer a major part of the forest ecosystems in southern Iowa (Thompson, 1992), some other form of disturbance is needed to release the *Quercus rubra* regeneration from its competition. Removal of all non-*Quercus* trees and treating their stumps with herbicide, and herbicide application to the remaining understory less than 2.54 cm in dbh was used to release *Quercus rubra* seedlings from its competition in this study. The reduction of competition by herbicide application was significant during the first year of this study (Bardon, 1992).

At the end of the five growing seasons, at the McNay site, the underplanted *Quercus rubra* seedlings were as tall as the competition (Table 71). Separating the *Quercus rubra* seedlings by root class, spraying the area with herbicide prior to planting, or using tree shelters to protect the *Quercus rubra* seedlings had no impact on total height of *Quercus rubra* seedlings when compared to the competing understory vegetation at the McNay site (Table 72). Broadcast spraying of herbicide had no impact on total height comparisons between *Quercus rubra* seedlings and the understory competition. The lack of herbicide impact on total height comparisons is because of the crew doing the initial thinning during the 1990-1991 winter of the McNay site. The crew was only supposed to remove non-*Quercus* woody vegetation greater than 2.54 cm dbh. The woody vegetation less than 2.54 cm dbh that was left would then be the basis for the testing of broadcast spraying of herbicide. The crew removed all understory and overstory non-*Quercus* woody vegetation, no matter what size the woody vegetation was, consequently creating the same effect as broadcast spraying the whole area. Another significant factor affecting impact of herbicide on total height is that much of the area prior to thinning and spraying was under a dense understory of *Ostrya virginiana*, in which there was not much else growing.

The rapid growth the first couple of growing seasons at the Stephens site for *Quercus rubra* seedlings inside the tree shelters and the reduction of competition by applying herbicide prior to planting contributed to the seedlings being as tall as the competition after the first five growing seasons (Table 73 and 74). Results from this study, as well as studies by others, have shown that if *Quercus rubra* seedlings are released from competition then they are capable of competing in the understory (Lorimer, 1989; Teclaw and Isebrands, 1991). These results are consistent with Coder (1985), Lorimer (1989), and Teclaw and Isebrands (1991) who indicate that reducing understory vegetation may be as important as controlling overstory shade. Controlling understory vegetation with herbicide increases the amount of light reaching the *Quercus rubra* seedlings as well as controlling the amount of understory competition after the shelterwood is removed (Johnson, 1994).

Results from this study suggest that understory control is needed at the time of planting for the underplanted, 1-0, *Quercus rubra* seedlings to maintain at least the same height as the understory competition after five growing seasons. Herbicide or mechanical methods are needed to reduce the amount of understory competition. For the underplanted, 1-0, *Quercus rubra* seedlings to maintain dominant and codominant positions in the understory competition, herbicide or mechanical methods of reducing the understory competition should be used until the *Quercus rubra* seedlings reach approximately 1.5 m in height (Sander, 1977). When the *Quercus rubra* seedlings are approximately 1.5 m in height the remaining overstory should be removed to release the underplanted seedlings. Review of the literature suggest removing the overstory three growing seasons after planting (Johnson, et al., 1986), but this study suggests that the underplanted *Quercus rubra* seedlings may not be tall enough. So the exact time of overstory removal should depend on the height of underplanted seedlings.

CONCLUSION

Results of this study indicate using shelters and root grading had the greatest impact on survival and growth of the underplanted seedlings. Annual survival and growth of non-sheltered seedlings was greater than sheltered seedlings after three growing seasons. Survival of non-sheltered seedlings was greater than sheltered seedlings after five growing seasons. Underplanted, 1-0, *Quercus rubra* seedlings with five or more permanent first-order, lateral roots had greater height growth compared to seedlings with 0-4 first-order, lateral roots. Poor relationships were found between growth or mortality, and photosynthetic active radiation, red to far red light ratio, basal area, average stand diameter, number of trees per hectare, percent stocking and combinations of the fore-mentioned variables. Spraying and mechanical clearing of the understory prior to underplanting allowed *Quercus rubra* seedlings to maintain a competitive position in the understory.

Based on the literature (Sander, 1977; Teclaw and Isebrands, 1993ab; Johnson, 1994) and results of this study, to have a *Quercus* component in future stands intensive management is needed on good quality sites. More intensive management means planting high quality seedlings, removing undesirable understory competition, and reducing the overstory competition. In most cases, tree shelters should not be used in establishing underplanted, 1-0, *Quercus rubra* seedlings because they are not biologically or economically feasible (Bardon, 1992).

To establish underplanted *Quercus rubra* seedlings in south central Iowa, resource managers should: (i) plant 1-0 planting stock that have at least five or more permanent, first-order, lateral roots greater than 1 mm in diameter, (ii) use herbicide or mechanical methods to reduce the amount of understory competition at least at the time of planting and preferably up to three to five years after planting, (iii) reduce the overstory to approximately 60 percent stocking (Johnson, 1994), and (iv) remove the remaining overstory when the underplanted *Quercus rubra* seedlings are 1.5 m in height (Sander, 1977).

This study is one of the few studies on *Quercus rubra* regeneration that has lasted greater than three years and should be continued in order to determine if the underplanted *Quercus rubra* seedlings will become a major component in the new stand. Further research is also needed in order to understand the genetic and adaptive strategies of *Quercus rubra* seedlings.

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