To the Graduate Council:

I am submitting herewith a thesis written by Jason P. Hartman entitled "Northern Red Oak Regeneration in Oak and Pine Stands: Long-term Effects of Mechanical Competitor Removal and Short-term Effects of Prescribed Fire." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

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NORTHERN RED OAK REGENERATION IN OAK AND PINE STANDS: LONG-TERM EFFECTS OF MECHANICAL COMPETITOR REMOVAL AND SHORT-TERM EFFECTS OF PRESCRIBED FIRE

A thesis presented for the Master of Science Degree

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Jason P. Hartman
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To my father and grandfather, who took me along on outdoor pursuits while I was young

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Abstract

Northern red oak (*Quercus rubra*) stands in northern lower Michigan are maturing on intermediate quality sites formerly dominated by mixed red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) forests. White pine and red maple (*Acer rubrum*) regeneration has been more prevalent than oak regeneration in oak stands throughout several forest regions of eastern North America. It has been hypothesized that the absence of wildland fire is supporting greater components of red maple in the present oak/pine stand type than in presettlement stands.

Maintaining the current oak resource has become a priority for forest managers, in Michigan and elsewhere, due to the high wildlife and timber values oak provides. Factors such as canopy composition, cover, and fire may influence oak regeneration by affecting red maple competition, late spring frosts, and deer browsing. Questions need to be addressed regarding effects of specific treatments on oak regeneration success in regions where hardwoods did not dominate historically.

Objectives included: 1) Testing the hypothesis that prescribed burning will reduce the abundance and cover of red maple and other competitors relative to oak, 2) Testing the hypothesis that oak seedling pre-burn height and/or basal diameter can be used to predict post-burn sprout growth, and 3) Investigating effects of interactions between prescribed fire and forest cover type (oak vs. pine), canopy cover, and deer browsing on oak and competitors of oak.

Study sites consisted of three natural northern red oak stands and three red pine plantations. Overstory removal treatments and understory manipulations were completed in 1991, when northern red oak acorns and nursery seedlings were planted with and without protection from browsing. Natural regeneration and planted oaks were measured and evaluated for growth and mortality July through August, in 2001 and 2002, before and after prescribed burning.

One decade after initial treatment, before prescribed burning, red maple density was already significantly less abundant in pine stands compared to oak stands. Mortality of planted oak seedlings was greatest in pine clearcuts and lowest in plots originally thinned to 75% canopy cover plots within pine stands. Caged seedlings exhibited greater survival in pine stands while uncaged seedling survival was nearly equal between cover types. Natural oak regeneration was significantly most abundant in plots originally thinned to 25% canopy cover plots within oak stands.

Prescribed fire was applied across all replicates in May, 2002. Following burning, the 25% canopy treatment within oak stands maintained significantly more oak stems than all other treatments. Post-burn oak sprout growth was greatest in clear-cut and 25% cover plots. Nearly all red maple < 2m tall were top-killed, while many larger maple sustained bark damage and infection by pathogenic fungi. These stressed stems sprouted prolifically even though the main stem survived. A noticeable increase in deer browsing of red maple compared to previous years was documented. Following burning, the percentage of uncaged oak seedlings browsed decreased in all plots within oak stands and increased in pine shelterwood plots. Results indicated that, on intermediate sites, a pine canopy had more negative effects on red maple development than did a single prescribed fire. Therefore, prescribed burning to control understory competitors was less critical in pine than in oak stands on these sites. The results also suggested that prescribed fire use is most successful for maximizing oak regeneration in oak shelterwood stands with 25-50% canopy cover, where oak regeneration was present before burning. First year fire effects indicated that red maple control was most successful in uncut plots. Future sampling will be needed to determine the effect fire had on larger red maple saplings in clear-cuts and 25-50% canopy cover treatments.

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Chapter 1: Review of Literature

Oak values

Together, the forest products and forest recreation-based tourism industries contribute $3.5 billion annually to the Michigan economy (North Central Research Station 2003). In 1994, wages earned in the forest products industry totaled $1.8 billion and the total value of shipments was approximately $9.1 billion (Schmidt et al 1997). Forest Inventory Analysis data (1993) indicated that approximately 453,166 ha of oak dominated forests are present in the northern Lower Peninsula of Michigan, which contribute substantially to the economic vitality of the region.

Oak species are the dominant mast producers in the eastern United States. One hundred and eighty six different species of game and non-game wildlife feed in one way or another on some portion of oak tissue (Van Dersal 1940). Several wildlife species depend on oak mast for more than 25% of their diet, including the wood duck (*Aix sponsa*), wild turkey (*Meleagris gallapavo*), squirrel (*Sciurus spp.*), blue jay (*Cyanocitta cristata*), raccoon (*Procyon lotor*) and black bear (*Ursus americanus*) (Martin et al. 1951). White-tailed deer (*Odocoileus virginianus*) also extensively utilize oak mast and browse. Thus the presence of oak affects hunting opportunities and, in turn, forest recreation-based revenue.

Oak physiology

Viable seed is the first factor affecting oak reproduction. The *Quercus* genus tends to have large variations in seed crops (Crow 1988). However, the unpredictability of seed production may be reduced through overstory thinning. Differences in mast production were found to be greatest between thinned and unthinned stands when overall production was the lowest (Healy 1997), which indicated that tree vigor had substantial impacts on acorn production.

White oaks take only one season to develop relatively small acorns that germinate in the fall. Red oak acorns take two years to mature into a larger and heavier acorn than white oak and germinate in the spring (Rogers 1990). Oak germination is best when acorns are in contact with mineral soil and buried below the litter (Sander 1990). The physiological characteristics of oak acorns may impact germination following seed dissemination into different seedbed environments.

Growth patterns of juvenile oaks have been described as semi-determinate compared to the steady, indeterminate growth of *Populus* species and the determinate growth of white pine (*Pinus strobus*), both of which flush only once each season (Dickson 1991). The oak seedling physiological characteristic of non-constant, but somewhat predictable pattern of stem elongation may be related to their ability to respond vigorously when damaged.

Young oak seedlings allocate a larger proportion of photosynthate to root growth than to stem elongation (Dickson 1991). Nutrient redistribution toward roots usually occurs following the first spring flush (Dey 1996), making spring the ideal season for rapid height growth. Dickson (1991) concluded that the ideal northern red oak seedling would produce two or three flushes of growth early and use the remainder of the growing season for root growth, caliper growth, and starch storage. Crow (1988) found that as many as six to eight flushes of terminal growth can occur within a few months under controlled greenhouse conditions and concluded that the potential for rapid seedling growth is very great. In the field, however, increased numbers of spring flushes may only be possible if seedlings exhibit a higher proportion of root compared to shoot mass. Harmer (1990) found that root growth did not decrease during periods when stem elongation increased, which indicated that root growth might not be negatively affected as oak stems are continually top-killed and re-sprout. Research has indicated that large root systems of oak seedlings have benefited more than hindered oak competitive ability during periods of increased rates of disturbance (Crow 1988).

In general, oaks can maintain photosynthesis during drought (Abrams 1992) through "adaptations including deep roots, xeromorphic leaves, low water potential threshold for stomatal closure, and the ability to adjust osmotically" (Abrams 1990). Northern red oak has low to intermediate tolerance of shade compared to competitors, such as red maple and sugar maple, and is the least drought-tolerant within its genus, restricting it to more open mesic sites (Crow 1988, Ashton 1994). Increased abundance of shade tolerant competitors with increased site productivity makes the importance of high disturbance rates more pronounced on more productive sites (Abrams 1992).

Symbiotic interactions between residual trees and oak seedlings may exist, but are not easily revealed. It has been hypothesized that ectomycorrhizae may enhance a seedling's ability to acquire increased soil resources if they are growing in an environment where resources are not already abundant. Zhou (1998) found that partial canopy cover produced greater root/shoot ratios and increased the incidence of ectomycorrhizal (ECM) development, while clear-cut treatments produced the least amount of ECM infection. Increased infection of northern red oak seedlings with symbiotic ectomycorrhizal fungi has been documented when northern red oak seedlings are grown in close proximity to chestnut oak (*Quercus montana*) stumps (Dickie 2002). Dickie (2002) suggested, "while indirect facilitation between overstory trees and oak seedlings occurs on all sites, it is usually overridden by competition at high stem densities."

Oak physiological characteristics may be beneficial as disturbances gradually break up the canopy. Oaks were able to compete in uneven-aged stands prior to European settlement (Abrams 1992, Lorimer 1994) and episodic growth patterns that occurred in periods of increased availability of light and nutrients (Barnes and Wagner 1981) may have enabled oak to compete in these forests. In Michigan, partial canopy cover may indirectly enhance growth rates of northern red oak seedlings by reducing negative impacts of frost and browsing, which are most severe with little vegetative cover (Buckley et al. 1998).

Red maple physiology

Red maple is one of the first trees to flower in the spring and can be a fruitful seed producer in the sapling stage. A sawlog size tree can produce up to one million seeds each year and red maple samaras are among the lightest of maple fruits (Walters and

Yawney 1990). Germination is best on moist mineral soil and optimum growth is achieved on northeast facing slopes. "Red maple can thrive on a wider range of soil types, textures, moisture, pH, and elevation than any other forest species in North America" (Walters and Yawney 1990). However, red maple can be limited by the affects of high acidity, low moisture, and greater rates of disturbance. In northern Lower Michigan, it is nearly completely absent in jack pine stands growing in relatively close proximity to hardwood stands where it thrives.

Physiologic characteristics cause red maple to have low resistance to fire (Abrams 1992, Brose et al. 2001). Consequently, the species has expanded past its traditional lowland range because of fire suppression (Barnes and Wagner 1981). One reason red maple is susceptible to fire is due to the prevalence of decay and stem rot fungi following wounding (Walters and Yawney 1990). Other diseases may also attack red maple through wounds created by fire. Verticilium wilt (*Verticilium albo-artrum*) is a common red maple disease in urban areas (Walters and Yawney 1990), but in the forest it persists as a soil borne fungus before establishing infections in root and stem wounds (USDA Forest Service 1979). Lower starch reserves compared to oak, and carbon allocation favoring rapid stem growth (Huddle 1999) may also cause red maple to have low resistance to fire by reducing it's ability to sprout vigorously once damaged.

Development of northern Michigan oak forests

Glacial disturbance

Glacial retreat coincided with increased charcoal abundance and oak dominance in eastern North America, accompanied by warmer and drier climatic conditions (Mason 1958, Davis 1985). The most recent retreat of glaciers from Michigan occurred approximately 10,000 years ago (Mason 1958). Following reorganization of the landscape, tree species composition in Michigan has changed continuously. Several temperature and moisture fluctuations affected the pathways of primary succession. During the late Wisconsian glacial maximum, forests of jack pine (*Pinus banksiana*) and spruce (*Picea spp.*) grew as far south as Middle Tennessee (Delcourt 1979). Throughout the eastern United States, spruce began to decline during the same period as glacial retreat. In Michigan, jack pine dominated for a short time, declined, and was replaced by more mesic pine species approximately 6,000 years ago (Mason 1958). In some areas, a transition to mixed pine/oak forest was catalyzed by a warming climate 4,000 years ago (Mason 1958). By 2,500 years before present, cooler climates again prevailed (Mason 1958). During this cooling period, eastern hemlock (*Tsuga Canadensis*) invaded the region and charcoal deposition largely ceased, implying a reduction in fire frequency (Lorimer 2001). During the period of A.D. 700-1,200, the climate returned to warmer and drier conditions, and was again followed by another moist and cool period that continued into the 19th century (Kapp 1999).

Post-glacial disturbance

Fires that perpetuate forests of oak and pine are usually human induced (Pyne 1982). Native Americans entered Michigan practically on the heels of retreating glaciers. The earliest appearance of man in Michigan can be dated to 13,500 years B.P. (Mason 1958). Native Americans were the keystone species in the Americas for several thousand years. They manipulated the landscape in a way that suited their needs, which implied that the common notion of expansive untrammeled wilderness, prior to European settlement, is simply a "pristine myth" (Mann 2002). Surveyors of the northern Lower Michigan interior describe areas as large as townships that were almost completely barren because they were burned over so often (Whitney 1986). The purpose of these intentional fires may have been to encircle game, increase browse, improve berry production, and/or conduct warfare (Pyne 1982). Fire was also used extensively to increase ease of travel.

The population of Chippewa in Michigan was about 30,000 when the Europeans arrived, not including other members of the "Council of Three Fires", the Ottawa and Potowatomi (Karpinski 1931). The interior region of northern Lower Michigan had low permanent populations compared to the southern part of the state (Voeglin 1974), which suggests a lower rate of fire return. However, Guyette and Dey (2000) conclude that indigenous population densities of .64 humans/ha are sufficient to "pyro-saturate" the landscape. Research indicated that ten times more surface fires occurred in pine stands near river mouths along the coast of Lake Superior before 1910 than after 1910 (Loope and Anderton 1998), suggesting fire frequency was increased near indigenous settlements. In Lower Michigan, several small bands of Chippewa from the East and Ottawa from the West annually left their coastal homes following rivers approximately 110-130 km to their wintering grounds in the interior (Voeglin 1974, Tanner, 1974). Chippewa regarded this region as impenetrable (Voeglin 1974). Several lowland swamps scatter the interior, where the headwaters of the Au Sable, Manistee, and Muskegon watersheds are located. Johnson (1992) suggested that trails through northern forest swamps were kept open through intentional spring fires. These portage connections soon connected to land routes as well. The Mackinaw and Saginaw trails ran directly through this region connecting Upper and Lower Michigan at the Straits of Mackinaw (Voeglin 1974). Fire frequency may have increased dramatically along these travel routes. Dey and Guyette (1996) documented a mean fire interval of 14 years on a presettlement travel corridor in south-central Ontario and concluded that the proximity of the site to travel routes accounted for the regularity of ignition. The extent of fire frequency across heavily traveled landscapes is well supported and can be considered one of the most likely causes for repeated fires affecting the development of pine stands with hardwood understories dominated by species such as oak.

Government Land Office records document surveyor descriptions of a stunted layer of hardwood regeneration in the understory of many of the mesic pine stands of the northern Lower Peninsula interior (Whitney 1986). Whitney (1986) used documentation of species of "witness" trees to calculate percentage of overstory species within different site types. Tree species composition within the mixed pine/pine-oak forest type was: *Pinus resinosa* 41 %, *Pinus strobus* 19%, *Pinus banksiana* 18 %, *Quercus spp.* 13 %, *Populus spp.* 5 %, and *Acer rubrum* only .4 %. Of the *Quercus* species, 9 % were identified as white oak and 4% red oak. White oak tends to have thicker bark than red oak (Lorimer 1985), and is better at compartmentalizing decay, suggesting that it is more resistant to reoccurring surface fires and was therefore able to survive longer than northern red oak in uneven aged stands (Lorimer 1985, Marks 1942). White oaks may dominate in old stands due to other characteristics as well. Goebel et al. (1997) found that white oak dominated the canopy compared to other oak species in stand development stages beyond stem exclusion.

Northern red oak received its greatest ecological advantage following stand-initiating disturbances from logging and fire (Crow 1988). The existence of northern red oak on high quality sites dominated by northern hardwoods may also be attributed to fires before and after logging disturbances (Abrams 1992). Michigan led the nation in production of pine lumber between 1870-1890 (Benson 1976). Following the logging era, the combination of thick continuous slash and ferocious winds produced very intense, landscape scale fires. More than one million acres burned each year in 1871, 1881, and 1908 (Sodders 1997). Kittredge and Chittenden (1929) suggested fire return intervals of nine years during these periods when fires burned over "large" areas of Michigan. From the period between 1911 and 1933, fires burned over 100,000 acres of the state at an average rate of every other year (Sodders 1997).

Intense fires consumed nearly the entire organic surface horizon in some areas. Farmers homesteaded on these soils, which they soon found unsuitable for food production. Fires killed most of the pine left behind by loggers, destroying the seed source necessary for pine re-establishment (Whitney 1986). Species with physiological characteristics for vigorous sprouting and early seed dissemination dominated the landscape at the expense of white and red pine, which do not resprout and develop cones later in life.

The glacial landforms in northern Michigan affected the distribution of ecotypes as well as the disturbance regimes they facilitated (Host and Pregitzer 1992). Landform position affected frost patterns and consequently the distribution between jack pine and deciduous species that are tolerant and intolerant of growing season frosts, respectively (North Central Research Station 2003).

Following the effects of logging and fire, the northern Michigan whitetail deer (*Odocoileus virginianus*) herd drastically increased to an estimated 1 million animals. Unregulated hunting decimated the population, but game laws were established in the 1940's, which resulted in herd growth to more than 1.5 million animals with the majority living in the northern part of the state (Michigan Department of Natural Resources 2003).

Fire Suppression

"The situation left one choice: mechanize or burn" A.A. Hartman USFS 1949 (Pyne 1982)

The attempted farming of the north woods between 1870 and 1920 catalyzed fires that brought about major socioeconomic reforms. Fire control became the responsibility of state government. In 1925, Michigan established the Forest Fire Experiment Station at Roscommon. Under direction of the Department of Conservation, the facility became the nation's center for heavy firefighting equipment research (Pyne 1982). The commitment to equipment development and fire behavior research gave Michigan an unusually strong suppression organization (Pyne 1982), which resulted in a major reduction of acreage burned by wildfire.

The oak- pine relationship

"Probably millions of acres of existing oak forest, both in the northeast and southeast originated as an understory beneath a pine canopy" (Lorimer 1992)

Oak species were able to maintain themselves in forests dominated by pine throughout history. Studying pollen deposits in the New Jersey Pine Barrens, Forman (1998) concluded that oak and pine association could be traced well into pre-history, approximately 14-65 million years ago. The pattern of white pine regeneration in oak stands has been attributed to white pine redevelopment following its exploitation. However, this effect may have occurred before Europeans substantially altered forest ecosystems. In 19^{th} century New England, Henry David Thoreau described white pine invading the understory of oak stands and oak invading the understory of pine stands (Whitney and Davis 1986).

The presence of oak stands on sites previously dominated by pine, the current development of pine beneath oak stands, and oak seedling presence under pine canopies indicate a possible cyclic relationship between these species (Crow 1988, Sarnecki 1990, Johnson 1992). However, it cannot be expected that oak and pine will necessarily continue to interact as they had in the past. White pine reinvasion of hardwood sites was found to be unpredictable due to several allogenic and autogenic factors, several of which were affected by variation in fire return intervals (Sharik et al 1989). Crow (1988) suggested that a realistic goal, in areas where pine dominated historically, would be to manage northern red oak in mixed stands.

Even-aged mixtures of oak and pine are common in the southeast. In discussing silvicultural techniques for even- aged stands of cherrybark oak (*Quercus pagoda*) and loblolly pine (*Pinus taeda*), Clatterbuck (1989) suggested a two-age technique in which faster growing pine can be thinned to release slower growing oaks. The description of this technique was similar to those practiced in Europe between oaks, spruce, and/or larch (Penistan 1974).

In Michigan, hardwood species account for 72% of the total volume of growing stock, while red pine has the greatest average growing stock volume per hectare of any species in the region (North Central Research Station 2003). Market prices for small diameter stems are important when determining if one species should be used in the establishment of another. Generally, high quality oak sawlogs are more valuable than pine sawlogs. In contrast, pine pulpwood is sold at higher prices compared to hardwood pulpwood.

Puettmann and Saunders (2000) conclude that established white pine is capable of replacing hardwood stands and can be released to promote increased growth rates. Taking advantage of the initial volume in small pole sized pine trees, while still managing for oak recruitment, may increase the overall timber output within each stand. In stands where very few pole-sized oaks exist, releasing well-established pine shouldn't necessarily preclude oak seedling development. After years of visual documentation, managers in Michigan suspected that pine species provide thermal protection by creating "greenhouse-like" conditions favorable for oak survival (Michigan Department of

Natural Resources 2000). They also suggested that in order to benefit from frost protection, twenty-five percent crown cover must be retained, in pine stands, while 40-50% is necessary in hardwood stands. Releasing mid-story white pine while maintaining light availability may reduce the need to retain so many oak canopy trees within a shelterwood treatment that are too old in order to benefit from crop tree release and most likely will not increase seed yield when competition is reduced.

Researchers have indicated that blue jays prefer to live in evergreen forests and hide far more acorns than they eat (Sanford 1984). Therefore, blue jays play a critical oak establishment role in pine stands where there is not an oak seed source in the immediate vicinity. Caching of acorns in pine litter may disseminate acorns into ideal locations for early oak seedling regeneration. A pine canopy may indirectly benefit oaks when they are initially established by creating conditions unsuitable for competitor establishment. Very little understory growth occurs in pine stands with high stem density due to low amounts of soil moisture (Anderson et al 1969). The herb-layer in pine stands is often dominated by blueberry (*Vaccinium spp.*). Young oak seedlings were found negatively correlated with blueberry cover, while sapling density and blueberry were positively correlated (Frederickson et al 1998). The effects described by Frederickson (1998) and Anderson (1969) indicated that when oak seedlings are first established, reduced soil moisture, and consequently reduced herbaceous competition, benefited oak seedling survival, while increased herbaceous competition resulting from increased resources was less inhibiting when they grew into the larger size class because the larger oak seedlings were able to compete for increased resource availability. Thus, increased herbaceous competition with decreasing overstory competition might not have negative effects on well-established oak seedlings.

Thinned pine stands produce the ideal conditions for using prescribed fire as a management tool. In these stand types, fire is most likely to be used to control hardwood regeneration through the application of two consecutive summer fires (Rouse 1988). However, repeated burning during the dormant season can produce a layer of hardwood regeneration consisting of species resistant to reoccurring fires. In a 30-year loblolly pine (*Pinus taeda*) prescribed fire study, less intense dormant season fires on relatively short intervals caused an increase in oak stem densities less than 5 cm dbh, while stems over 15 cm dbh survived (Waldrop et al. 1987).

Disturbances associated with logging were traditionally thought to slow down the effects of succession (Odum 1959). However, Abrams and Scott (1989) describe effects of disturbance-accelerated forest succession from jack pine to oak following logging and fire, which indicated that disturbances can affect species composition throughout succession.

The visual characteristic often referred to as a "climax" forest does not embody a truthful description of ecological systems (DeAngelis and Waterhouse 1987, Sharik et al 1989) and past assumptions about ecosystems reaching peaks and possessing the ability to remain stable are questionable. Ecosystems may actually be very unstable due to the effects of natural selection, spatial interaction, and disturbance (O'Neil 2001). Instead of preserving individual species, conserving functions between species groups may consequentially produce the positive effects desired for individual organisms through the restoration of ecosystem function. Wildland fire is a process nearly lost in certain forest types where it was historically important. Fire induced disturbance may have been one of the most essential mechanisms through which oak and pine species interacted to promote each other (Pyne 1982).

The oak regeneration problem

Closed canopy forests developed following fire suppression, resulting in more mesic understory conditions (Crow 1988, Abrams 1992). Managers scheduling harvests of oak timber that originated following repeated fire and fire suppression presently do so in the midst of a very different disturbance regime. Concern has been raised about the rate of mature oak mortality and removal and the lack of pole-sized oak stands necessary to sustain the ecological role mature oak provides (North Central Research Station 2003). Most early ecologists considered the abundantly distributed oaks to be "climax" species on upland sites because of their relatively shade tolerant character (Weaver and Clements 1938). Therefore, oak regeneration was not seen as a serious problem by early foresters. After years of harvesting without adequate knowledge of oak physiology, the oak regeneration problem in the eastern United States became apparent by the 1970's (Lorimer 1989).

The ability for northern red oak and white oak to remain dominant on intermediate quality sites has been questionable due to dense understories of shade tolerant species (Lorimer 1989, 1994). Substantial red maple development on average oak sites has been documented across eastern North America. Many professionals were not convinced that red maple could dominate on sites where they were sub-dominants historically, but research up to the present time suggests that oak would indeed be replaced (Lorimer 1989). The slow growth rate of oak seedlings under optimum light conditions with moderate competition may be the most direct cause for oak regeneration failures. Researchers have suggested that mature oak removal without understory control would speed up oak replacement by undesirable species (Lorimer 1989).

Red maple is exhibiting competitive ability in big-tooth aspen (*Populus grandidentata*) stands as well (Palik and Pregitzer 1992). Michigan has the highest ratio of timber growth compared to removals of any state in the north central region (Shifley 2002), which is a very positive situation. However, it also helps illustrate how quickly, through succession, the areas comprised of important forest types such as aspen, jack pine, and northern red and white oak have been reduced. Wildland fire is no longer a major component affecting forest composition. Therefore, it cannot be stated that Michigan forests are simply returning to their prior state. Most silviculturists agree that the excessive development of red maple is partly caused by the reduction in land area burned by fire.

The ability to reintroduce wildland fire across the Michigan landscape has been complicated by several factors, almost all of which are related in some way to the increasing population in the wildland-urban interface, which has been created through continued parcelization of properties to less than 4 ha (10 acres) (North Central Research Station 2003). Severe wildfires including one caused by an escaped prescribed fire have resulted in decreased public support for the use of fire as a management tool. Obtaining interviews of homeowners in Crawford County, Michigan, Winter and Fried (2000) concluded that local residents believed wildland fire is random and uncontrollable.

Residents were unsupportive of firefighting infrastructure investments and universally against the use of prescribed fire as a management tool.

Historical large-scale logging and fire disturbances provided air circulation, which prevented the formation of frost pockets. In contrast, current forest area maps depict a mosaic of even-aged stands in several stages of development (Michigan Department of Natural Resources 2000). Regeneration in these stand types was found to be very susceptible to late spring frosts and deer browsing, which led Buckley et al. (1998) to conclude that the negative impacts of frost and browsing may override the potential for optimum oak growth on sites with little vegetative cover.

Deer browsing may also indirectly affect oak success. Greater levels of fern cover have been described in heavily browsed areas of Pennsylvania (Frederickson et al 1998). Dense fern coverage can prevent seedling establishment by shading the forest floor (Horsely 1993).

The number of sound acorns available for germination has a profound influence on initial oak seedling density. Consumers can eat or damage 80% of acorns in a good mast year and 100% in a poor seed year (Sander 1990). Marquis et al (1976) suggested that negative effects of acorn predation by weevils, deer, and rodents varied greatly between stands in close proximity. Scheduling regeneration harvests to coincide with mast production can be a forester's logistical nightmare. Oaks produce mast on various cycles based on species, weather, and genetics. The reduction of mature oaks across the landscape may contribute to lowered rates of oak dissemination into new stands. Health problems including oak decline, oak wilt, and gypsy moth are of particular concern (North Central Research Station 2003). Researchers have suggested that mortality caused by oak wilt and gypsy moth should be expected to release non-desirable advanced regeneration (Collins 1961). Most of these non-endemic oak consumers were not a problem in presettlement forests. Spurgel (1991) poses and important question: "What is 'natural' vegetation in a changing environment?" Managers may not be able to restore forests to a particular time period when the environmental conditions continually change. As the climate changes, "natural" conditions become a product of a new environment. Consequently, management practices have to evolve as well. Current environmental and social conditions determine the best goals and techniques in oak management.

Oak management responsibility

In Michigan, the regeneration of species such as oak, on public land, is imperative because government agencies control most of the manageable oak dominated forestland. Of Michigan's 19 million acres of timberland, 36% is publicly owned and only 9% is forest industry land (North Central Forest Research Station 2003). Corporate ownership of hardwoods is mostly dominated by sugar maple stands and oak is not a widespread resource in regions of the state where industry land exists. Non-industrial private landowners own more forestland than all other stakeholders (46%) (North Central Research Station 2003), which indicated a potential problem with regenerating a species that may require intensive techniques. Most landowners have not exhibited a pattern of interest in long-term management plans required to sustain productive oak forests on their properties. Landowners also have demonstrated opinions that have affected public land management. Forest management decisions have increasingly involved citizens with little knowledge of forest ecology and silviculture. Therefore, education about the benefits and required methods to sustain oak forests have became necessary in order to conserve it as a resource.

Suggested solutions

Immature oak stands need to have approximately 1070 dominant and codominant oak stems per hectare, which are 1.4 m tall in order achieve minimum stocking (546 stems/ha) when grown to 7.6 cm dbh (Sander et al 1976, Gingrich 1967). Lorimer (1989) suggests techniques for enhancing early growth and reducing the need for tall oak seedlings prior to the regeneration harvest include pre-harvest herbicide treatment or shelterwood cutting combined with understory control. Researchers and managers have concluded that using prescribed fire to control undesirable competition can be successful. In loblolly pine (*Pinus taeda*) stands burned for a quarter century, 58-70% non-oak species were killed, while only 40% oak mortality occurred (Waldrop et al 1987). In Wisconsin, red maple seedling density was reduced by 70% following a low intensity surface fire (Reich et al 1990) and prescribed fire increased root/shoot ratios for oaks in South Carolina, providing an opportunity to increase oak's competitive ability (Barnes and Van Lear 1998). Sander (1971) suggests average oak seedling basal diameter needs to be at least 1.3 cm (.5 in.) in order for oak sprouts to overcome undesirable species. Achieving the ideal fire intensity may cross the threshold of mortality and survival for competitors while not inducing oak mortality. Vegetation is nearly immediately killed if it reaches 63° C (146° F) (Rouse 1986). Heat per unit area (btu/sq/ft) may play a major role in controlling hardwood regeneration. As fuel loads increase, rates of fire spread decrease, allowing longer heat residence time. Greater hardwood survival was found in stands with less available fuel, while survival was lower in areas with high fuel loads (Huddle 1999).

Using data collected in the southeast, Brose and Van Lear (2001) suggested: a shelterwood cut to create approximately a 50% canopy opening, followed by a several year wait for the existing regeneration to develop, then a moderately hot growing season fire to favor oak regeneration over that of other species. Arthur et al (1998) provided evidence suggesting repeated application of periodic fires is more successful at reducing red maple density compared to single fires. Several other treatments can be combined with prescribed fire. Lorimer (1989) suggested accompanying understory control with artificial regeneration and perhaps including additional techniques such as manipulating root systems, and planting seedlings in plastic tubes. Larsen and Johnson (1998) suggested successful natural oak regeneration depends on accumulating several cohorts of seedlings for up to two decades.

Long term and/or intense methods of establishment raise questions about the most productive environments the manager can create for oak, while keeping costs down and protecting wildlife habitat and aesthetics. Concern has been raised regarding the likelihood that repeated fire damage to crop trees might reduce lumber quality making shelterwood burning an economically unjustifiable method. Fire can increase the nutritional value for many species of browse by increasing levels of Nitrogen, Phosphorous, and Potassium (Reich et al 1990). The effects of certain treatments have suggested that competition control can have more negative than positive effects by making oaks more susceptible to browsing (Gordon et al. 1995, Buckley et al. 1998)

Techniques have been suggested that may mitigate many of these negative impacts. Fire behavior can be adequately controlled to produce wounds less than 15 cm wide (Loomis 1974), which may enable oaks to compartmentalize wounds and prevent rot (Abrams 1996). Crow (1988) suggested managers apply treatments that mimic the size of natural disturbances. Increased treatment size would reduce edge, and consequently effect browsing patterns, while reducing prescribed burning costs per acre. Larger treatments likely have biologic and economic merit, but social consequences may prevent their application. This type of technique can deteriorate game habitat through reduced edge and the public most likely prefers the aesthetic value of staggered small treatments compared to large continuous ones. In the future, the deer browsing problem may be indirectly solved by past decades of overabundant deer populations. Several negative effects of deer overpopulation have been escalating over recent years (Michigan Department of Natural Resources 2003) and aggressive population control through liberal antlerless hunting permits in northern lower Michigan is currently taking place (Matthews 2003).

Questions arise about the regional applicability of the most promising techniques for enhancing oak re-establishment. Using fire to promote oak regeneration by reducing understory competition has been tested in certain regions of the country, most of which were in regions where oak dominated in the presettlement forest. Testing of the shelterwood-burn technique and other treatments in all regions of the eastern United States is incomplete.

Chapter 2: Project History

This research is an extension of an oak regeneration study established in 1990. Objectives in 1990 were to determine if oak regeneration was more successful in pine than in oak stands, and if the removal of overstory and understory competitors would increase the performance and survival of oak seedlings. Underlying questions about the differences between levels of competitor removal within oak and pine cover types involved analysis of nitrogen and phosphorous dynamics, ectomycorrhizal colonization, photosynthetically active radiation (PAR) and leaf area index (LAI) relationships, soil moisture, and removal of planted acorns by rodents.

Acorn removal in pine stands by rodents was significantly greater in uncut compared to clearcut treatments and a trend of decreasing levels of acorn removal with less canopy cover was identified (Buckley et al. 2002). Strong relationships between canopy cover, PAR, and LAI suggested that technicians can use basal area measurements to set up desired levels of canopy cover and PAR in similar even-aged oak and pine stands (Buckley et al. 1999). Treatments originally thinned to 75% canopy cover led to a significant reduction of litterfall and nutrient inputs in oak stands, while the same treatment in pine stands did not reduce these inputs. In contrast, litterfall inputs following 25% canopy cover treatment decreased more in red pine than in oak stands (Kim et al. 1996). During the first growing season, a significantly larger root collar on planted oak seedlings was identified in pine than in oak stands. Significant correlation between ectomycorrhizae and root/shoot ratios indicated that ECM might have affected root production more than shoot growth. The greatest ECM development was identified in shelterwood treatments with 25% canopy cover while ECM infection was lowest in clear-cuts (Zhou et al. 1998). Competitor removal treatments increased oak seedling growth, but simultaneously increased mortality due to frost damage and deer browsing. The hypothesis that oak regeneration was more successful in pine than oak stands could not be supported because there was less available soil moisture and greater damage associated with deer browsing and frost damage within pine than oak stands. (Buckley et al. 1998).

With the exception of shrub-layer removal treatments, understory competition became annually more apparent after initial analyses. After more than a decade of understory development, the need to release oak from red maple competition became clear in the oak stands.

Chapter 3: Objectives

This research project had three major objectives. The first objective was to test the hypotheses that prescribed burning will reduce the abundance and cover of red maple and other competitors relative to oak.

The second objective was to test the hypothesis that oak seedling pre-burn height and/or basal diameter can be used to predict post-burn sprout height growth. Regression equations allowing the prediction of post-burn sprout growth from pre-burn size measurements could be used by managers to determine the ideal oak seedling size required before burning to produce optimum sprout growth following burning.

The final objective incorporated both the long-term effects of initial treatments, which have not been defined, and the short-term effects of prescribed fire. Specifically, this final objective was to investigate the effects of interactions between prescribed fire and forest cover type (oak vs. pine), canopy cover, and deer browsing on both oak regeneration and regeneration of oak competitors.

Chapter 4: Methods

Regional Classification

The interior region of Michigan's northern Lower Peninsula has been classified as the Highplains subsection (Figure 1). The landscape is characterized by gently rolling plains of outwash sands dominated by jack pine (*Pinus banksiana*). Several north-south facing ridges of pitted outwash are dominated by oak stands, while northern hardwood communities occupy higher-quality sites. The Highplains sub-section encompasses $13{,}414^2$ km ($8{,}335^2$ miles) and is divided into the Cadillac, Grayling Outwash Plain, and Vanderbilt Moraine sub-subsections. The region has the most severe climate in Lower Michigan, with a 70-130 day growing season and a high potential for late-spring and early summer frosts. Annual precipitation averages 71-81 cm (28-32 in.) most of which occurs as snow. The Grayling Outwash Plain sub-subsection is centrally located within the Highplains and encompasses each study site (Figure 1). Grayling sands dominate soils with slight changes to loamy sands of Alfic Haplorthods on intermediate sites. Slopes from 0-6 % characterize most of the sub-subsection, but slopes from 19-25% do occur (Albert et al. 1995).

Combinations of factors produce a fire climate in the Highplains subsection. The Great Lakes give Lower Michigan a semi-marine climate (Simard et al 1983). Daytime buildup of heat in the interior causes unstable air masses, which increase wind speeds. Most fire weather occurs on the back edge of a Hudson Bay high-pressure cell where southwest winds persist. These cells can occupy the region for long periods of time,

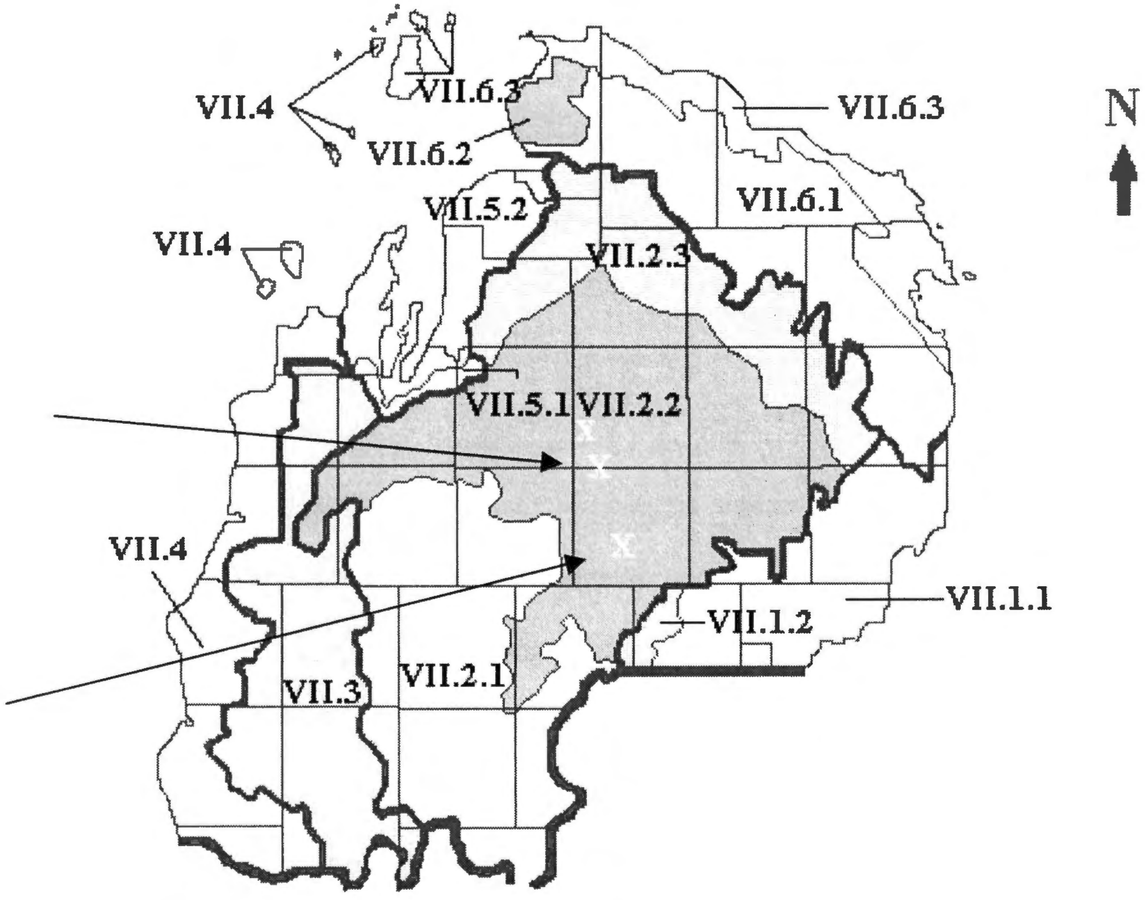


Figure 1. Ecoregion classification boundaries for the northern Lower Peninsula of Michigan (Albert et al. 1995). VII.2.1 = Cadillac sub-subsection, VII.2.2 = Grayling outwash plain sub-subsection, and VII.2.3 = Vanderbilt sub-subsection. All sub-subsections are located within the Highplains subsection (VII.2). Study site locations are labeled X.

allowing substantial fuel moisture reduction. Average wind speed reaches its peak in April, while average monthly relative humidity is lowest in May. These combined weather characteristics make spring the predominant fire season. Evaporation nearly doubles precipitation throughout summer (Simard et al 1983). Thus a fire environment is also created later in the growing season when dry weather reduces live fuel moisture.

Study sites

All three oak blocks are located in the same township of Crawford County at T25N R4W. Oak block 1 and 2 are located in the southwest corner of section 26 and oak block 3 is located in the northeast corner of section 35. Pine block 3 is located northwest of the oak stands in the same township within section number 26. Pine block 1 and 2 are located in Roscommon County at T21N R3W in the northeast corner of section 5.

Treatments originally applied in 1990 (Figure 2) are organized as a split plot design with several splits within replicate blocks nested within two forest cover types. Study sites consist of three mixed oak stands located on a north facing aspect with 5% slope and three pine plantations with very little slope. Both stand types are located on pitted outwash soils similar to Site Unit 5 (Oak-Pine-Vaccinium) of the Ecological Classification of the State Upland Forest in northern Lower Michigan (Pregitzer et al). 1987). According to northern red oak site index curves developed in Wisconsin, site

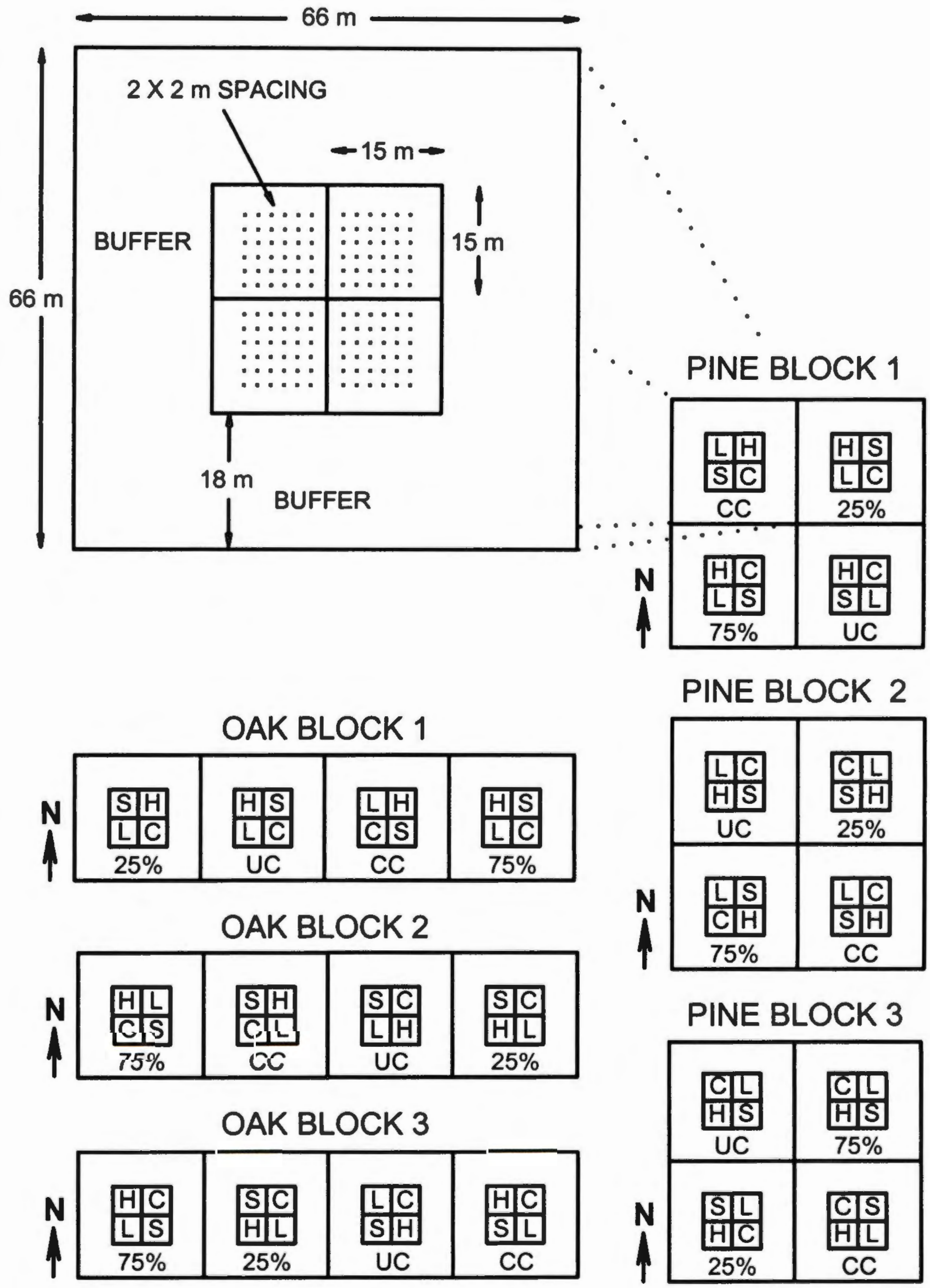


Figure 2. Experimental Design

index at age 50 was approximately 17.8 m (58 ft.) for oak stands (Carmean et al 1989). Red pine site index curves developed in Minnesota indicated a site index at age 50 of 17.2 m (56 ft.) for red pine stands (Gevorkiatz 1957). Northern red oak, white oak, red maple, and white pine occupy the mixed oak stands and pine stands are dominated by red pine planted in the early 1900's.

Each stand is subdivided into four plots receiving four canopy treatments at random: clear-cut, 25% shelterwood, 75% shelterwood, and uncut. The canopy cover in pine 25% shelterwoods actually measured 50% in 1991. Therefore, additional pines were cut in the winter of 1991-1992. Overstory treatments were further divided into understory subplots receiving four treatments: shrub-layer removal (vegetation 25 cm tall- 2.54 cm dbh) herb-layer removal (vegetation <25 cm tall), litter removal, and control (Figures 2, 3). Understory treatments were last repeated in 1996. The majority of vegetation removed in the shrub-layer removal treatment consisted of red maple saplings and bracken fern (*Pteridium Aquilinum*). Herb-layer treatments removed mostly *Vaccinium spp., Graminoid spp.,* and non-oak tree seedlings. Litter was removed in 1m^2 patches around each planted oak seedling in the litter removal treatment. Twelve northern red oak nursery seedlings and twenty direct seeded acorns were planted on 2x2 m spacing within each understory treatment. Six of each were protected from deer browsing using chicken wire exclosures. In 1991, seedlings established across the entire study area numbered 2,880.

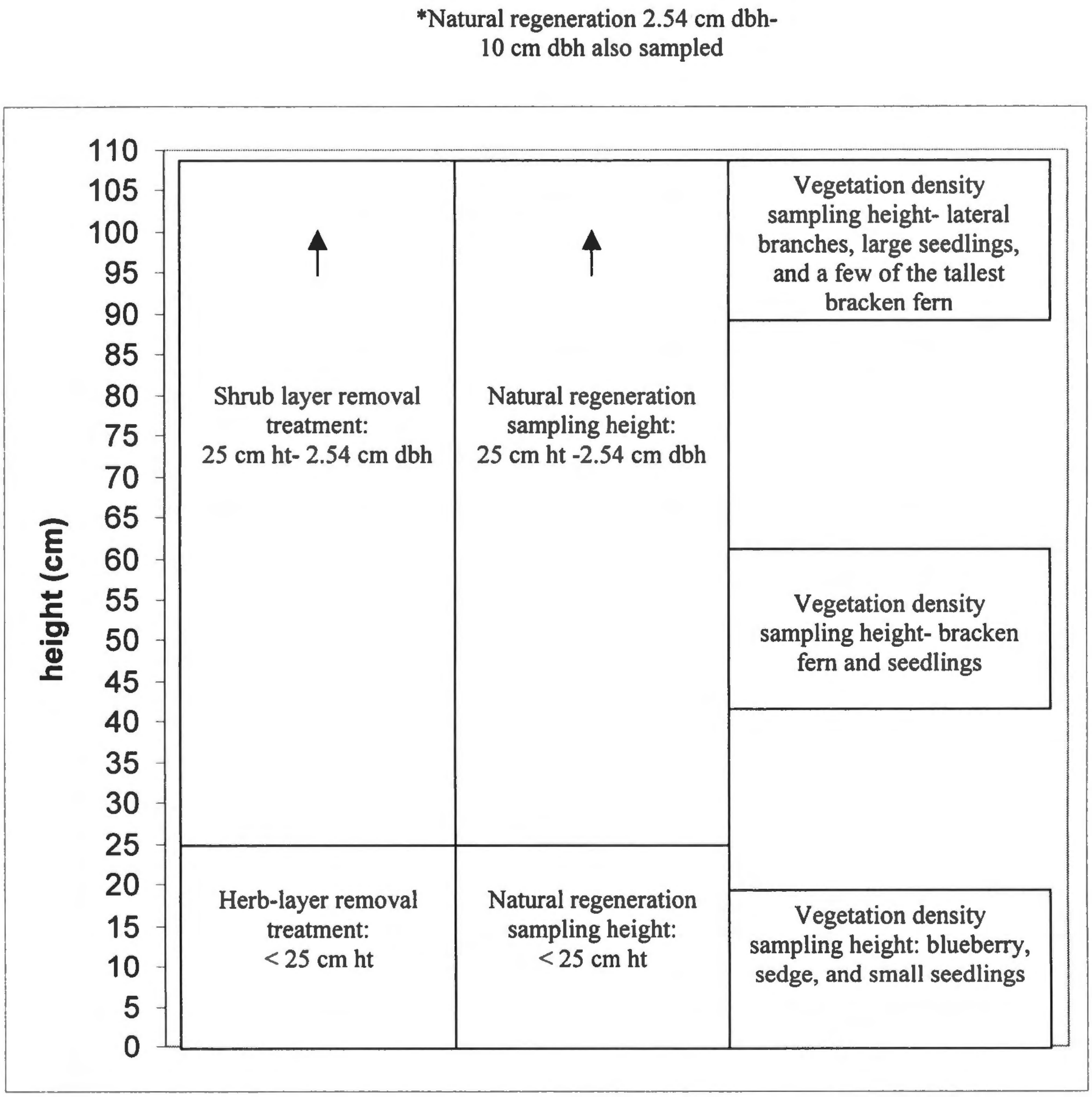


Figure 3. Schematic of understory vegetation layers treated and sampled

Prescribed fire treatment

All prescribed fire treatments could not be applied under identical burning conditions due to excluded wind directions for certain sites determined in pre-burn planning and varying precipitation received at different block locations. However, average relative humidity, which strongly influences fine fuel moisture, was nearly the same across the region during the period when all treatments were applied and wind speeds were remarkably uniform. Treatment of the oak stands became a primary objective as the 2002 spring fire season allowed minimal burning opportunities due to precipitation. Pine stands could have been burned later in the season if necessary. Goals for the prescribed fire included strip-head fires with .9 m (3 ft.) flame lengths in order to top-kill all seedling oaks along with their competitors, and torch sapling white pine in clear-cut oak stands.

Oak stands were burned on May 15, 2002. At the nearest weather station to the oak stands .15 cm (.06 in.) of precipitation occurred two days prior. On-site dry bulb temperature was 18° C (65° F) and relative humidity was 34%. Wind speed at the weather station was 16 km/h (10 mph), while mid-flame wind speed averaged only 1.6 km/h (1 mph). The combined effects of southwest winds and a north-facing slope retarded effective wind speed on the oak site.

Pine stands were treated on May 21, 2002. At pine block three, the last rain occurred five days prior to treatment and measured .13 cm (.05 in). Mid-flame winds were from the west averaging 2.6 km/h (1.6 mph). The dry bulb temperature was 11° C (52° F) and the relative humidity was 37%.

At pine block one and two, the most recent rain event measuring .23 cm (.09 in) occurred eight days prior to treatment at the nearest weather station. Mid-flame winds were from the north-northwest averaging 2.1 km/h (1.3 mph). Dry-bulb temperature averaged 12° C (53° F) and relative humidity averaged 42%.

Rate of spread (chains/hour), fireline intensity (btu/second/ft), and heat per unit area (btu/ft^2) were projected from two fuel models, which distinguished clear-cuts and 25% canopy cover treatments from 75% and uncut plots. These values were not converted to metric equivalents due to the well-established use of british thermal units in fire behavior analyses. Appendix B of the fireline handbook (National Wildfire Coordinating Group 1993) was used to determine fine dead fuel moisture and BehavePlus (USDA Forest Service Rocky Mountain Research Station Systems for Environmental Management 2002) software was used to compute projected fire behavior. Consistent fireline intensity was promoted through the strip head fire technique with 6 m (20 ft) average strip width. Complete coverage was successful on all pine sites. However, in the clear-cut of oak block two, near the base of the slope, one understory treatment did not burn and strips skipped over some green vegetation in pine clear-cuts. Flame lengths averaged .2-.3 m (.5-1 ft.) in oak stands and .6-.9 m (2-3 ft.) in pine stands. Fire torched only the small white pine seedlings in the oak stands and most medium sized balsam fir saplings in pine stands. Temperature indicating paints (Tempilaq paints, B.J. Wolfe Enterprises Inc.) were used to quantify field measurements of fire temperature. Eight separate paints calibrated to liquefy at 79°, 149°, 204°, 260°, 316°, 371°, 593°, and 816°C (175°, 300°, 400°, 500°, 600°, 700°, 1100°, 1500° F) were painted onto ceramic tiles mounted on steel rods face down in the center of each understory treatment .6 m (2 ft) above the soil surface. Following prescribed fire treatment, average bole scorch height was measured using the nearest canopy tree to each understory sampling plot. In the same location, average scorch height on the understory saplings was also recorded within oak stands.

Measurement of planted oak performance, damage, and survival

Before and after burning, from July-August of 2001 and 2002, total height was recorded to the nearest cm for the tallest stem on each planted oak. The number of stems was also recorded to determine the growth and sprout capability of various planted oak sizes. Basal diameter was measured 10 cm above the ground to the nearest millimeter using vernier calipers. Effects of frost damage, deer browsing, dieback, and insect defoliation were also noted for each planted oak. Percent mortality in 2001 was determined by dividing surviving planted oaks within each understory plot by the total number originally established in 1990. Percent mortality in 2002 was calculated by dividing the number planted oaks alive in 2001 by the number of survivors in 2002 to document the mortality induced by fire and other causes.

Sampling plots

Natural regeneration was measured before and after prescribed fire treatment in three size classes: < 25 cm ht, 25 cm ht- 2.54 cm dbh, and 2.54 cm dbh – 10 cm dbh. One meter square quadrats and 2 meter and 4 meter diameter circular plots were used for sampling each respective size class (Figure 4). Species, height, and basal diameter were recorded for all stems. Diameter at breast height was also measured for saplings above 2.54 cm dbh.

Four sampling locations were placed inside each 15x15m understory treatment with smaller plots nested within larger ones (Figure 4). Average density and height of each species of natural regeneration was determined both before and after burning. Percent herb cover was also estimated before and after burning for individual species within each $1m^2$ sampling plot. Herbs were identified to the nearest genus and most and most were identified to species. Litter depths were measured in the center of each of the four sampling locations within each understory treatment before burning in 2001 and after burning in 2002.

Vegetation density

In order to capture understory vertical structure, vegetation density, in m^2 leaf silhouette/m^3 of space was measured, in July 2001 and 2002, before and after prescribed

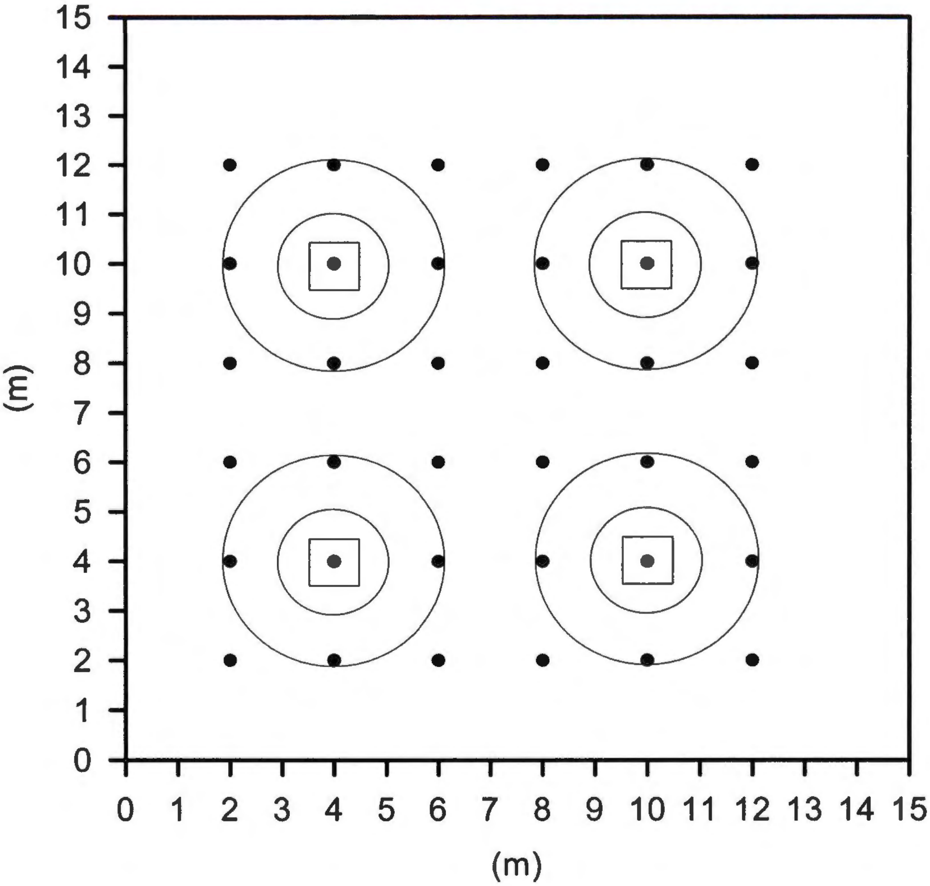


Figure 4. Sampling plots within one understory treatment

fire, using the density board method (MacArthur and MacArthur, 1961; McEvoy et al., 1980). Vegetation density was measured in the four cardinal directions from the center of each understory treatment by recording the distance at which 50% or more of a 20 x 50 cm target was covered by vegetation. In each cardinal direction, measurements were taken from 0-20 cm, 40-60cm, and 90-110cm above ground (Figure 3). The equation K=0.69315 / D was used to calculate m^2 leaf silhouette per m^3 of space where D= distance at which the target was 50% obscured by vegetation and K= m^2 leaf silhouette per m^3 of space (MacArthur and MacArthur, 1961).

Light and soil moisture measurements

Percent canopy cover was measured within each understory plot, using a spherical densiometer, in July 2002. Percent photosynthetically active radiation (µmol/s m^2) was measured at 1m and 15cm above the ground using two model SF-80 Sunfleck Ceptometers (Decagon Devices Inc, Pullman, WA) from 1:00 PM to 3:00 PM on a partly cloudy day on August 15, 2002. One ceptometer was used to collect full sunlight measurements in the shrub removal clear-cut treatments at one-minute intervals. The second ceptometer collected measurements inside each understory treatment while time of measurement was recorded to the nearest 30 seconds. Data from both instruments were matched according to time of collection to ensure both instruments measured PAR under the same sky conditions to calculate percent full PAR. Canopy cover and PAR measurements included the effects of reduced light caused by large red maple saplings, which were not top-killed following prescribed fire. On August 19, 2002, percent volumetric soil moisture was measured 15 cm below the soil surface using a Soilmoisture Model 6050XI Time Domain Reflectometry (TDR) probe (Soil Moisture Equipment Corporation, Santa Barbara, CA) two days following the last rainfall.

Data analysis

The experimental design was developed with the intent of using analysis of variance to evaluate treatment effects. Simple linear regression was used to examine relationships between post-burn sprout growth and pre-burn seedling size. All F tests were conducted at the $\alpha = .05$ level. Pair-wise comparisons between oak and pine stand types, canopy cover treatments, and understory treatments were conducted using Tukey's Honestly Significant Difference (HSD). Several different breakdowns of species, mean heights, caged and uncaged, browsed and unbrowsed, etc. were analyzed separately, but statistical differences were always analyzed and reported across cover type, canopy cover treatment, and sometimes understory treatment. Northern red oak and white oak density were combined prior to analysis. Separate analyses with reduced models were conducted within types of canopy composition when overall ANOVA indicated significant canopy composition x canopy cover interactions. The overall ANOVA model used to calculate the effects of oak and pine stands, canopy cover, and understory treatments was:

$$Y_{i(j)kl} = \mu + \beta_j + \tau_{i(j)} + \gamma_k + \lambda_l + \beta\gamma_{jk} + \beta\lambda_{jl} + \gamma\tau_{i(j)k} + \lambda\tau_{i(j)l} + \gamma\lambda_{kl} + \beta\gamma\lambda_{jkl} + \varepsilon_{i(j)kl}$$

where:

μ	=	Overall Mean
β_j	=	Canopy Composition
$\tau_{i(j)}$	=	Block (Canopy Composition)
γ_k	=	Canopy Cover
λ_l	=	Understory Treatment
$\beta\gamma_{jk}$	=	Canopy Composition x Canopy Cover
$\beta\lambda_{jl}$	=	Canopy Composition x Understory Treatment
$\gamma\tau_{i(j)k}$	=	Canopy Cover x Block (Canopy Composition)
$\lambda\tau_{i(j)l}$	=	Understory Treatment x Block (Canopy Composition)
$\gamma\lambda_{kl}$	=	Canopy Cover x Understory Treatment
$\beta\gamma\lambda_{jkl}$	=	Canopy Composition x Canopy Cover x Understory Treatment
$\varepsilon_{i(j)kl}$	=	Error term consisting of the interaction $\tau\gamma\lambda_{i(j)kl}$

$i = 1, 2, 3$
$j = 1, 2$
$k = 1, 2, 3, 4$
$l = 1, 2, 3, 4$

Chapter 5: Results

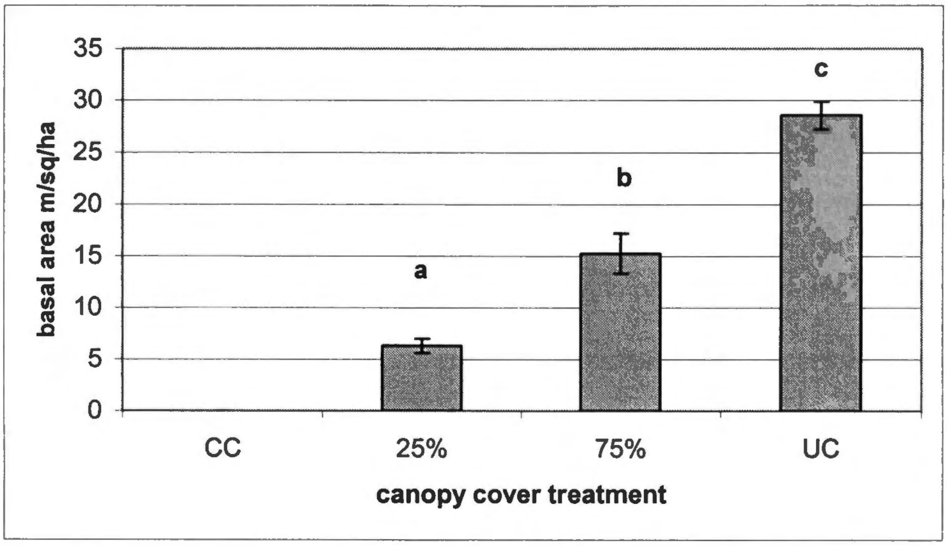
Basal area

Basal area was significantly greater in pine than oak stands (Figure 5). Differences in basal area between canopy cover treatments, in oak stands, remained significantly different 11 years following treatment application. Basal area in 75% shelterwood pine stands, however, increased substantially, and was no longer significantly different from the uncut plots (Figure 5). Substantial red maple and white pine basal area was measured in uncut oak stand treatments. Uncut plots, in oak stands, averaged 21 subordinate red maple suppressed by overstory northern red oak. Pine blocks 1, 2, and 3 contained 5, 2, and zero overstory red maple, respectively. Pine stands 1 and 2 contained 7 and 9 overstory white oaks and 1 and 2 red oaks, respectively. Based on leaf characteristics, some hybridization between northern red oak (*Quercus rubra*) and northern pin oak (*Quercus ellipsoidalis*) was likely amongst red oaks in pine stands. Pine block 3 did not contain any oak or red maple overstory trees, while the uncut treatment within this block contained some overmature jack pine exhibiting signs of senescence.

Canopy cover and photosynthetically active radiation (PAR)

Canopy structure in uncut oak stands was comprised of three main strata. Northern red oak dominated the main canopy, red maple was close to the main canopy

a) Oak



b) Pine

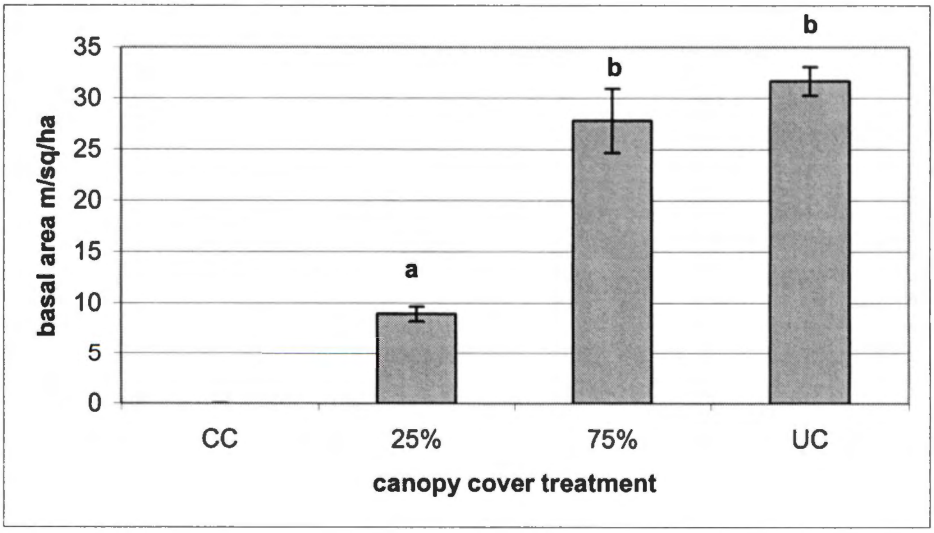


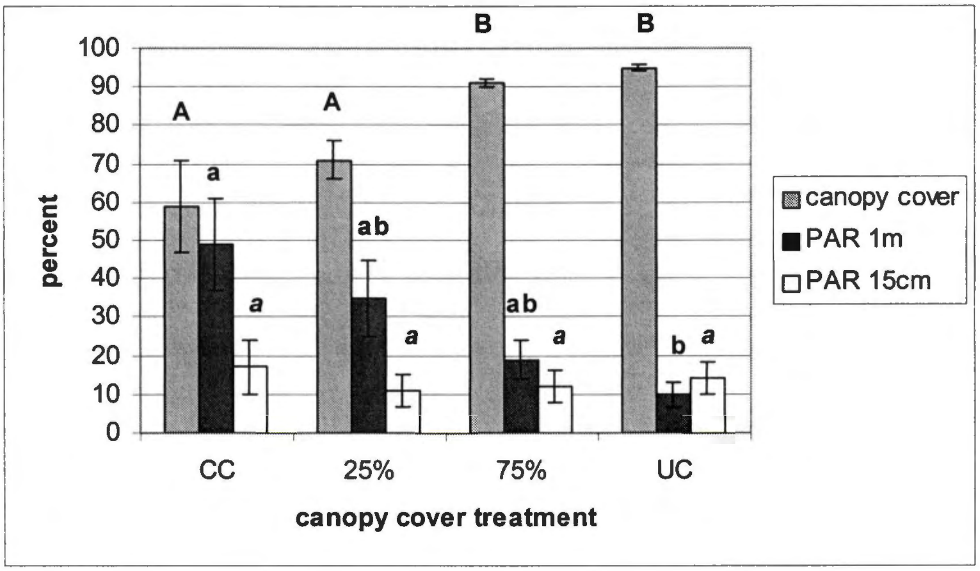
Figure 5. Basal area in m^2 per hectare by canopy cover treatment. Analysis conducted within a) oak and b) pine stands. CC= clear-cut, 25%= 25% canopy cover, 75%= 75% canopy cover, UC= uncut (control). Means with the same letter were not statistically different.

but subordinate to the oak, and white pine was present in a stunted sapling layer beneath both red maple and oak.

Within oak stands, canopy cover measured at 1m above the ground and averaged over all understory treatments was not significantly different between clear-cuts and 25% shelterwood stands or between 75% shelterwood and uncut stands (Figure 6a). Within pine stands, canopy cover was significantly different between clear-cuts and 25% shelterwood stands, but not significantly different between 75% shelterwood and uncut stands (Figure 6b). Percent canopy cover in shrub-layer removal treatments within 25% shelterwoods in the oak stands, where a sapling layer did not inhibit light, averaged 48%. An average of 46% canopy cover was measured in 25% canopy treatments within pine stands. Target percent canopy cover at the time of initial treatment (1990) is used throughout this document to refer to treatments, even though actual canopy cover values were greater in 2002.

PAR measurements, at 1m above the ground, exhibited an expected pattern of reduced PAR with increasing levels of canopy cover in both oak and pine stands (Figure 6). However, the values for PAR at 1m were substantially different between oak and pine stands at equal levels of canopy cover treatment (Figure 6). In clear-cuts and 25% shelterwood treatments, PAR measurements were 25-30% higher in the pine than oak stands. PAR 15 cm above the ground was not significantly different between canopy cover treatments within both oak and pine stands, but did show a pattern of reduced PAR availability with increasing canopy cover in pine stands (Figure 6b). Within the shrub-layer removal treatment of oak stands, PAR at 1m above the ground averaged 25% higher than all other understory treatments.

a) Oak



b) Pine

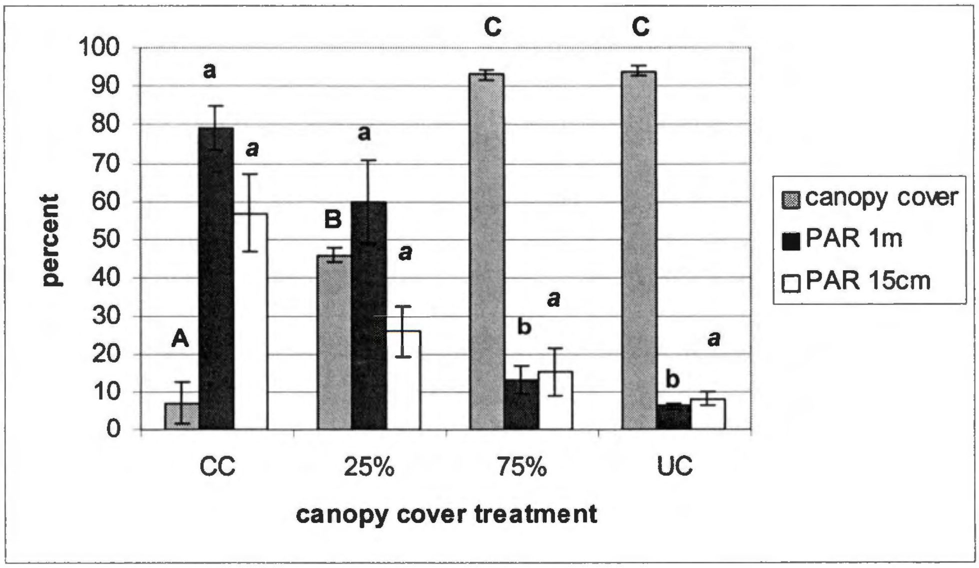


Figure 6. Canopy cover, PAR at 1m above the ground, and PAR at 15cm above the ground. Analysis conducted within a) oak stands and b) pine stands. Different colored bars with different letter styles represent separate analyses. Treatment codes and significance as in figure 5.

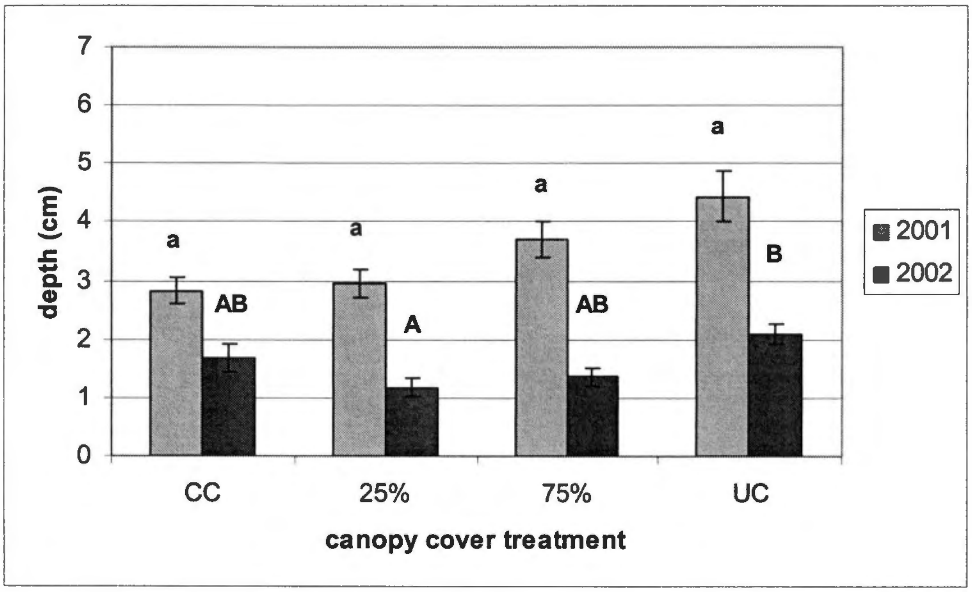
Soil Moisture

Percent volumetric soil moisture measured in 2002 was not significantly different between oak and pine stands, canopy cover treatments, or understory treatments. All measurements of soil moisture were very uniform, averaging 10-14%.

Litter depths

When averaged across all canopy cover treatments, prescribed fire reduced average litter depth by 2cm in oak stands and 1cm in pine stands (Figure 7). Pre-burn average litter depth was slightly lower in clear-cuts of pine compared to oak stands, but average litter depth in 75% shelterwood and uncut stands was 2 cm deeper in pine than in oak stands (Figure 7). In pine stands, litter depth was significantly greater in 75% and uncut treatments than in clear-cut and 25% cover treatments both before and after burning (Figure 7b). Within oak stands, significant differences in litter depth were only found after burning when litter depth in 25% cover treatments was significantly lower than in uncut plots (Figure 7a). Litter removal understory treatments, last applied in 1996, did not affect litter depth measurements in 2001 or 2002.

a) Oak



b) Pine

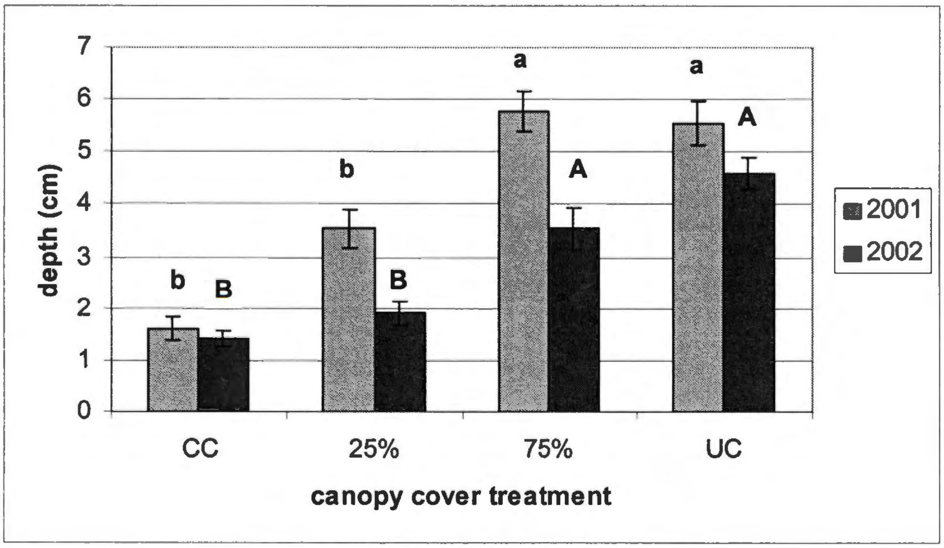


Figure 7. Litter depths in 2001 and 2002, before and after prescribed fire. Analysis conducted within a) oak stands and b) pine stands. Treatment codes and significance as in Figure 5.

Bole and understory sapling scorch

Bole scorch heights did not accurately represent flame lengths in pine stands because fire climbed the bark. In oak stands, bole scorch was very minimal, which made it difficult to detect fire behavior variability. These factors in oak and pine stands made bole scorch an inaccurate method of quantifying fire behavior differences between oak and pine stands and canopy cover treatments.

Measurements of understory scorch heights averaged two meters and were very uniform across all canopy cover treatments. Most scorched stems were large red maple saplings that were not top-killed by the fire. All stems with heights below two meters were top-killed.

Fire temperature

Fire temperature, measured .5 meters above the ground, was significantly lower in oak than in pine stands. Within oak stands, fire temperature was not significantly different between canopy cover treatments, and averaged 67° C (152° F). One understory treatment in the clear-cut within oak block 2 did not burn. Within pine stands, fire temperature was significantly lower in clear-cuts. Fire temperature averaged 137° C (278° F) in all other canopy cover treatments within pine stands. Projected outputs for heat per unit area (btu/m^2) were not different between oak and pine stands (Table 1), partly because fuel models used in projections did not distinguish between oak and pine

Table 1. Projected fire behavior

	Oak	Oak		Pine	Pine
	CC, 25%	75%, UC		CC, 25%	75%, UC
	Model 2	Model 9		Model 2	Model 9
inputs					
Time	1300	1300		1300	1300
RH%	34%	34%		31%	31%
slope	5%	5%		0	0
Aspect	N	N		-	-
Wind direction	SW 225	SW 225		NW 315	NW 315
Midflame wind speed- mph	1	1		2	2
Fine dead fuel moisture	7%	7%		7%	7%
Live fuel moisture	50%	50%		50%	50%
10 hour fuel moisture	8%	8%		8%	8%
100 hour fuel moisture	9%	9%		9%	9%
outputs					
Rate of spread- chains/h	4.5	1.2		9.7	2.3
Fireline intensity- btu/s/ft	40	8		86	15
Heat per unit area- btu/sq/ft	483	355		483	355
Flame length- ft	2.4	1.2		3.5	1.6
Direction of spread	SW 228	SW 228		NW 315	NW 315

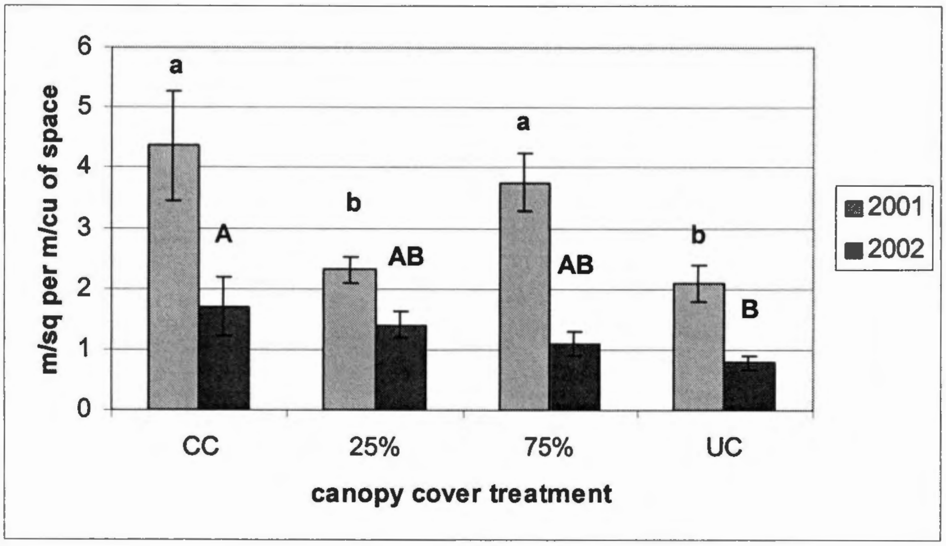
litter. Average relative humidity, which differed only 3% between oak and pine stand prescribed fires, projected equal fine dead fuel moisture inputs and, therefore, equal heat per unit area (btu/m^2) outputs. Greater fireline intensity (btu/s/m) occurred in pine stands.

Vegetation density

Vegetation density was greatest in the 0-20 cm stratum measured nearest the soil surface, but was reduced by prescribed fire in all canopy cover treatments within both oak and pine stands (Figure 8). Before prescribed fire treatment, vegetation density within this stratum was significantly greater in clear-cuts and 75% shelterwood treatments than other canopy cover treatments within oak stands and significantly greater in clear-cuts and 25% shelterwood treatments than the remaining treatments within pine stands. Following prescribed fire, vegetation density was significantly greater in clear-cuts than in uncut plots within oak stands. Within pine stands, clear-cuts had significantly more competition nearest the soil surface than all other remaining overstory treatments (Figure 8).

Vegetation density 40-60 cm above the soil surface was reduced by prescribed fire in all canopy cover treatments, within oak stands, but increased in clear-cuts and 25% shelterwood treatments within pine stands (Figure 9). Bracken fern height growth variability within pine blocks caused non-significant differences between 25% and 75% canopy cover treatments following burning. In both oak and pine stands, vegetation

a) Oak



b) Pine

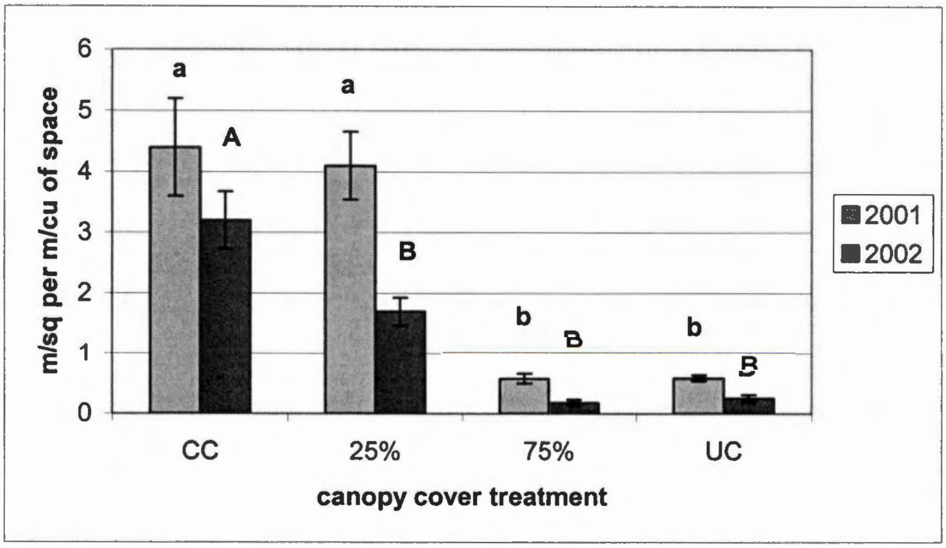


Figure 8. Vegetation density 0-20 cm above the ground. Analysis conducted before and after prescribed burning within a) oak stands and b) pine stands. Treatment codes and significance as in Figure 5.

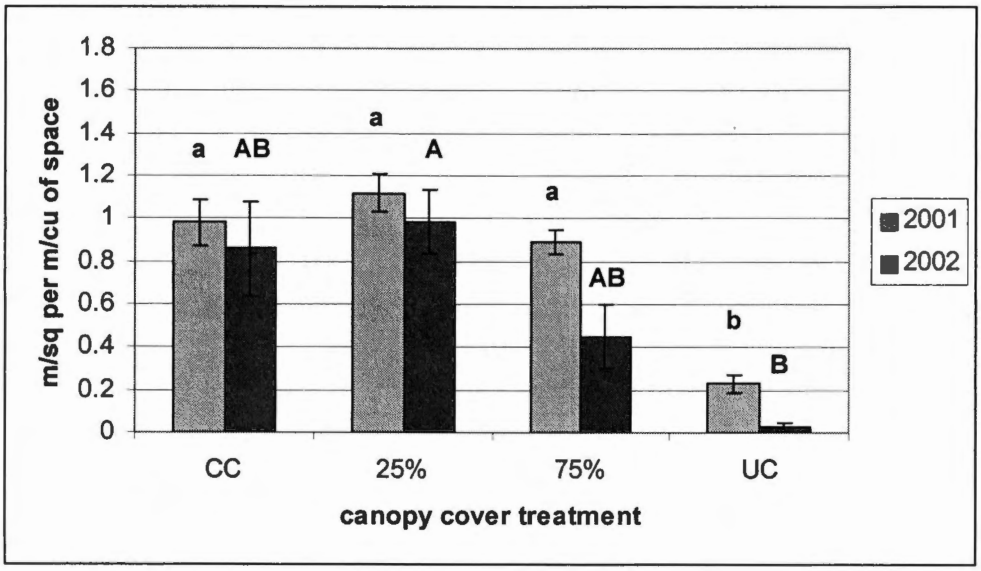
density 40-60 cm above the ground was greatest in 25% shelterwood treatments before and after burning (Figure 9). Vegetation density in this stratum was lowest in uncut treatments of both oak and pine stands, and was lower in uncut pine plots than in uncut oak plots. In 75% shelterwood treatments, there was substantially less competing vegetation in pine than in oak stands both before and after prescribed fire treatment (Figure 9).

Vegetation density 90-110 cm above the ground was reduced by prescribed fire in all canopy cover treatments within oak stands, but vegetation in this stratum was increased by prescribed fire in clear-cuts and 25% shelterwood treatments within pine stands, with substantial variability between blocks (Figure 10).

Bracken fern coverage

Bracken fern (*Pteridium aquilinum*) was the most abundant non-woody potential competitor of oak. Prescribed fire increased bracken fern coverage in clear-cuts and 25% shelterwood treatments, while fern coverage was either decreased or remained the same in 75% shelterwood and uncut plots, in both oak and pine stands (Figure 11). In treatments with less canopy cover, bracken fern coverage increased by approximately 20% in pine stands and 10% in oak stands. Both before and after burning, bracken fern coverage was lowest in 75% canopy cover treatments within pine stands (Figure 11).

a) Oak



b) Pine

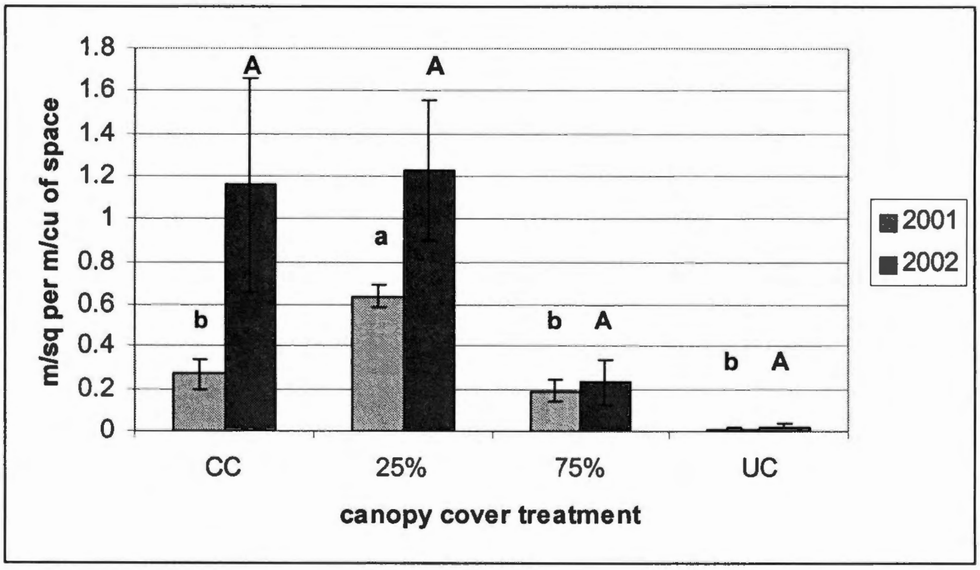
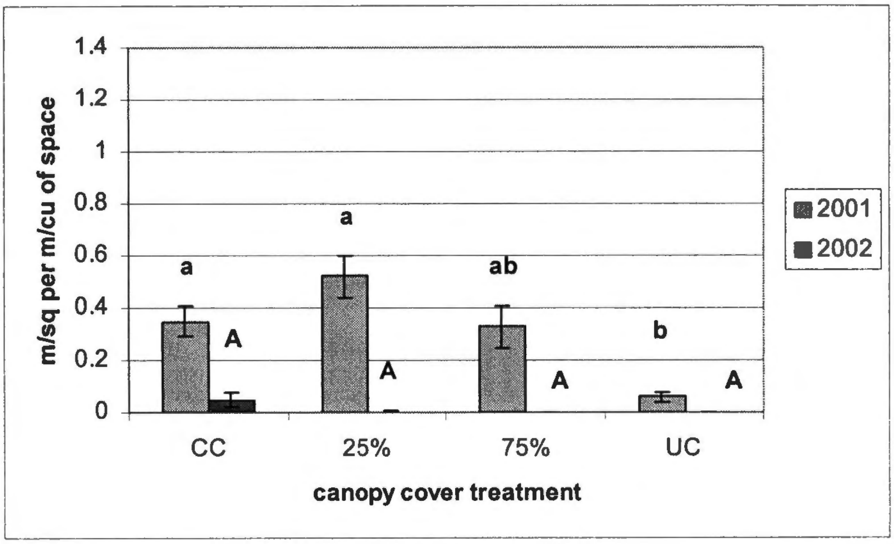


Figure 9. Vegetation density 40-60 cm above the ground. Analysis conducted before and after prescribed burning within a) oak stands and b) pine stands. Treatment codes and significance as in Figure 5.

a) Oak



b) Pine

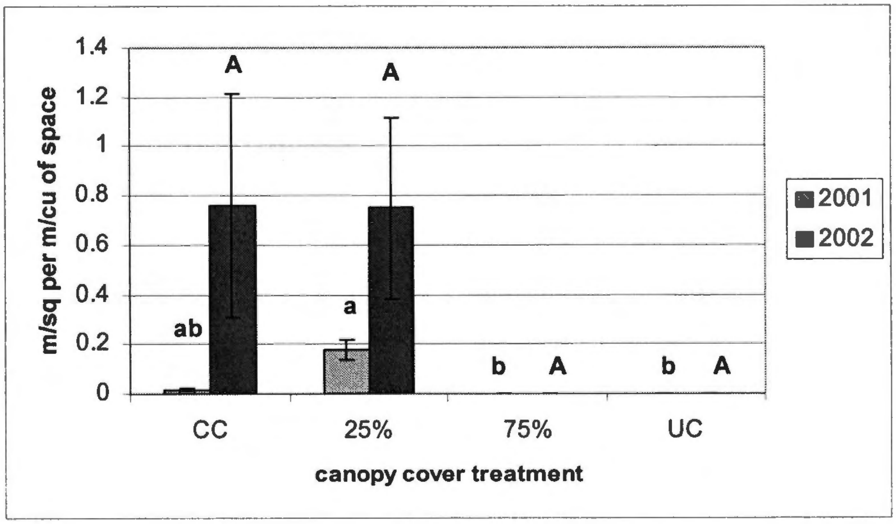
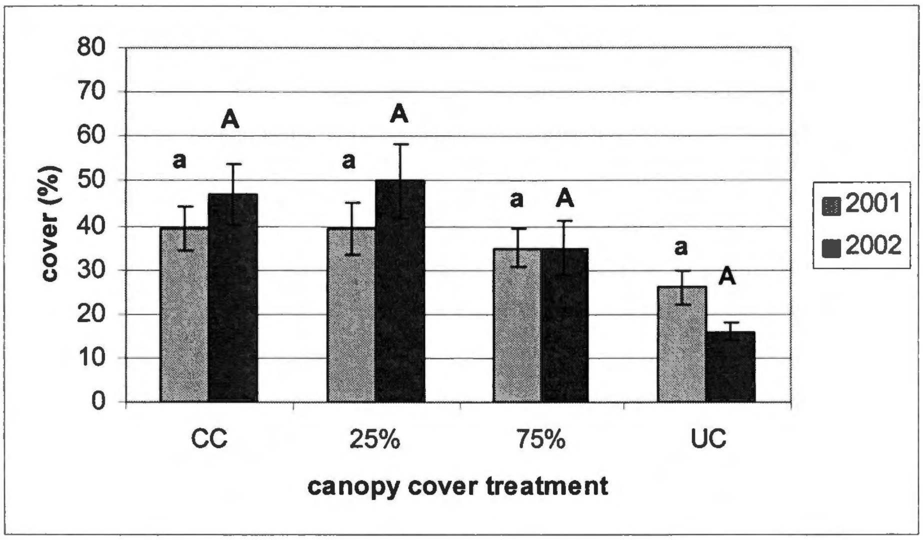


Figure 10. Vegetation density 90-110 cm above the ground. Analysis conducted before and after prescribed burning within a) oak stands and b) pine stands. Treatment codes and significance as in Figure 5.

a) Oak



b) Pine

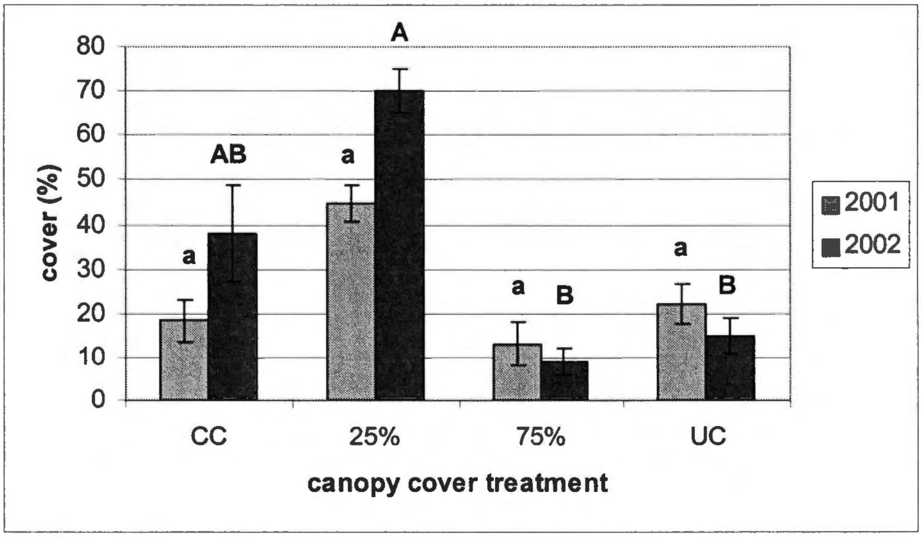


Figure 11. Percent bracken fern (*Pteridium aquilinum*) cover. Analysis conducted before and after prescribed fire within a) oak stands and b) pine stands.Treatment codes and significance as in Figure 5.

Herb-layer composition

Species richness, defined as the total number of species located within sampling plots, was reduced by prescribed fire in all canopy cover treatments within both oak and pine stands and was significantly lower in pine stands both before and after prescribed fire. Twelve herb-layer species disappeared in the first growing season following burning (Table 2). Average percent cover of blueberry and huckleberry (*Vaccinium spp. and Gaylussacia baccata*) was reduced in both oak and pine stands with the greatest reduction occurring the 25% shelterwood plots within pine stands. Following prescribed fire treatment, average percent cover of Pennsylvania sedge (*Carex pennsylvanica*) increased by 1% in oak stands and decreased by 5% within pine stands.

Natural regeneration

Before prescribed fire treatment, natural regeneration species composition patterns were evident between oak and pine stands (Table 3). Block differences had a substantial effect on average stem density.

Individual red maples in the 2.54 –10 cm dbh size class were most dense in oak block 2 near the base of the slope, while coppice regeneration dominated half of this size class of red maple regeneration in oak block 1. In oak block 3, located highest on the slope, nearly all red maple stems in the 2.54 –10 cm dbh size class were coppice regeneration.

Table 2. Species sampled in herb-layer. Taxonomy according to Voss (1972, 1985, 1996)

* species not re-located within plots following burning in 2002

Graminae (Grass Family)	
Panic grass	*Panicum latifiolium and P. depauperatum*
Rice grass	*Oryzopsis asperifolia*
* False melic	*Schizachne purpurascens*
* Hair grass	*Deschampsia flexuosa*
* Red top	*Agrostis gigantea*
Cyperaceae (Sedge Family)	
Hairy Solomon-seal	*Polygonatum pubescens*
Canada Mayflower	*Maianthemum canadense*
Pennsylvania sedge	*Carex pensylvanica*
Ericaceae (Heath Family)	
Teaberry	*Gaultheria procumbens*
Low-sweet blueberry	*Vaccinium angustifolium*
Canada blueberry	*Vaccinium myrtilloides*
Huckleberry	*Gaylussacia baccata*
* Trailing arbutus	*Epigaea repens*
Rosaceae (Rose Family)	
Northern dewberry	*Rubus flagellaris*
Wild red raspberry	*Rubus strigosus*
Blackberry	*Rubus allegheniensis*
Asteraceae (Daisy family)	
Devil's paintbrush	*Hieracium aurantiacum*
* Large-leaved aster	*Aster macrophyllus*
* Dandelion	*Taraxacum officinale*
Polypodiaceae	
Bracken fern	*Pteridium aquilinum*
Oak fern	*Gymnocarpium dryopteris*
Sweet fern	*Comptonia peregrina*
Pyrolaceae	
* Shinleaf	*Pyrola chlorantha*
* Prince's pine	*Chimaphila umbellata*
Araliaceae	
Sarsparilla	*Aralia nudicaulis*
Primulaceae	
Star-flower	*Trientalis borealis*
Rubiaceae	
* Partridge berry	*Mitchella repens*
Hypericaceae	
* St. John's Wort	*Hypericum perforatum*
Scrophulariaceae	
* Cow-wheat	*Melampyrum lineare*
* Mullein	*Verbascum thapsus*
Apocynaceae	
Spreading dogbane	*Apocynum androsaemifolium*

Table 3. Density (stems/ha) for all tree species by sampling size class across all canopy cover plots prior to prescribed fire.

	< 25 cm ht	25 cm ht- 2.54 cm dbh	2.54 cm dbh- 10 cm dbh	All size classes
OAK STANDS				
northern red oak (*Quercus rubra*)	8828	4004	29	12861
white oak (*Quercus alba)*	651	1277	12	1940
red maple (*Acer rubrum)*	15365	8944	1268	25577
black cherry (*Prunus serotina)*	0	613	149	763
quaking aspen (*Populus tremuloides)*	0	0	0	0
white pine (*Pinus strobus)*	339	365	108	811
red pine (*Pinus resinosa)*	0	17	0	17
balsam fir (*Abies balsamea)*	0	25	0	25
PINE STANDS				
northern red oak (*Quercus rubra*)	2240	1036	25	3301
white oak (*Quercus alba)*	156	216	25	397
red maple (*Acer rubrum)*	1953	862	17	2832
black cherry (*Prunus serotina)*	0	937	62	999
quaking aspen (*Populus tremuloides)*	0	58	62	120
white pine (*Pinus strobus)*	78	50	17	144
red pine (*Pinus resinosa)*	130	133	21	284
balsam fir (*Abies balsamea)*	0	33	4	37

The density of 2.54-10 cm dbh red maple within pine stands resulted solely from one clump of coppice regeneration located in the 25% canopy cover treatment within pine block 1, where all the red maple regeneration in the 25 cm ht- 2.54 cm dbh size class also occurred. The 25% canopy treatment in pine stand 1 also contained a well represented component of red pine regeneration.

Density of oak regeneration in the largest size class (2.54 –10 cm dbh), within pine stands, was comprised of individual saplings, most of which were located in the 25% canopy treatment within pine block 3, while oak regeneration density in this size class within oak stands was mostly affected by two northern red oak coppice clumps that bordered sampling plots. Northern red oak dominated 85% of natural oak regeneration, in oak stands, and 88% in pine stands.

Clear-cuts in pine blocks differed in species composition. Black cherry (*Prunus serotina*) dominated the composition in the clear-cut within pine block 1. No trees species responded in the pine block 2 clear-cut, where the surface was dominated by Pennsylvania sedge. Quaking aspen (*Populus tremuloides*) dominated the clear-cut within pine block 3.

Large shrub species found on oak sites included witch hazel (*Hamamelis virginiana*), beaked hazel (*Corylus cornuta*), serviceberry (*Amelanchier spp.*), and maple-leaved viburnum (*Viburnum acerifolium*). Witch hazel was the only large shrub species, of those listed, located within pine stands.

Patterns of oak regeneration across levels of canopy cover in pine stands were similar to patterns of red maple regeneration across the same canopy cover treatments in oak stands. Increases in sapling density with decreases in canopy cover and increases in small seedling density with increases in canopy cover was evident for red maple in oak stands and for oak in pine stands.

Overall, white pine was 83%, and red maple was 89% more abundant in oak than in pine stands. Therefore, these species could not be compared across levels of canopy cover within pine stands because there simply was not enough regeneration distributed throughout pine treatments for an accurate sample to be analyzed. Red maple regeneration was significantly less abundant in pine compared to oak stands within all canopy cover treatments and in all size classes before and after burning (Figure 12). The only pine treatment with a measurable red maple component was the 25% shelterwood treatment within pine block 1. This treatment had 61 red maple seedlings within sampling plots before burning, none of which produced sprouts during the first growing season following prescribed fire treatment.

Natural oak and red maple regeneration within oak stands

Before and after prescribed fire, density of red maple saplings (2.54 cm dbh- 10 cm dbh) was much greater than oak regeneration of the same size (Figure 13). Following burning, several stems died on two oak stump sprouts located within plots, leaving one or two dominant oak stems. This result accounts for the reduced density for oak in clear-cut and 25% canopy cover treatments following burning. Density of red maple saplings 2.54 cm-10 cm dbh was slightly reduced in each canopy cover treatment following burning (Figure 13). Nearly all of these stems produced foliage. However, in August, most red

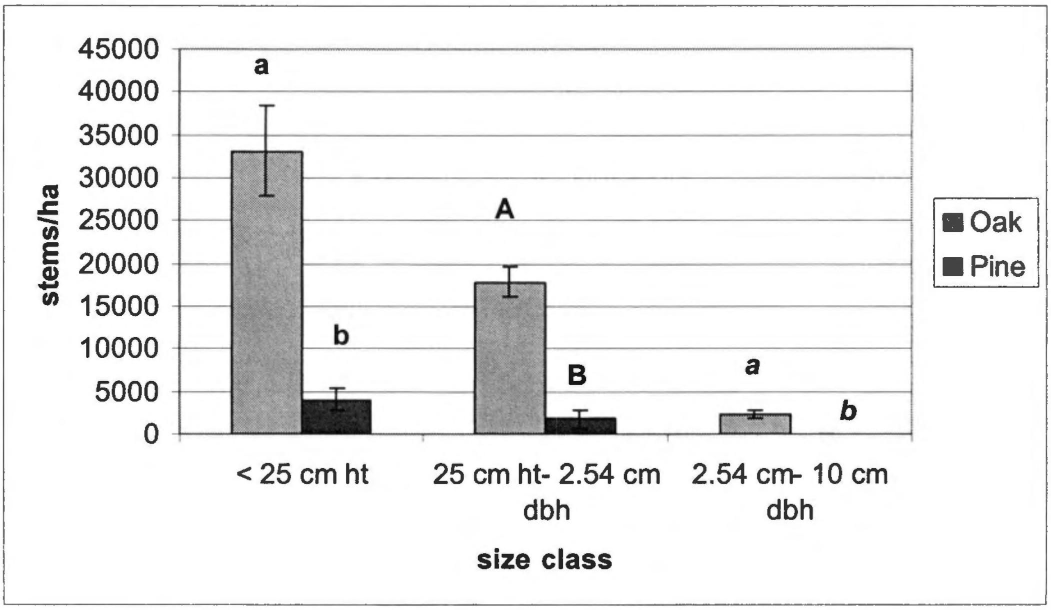
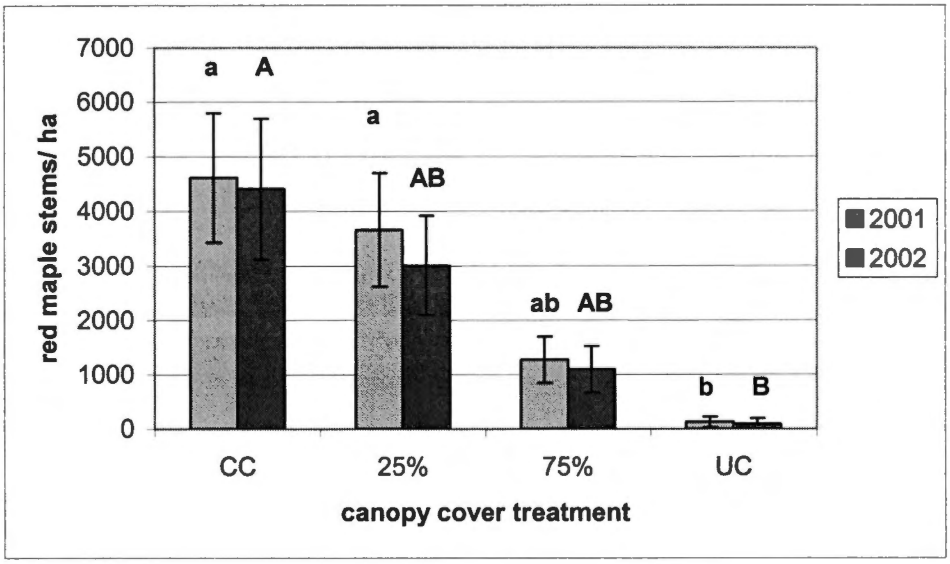


Figure 12. Red maple density in three different size classes within oak and pine stands before prescribed burning. Treatment codes and significance as in Figure 5.

a) **Red maple**



b) **Oak**

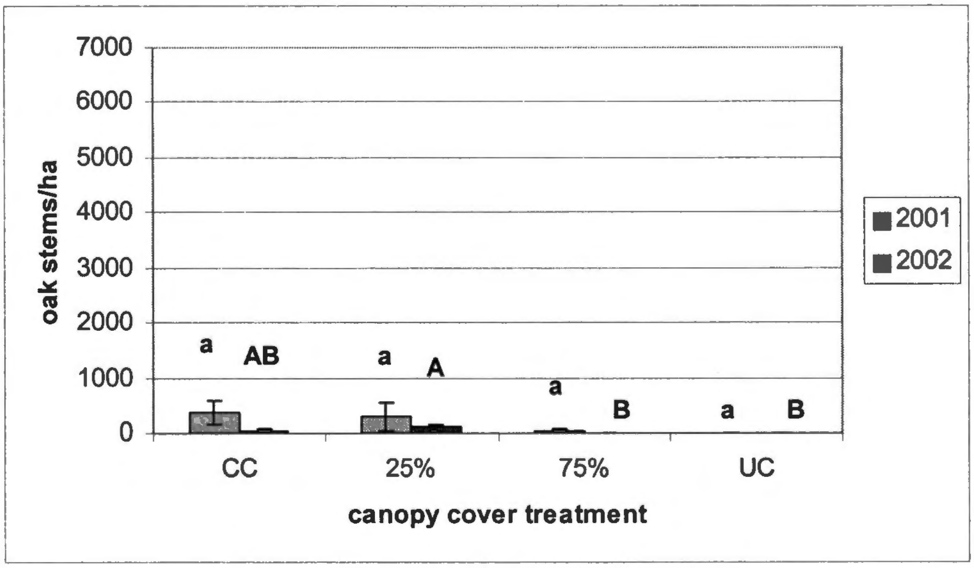


Figure 13. Sapling (2.54 cm dbh-10cm dbh) density for natural regeneration within oak stands. Analysis conducted before and after prescribed fire comparing a) red maple and b) oak. Treatment codes and significance as in Figure 5.

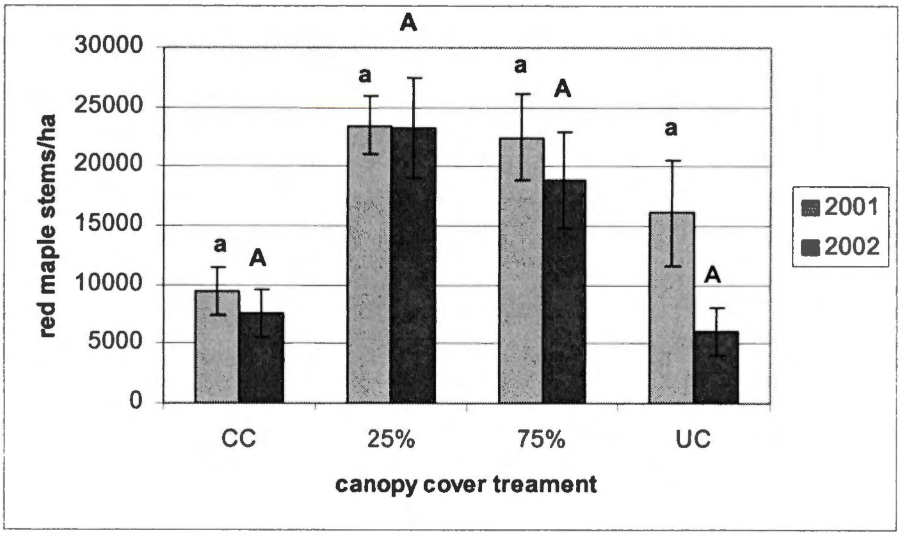
maple saplings began wilting and prematurely changing color. Oak stands were revisited in October to collect samples for possible identification of pathogenic fungi. *Verticillium spp.*, *Phomopsis spp.*, and *Trichoderma spp.* were isolated and identified from one sample, and other red maple stems appeared to be infected with the same fungi.

Density of red maple seedlings less than 2.54 cm dbh was most measurably reduced in uncut stands (Figures 13a, 14a). Sapling regeneration density was very low in uncut treatments as previously discussed. Red maple density in both seedling size classes (<25 cm tall and 25cm-2.54cm dbh) within clear-cuts was low compared to other treatments before and after prescribed fire because most stems were already in the largest regeneration size class.

Prior to prescribed fire treatments, density of red maple and oak seedlings (25cm-2.54cm dbh) in the 25% canopy cover treatment was nearly equal at approximately 24,000 stems per hectare for each species (Figure 13). Oak seedling (25cm-2.54cm dbh) density was significantly greater in the 25% canopy cover treatments than all other treatments before and after prescribed burning, while red maple density did not differ significantly between canopy cover treatments (Figure 13). Following prescribed fire, oak seedling (25cm-2.54cm dbh) density, within 25% canopy cover treatments, was reduced while red maple density was not impacted. Most oak sprout density was shifted into the below 25 cm height class and an influx of red maple into this size class occurred from sprouts of larger saplings within 25% canopy cover treatments (Figures 13, 14).

Even though red maple density was not measurably reduced in overstory removal treatments, the overall structure of the medium sized red maple regeneration cohort (25 cm tall- 2.54 cm dbh) was impacted. This effect was documented by the sapling scorch

a) Red maple



b) Oak

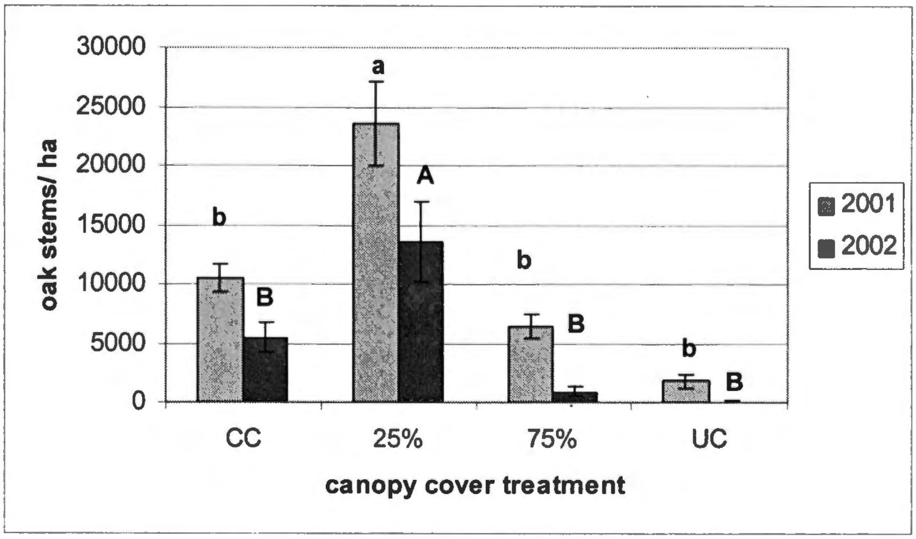
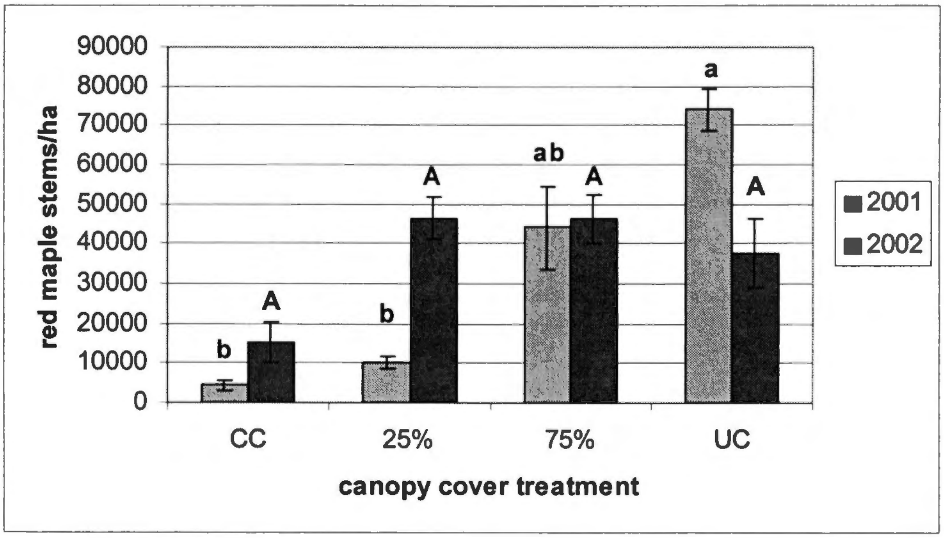


Figure 14: Seedling (25 cm height- 2.54 cm dbh) density for natural regeneration within oak stands. Analysis conducted before and after prescribed fire comparing a) red maple and b) oak. Treatment codes and significance as in Figure 5.

a) Red maple



b) Oak

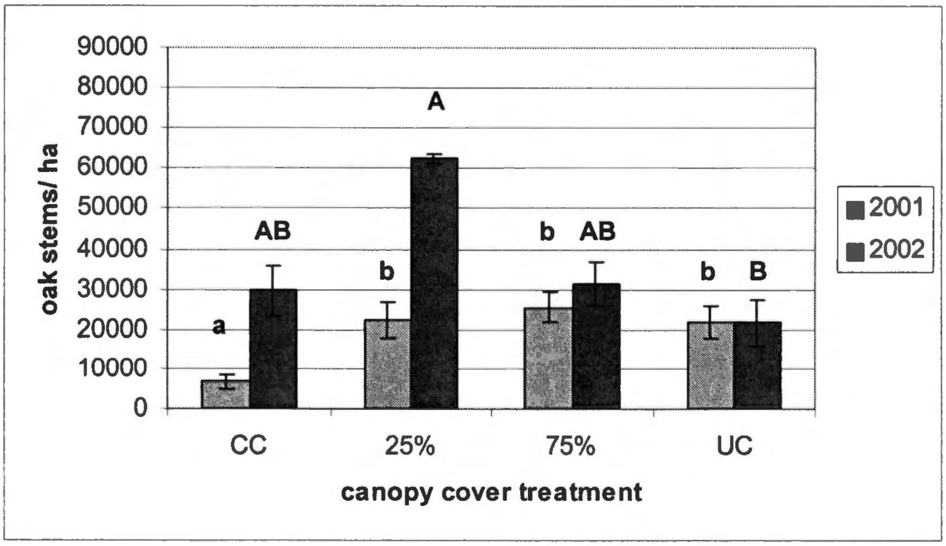


Figure 15. Small seedling (< 25 cm) density for natural regeneration within oak stands. Analysis conducted before and after prescribed fire comparing a) red maple and b) oak. Treatment codes and significance as in Figure 5.

height, and was reflected in the mean post-burn height of red maple regeneration within this layer (Figure 15). Mean height of red maple seedlings (25cm tall- 2.54 cm dbh) was reduced by 60-80 cm and sprout heights were uniform across canopy cover treatments.

Following fire, seedlings did not shift to different size classes in shrub-layer removal treatments within 25% canopy cover plots inside the oak stands. All regeneration before burning was below 2.54 cm dbh. Within these treatments, oak and red maple average sprout heights were equal following burning while red maple had a clear height advantage before burning (Figure 16).

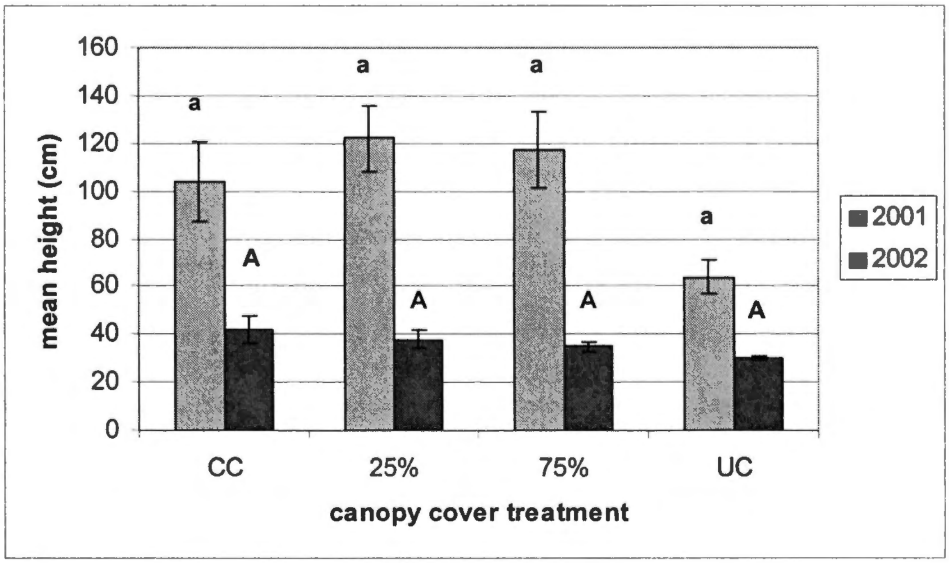


Figure 16. Average height of red maple in the seedling size class (25 cm height- 2.54 cm dbh) within oak stands. Treatment codes and significance as in Figure 5.

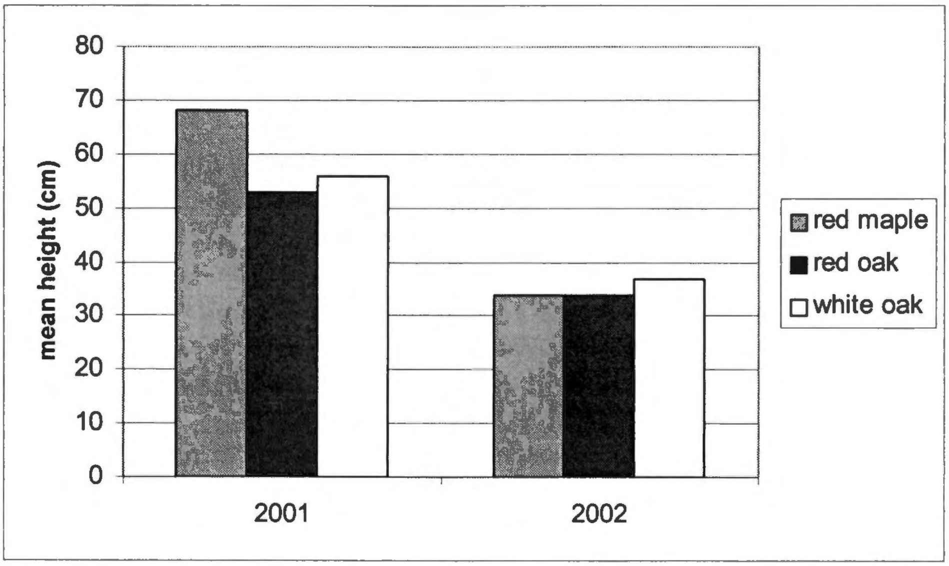


Figure 17. Mean height of oak and red maple before and after prescribed fire within oak stand 25% shelterwood shrub removal treatments. There were no statistical analyses conducted.

Natural oak regeneration in pine stands

Statistically significant differences in oak regeneration density were not found between canopy cover treatments in pine stands before or after prescribed fire (Figures 18, 19, and 20). However, differences in oak regeneration density across levels of canopy cover were identifiable, especially in smaller regeneration size classes.

The greatest density of natural oak sapling regeneration (260 stems/ha) occurred in the 25% canopy cover plots within pine stands. However, the standard deviation for the sampling plots was larger than the overall mean, which suggested substantial variation between the three pine stands (Figure 18).

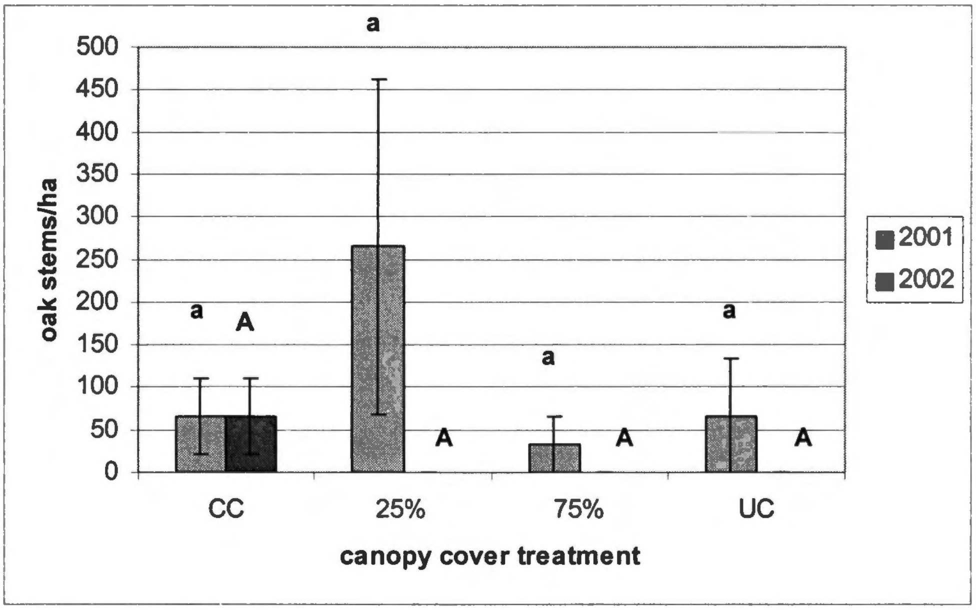


Figure 18. Natural oak sapling (2.54 cm dbh- 10 cm dbh) density within pine stands. Analysis conducted before and after prescribed burning. Treatment codes and significance as in Figure 5.

All oak saplings (2.54 cm dbh- 10 cm dbh) in 25% canopy cover pine treatments were located in pine block three. Prescribed fire top-killed all oaks in all canopy cover treatments except for clear-cuts, where none were top-killed.

In pine stands, natural oak seedling (25 cm ht-2.54 cm dbh) density was lowest in clear-cuts. Density of oak seedlings (25 cm ht-2.54 cm dbh) was greatest in 25% canopy cover treatments before burning, but was lowest in this treatment following burning (Figure 19). Density of small oak seedlings (< 25 cm ht) increased in all canopy cover treatments following prescribed fire (Figure 20). Oak seedlings below 25 cm ht exhibited a distinct pattern of increasing density with increasing levels of canopy cover (Figure 20).

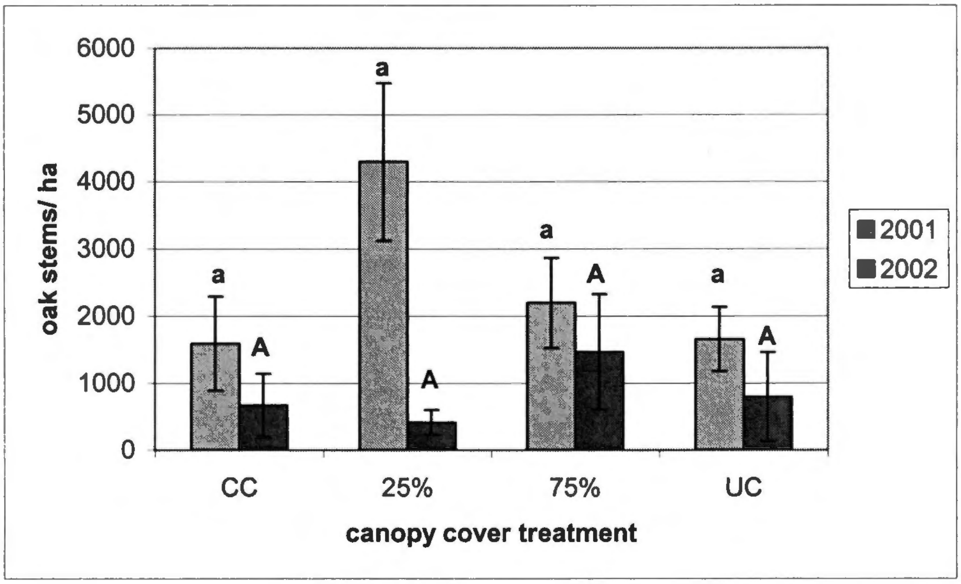


Figure 19. Natural oak seedling (25 cm ht- 2.54 cm dbh) density within pine stands. Analysis conducted before and after prescribed fire. Treatment codes and significance as in Figure 5.

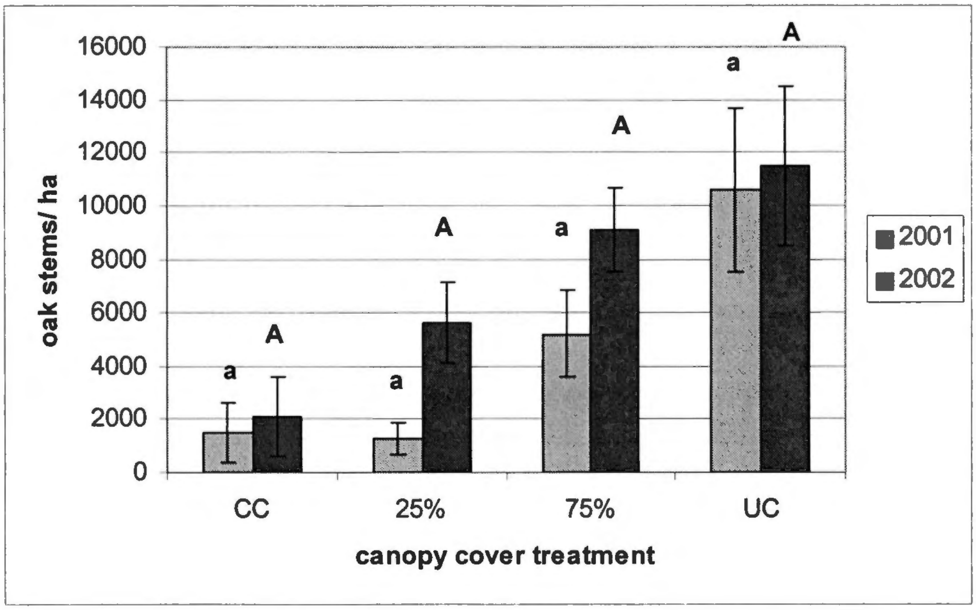


Figure 20. Natural small oak seedling (< 25 cm ht) density within pine stands. Analysis conducted before and after prescribed fire. Treatment codes and significance as in Figure 5.

Planted oaks

Mortality

Although differences were not statistically significant between oak and pine stands, caged seedlings tended to have greater average percent mortality in oak compared to pine stands ten years following establishment and before prescribed burning (1991-2001) (Figure 21). Error bars did not overlap for caged seedlings within oak and pine stands, suggesting that differences may have been significant using a higher alpha level. Uncaged seedling average percent morality was not different between oak and pine stands (Figure 21). When averaged across all canopy cover treatments, direct-seeded seedling mortality averaged 20% greater for uncaged seedlings and 10% greater for caged seedlings.

Percent mortality of planted oak seedlings exhibited similar patterns across canopy cover treatments ten years after establishment (1991-2001) and after prescribed fire (2001-2002) (Figures 22, 23). Most seedlings that did not sprout in 2002 were documented as having been heavily stressed by low resource levels, frost, or deer browsing before prescribed fire treatment. Approximately 50% and 70% cumulative mortality for planted oak seedlings occurred prior to burning in oak and pine clear-cuts, respectively (Figure 22). Prior to prescribed fire treatment, 75% pine canopy cover treatments contained the lowest planted oak mortality (Figure 22). Following burning, 75% canopy treatments in pine stands and 25% canopy treatments in oak stands had the lowest 2001-2002 mortality (Figure 23).

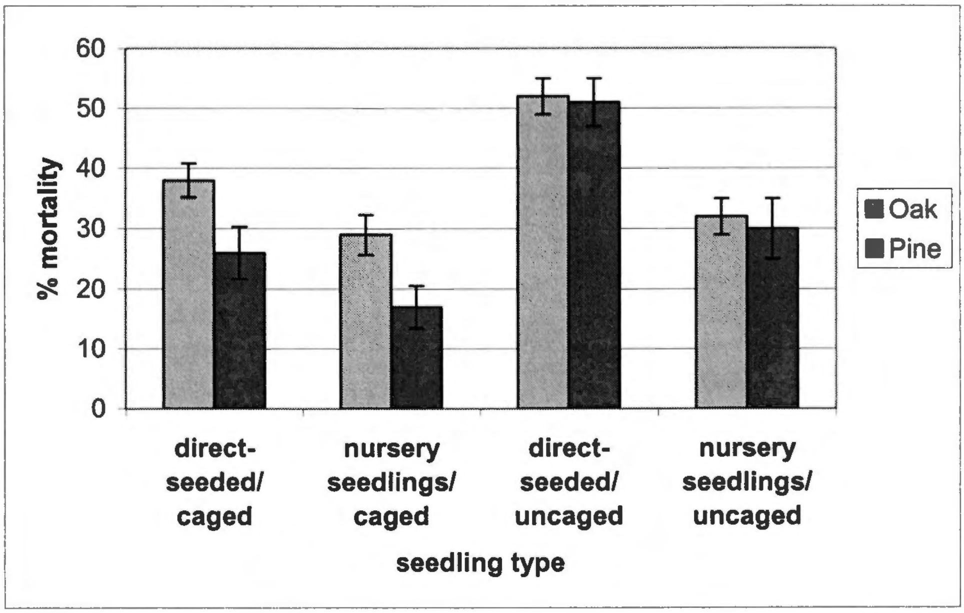
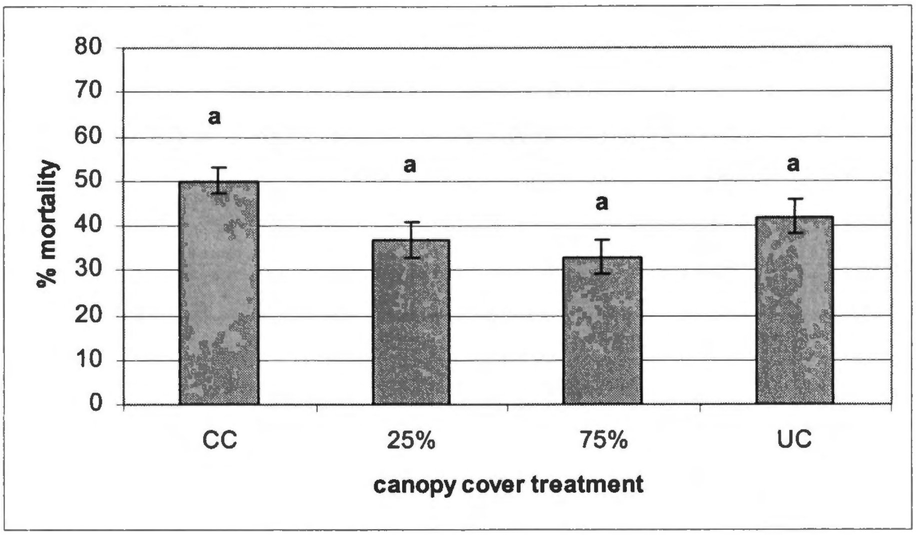


Figure 21. Percent mortality of planted oaks before prescribed fire (1991-2001) by seedling type. Analysis conducted comparing oak to pine stands within each seedling establishment type. There were no statistical differences between oak and pine stands using α= .05.

a) Oak



b) Pine

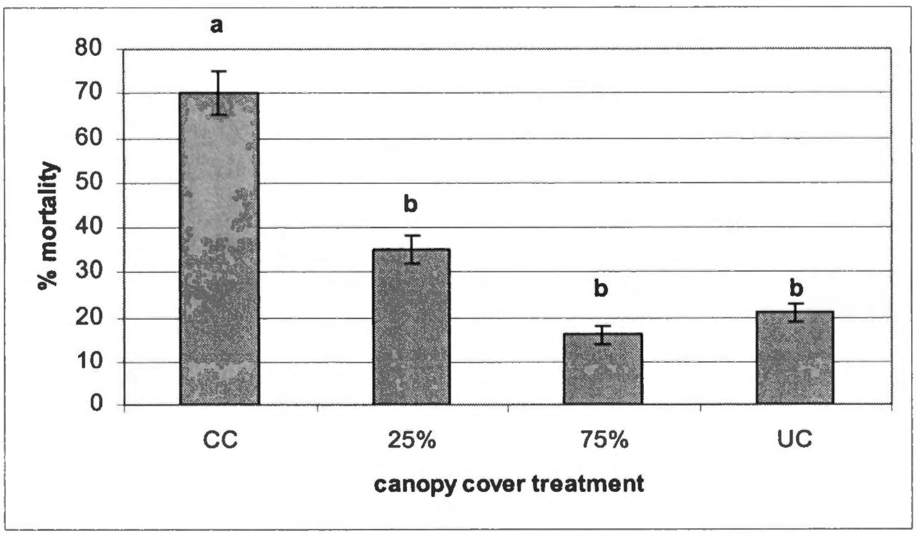
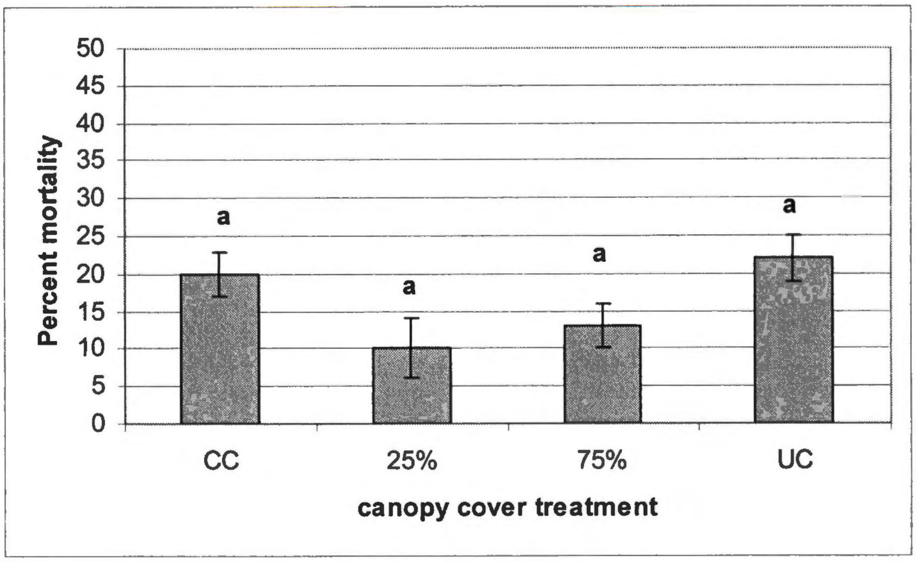


Figure 22. Percent mortality of planted oaks before prescribed fire (1991-2001). Analysis conducted within a) oak stands and b) pine stands. Treatment codes and significance as in Figure 5.

a) Oak



b) Pine

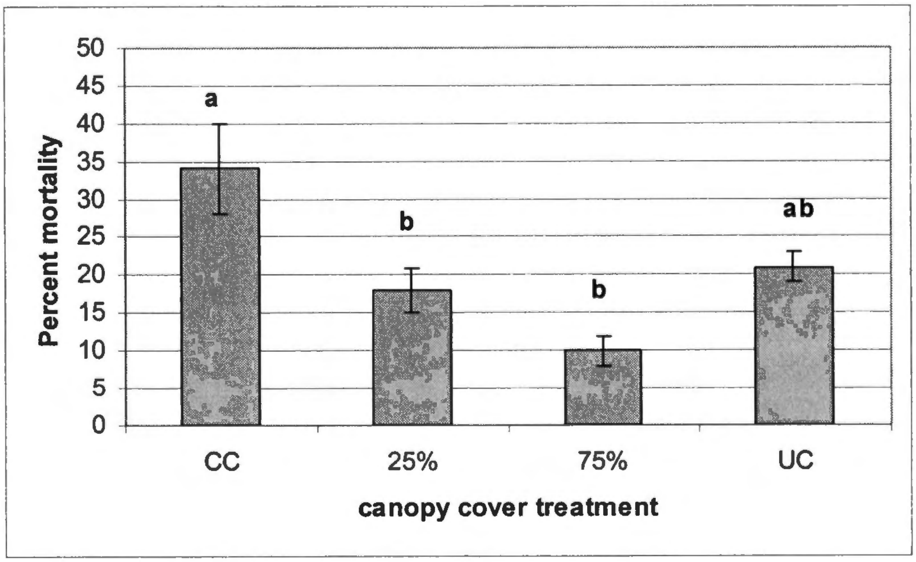


Figure 23. Percent mortality of planted oaks following prescribed fire (2001-2002). Analysis conducted within a) oak stands and b) pine stands. Treatment codes and significance as in Figure 5.

Across all treatments within oak stands, browsing was reduced by approximately 15% following prescribed fire treatment (Figure 24). Browsing was significantly lower in 75% and uncut treatments following burning, while percent of browsed seedlings was not significantly different between canopy cover treatments prior to burning (Figure 25a). Within pine stands, percent browsing slightly increased in shelterwood treatments and decreased in clear-cut and uncut plots (Figure 25b).

Mean heights

Although differences were not statistically significant, height of caged oak seedlings averaged 30 cm taller in pine compared to oak stands before prescribed fire treatment. Error bars did not overlap in this comparison, which suggested differences would have been significant at a higher alpha level. Uncaged seedling heights were recognizably not different between oak and pine stands (Figure 26).

The canopy cover treatments that produced the greatest pre-burn heights consistently produced the greatest post-burn sprout growth for both caged and uncaged seedlings (Figures 27, 28). Uncaged oak seedling and sprout heights averaged half that of caged seedlings (Figures 27, 28).

Within oak stands, mean caged oak pre-burn seedling height was greatest in clear-cut and 25% canopy cover treatments and mean post-burn sprout heights was significantly greater in clear-cuts compared to other canopy cover treatments (Figure27a). Mean caged sprout height in 75% canopy cover treatments was significantly lower than

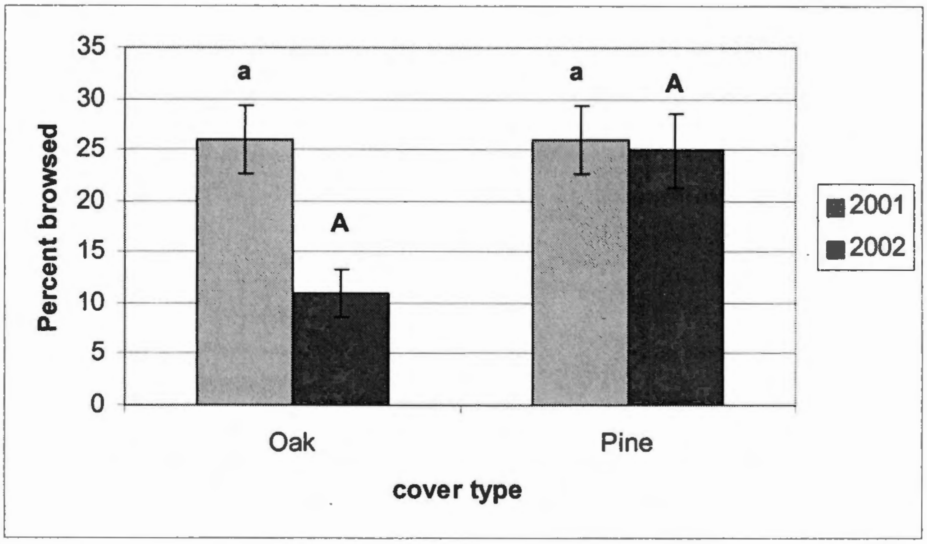
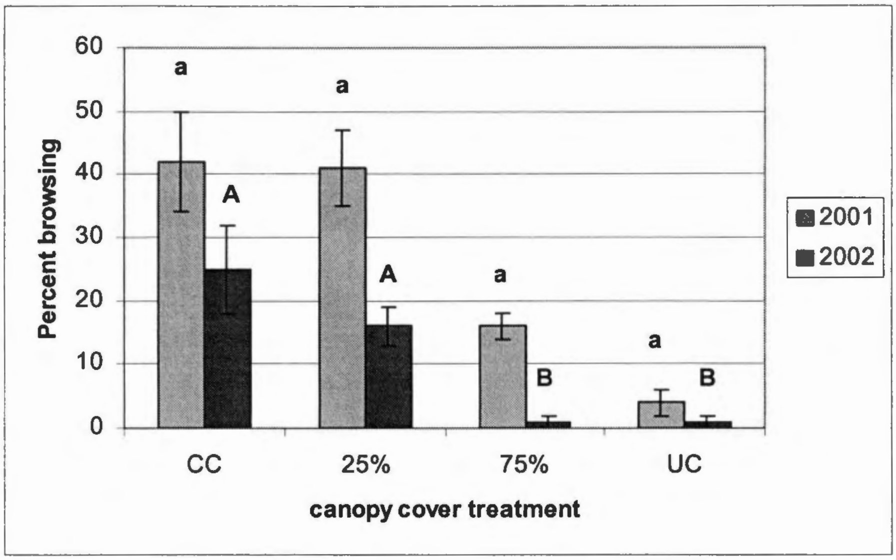


Figure 24. Percent browsing of uncaged planted oak seedlings by cover type. Analysis conducted before and after prescribed fire within oak and pine stands.

a) Oak



b) Pine

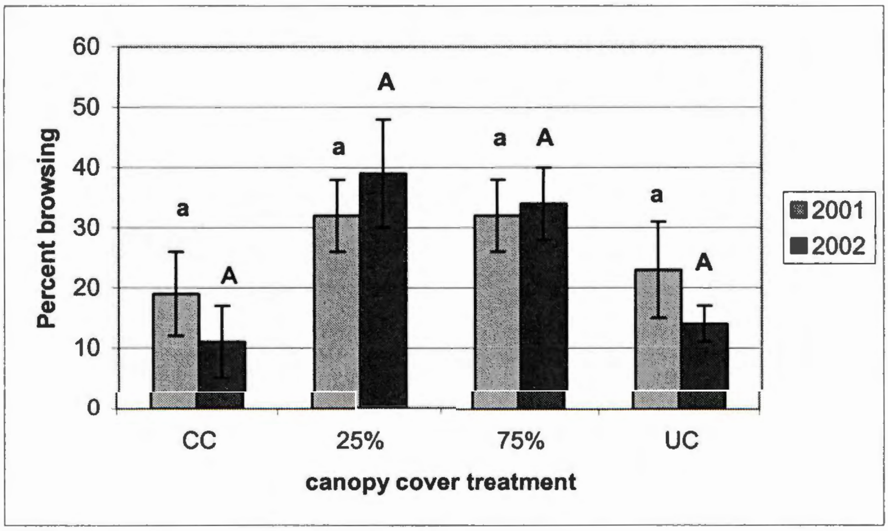


Figure 25. Percent browsed uncaged planted oak seedlings. Analysis conducted before and after prescribed fire within a) oak stands and b) pine stands. Treatment codes and significance as in Figure 5.

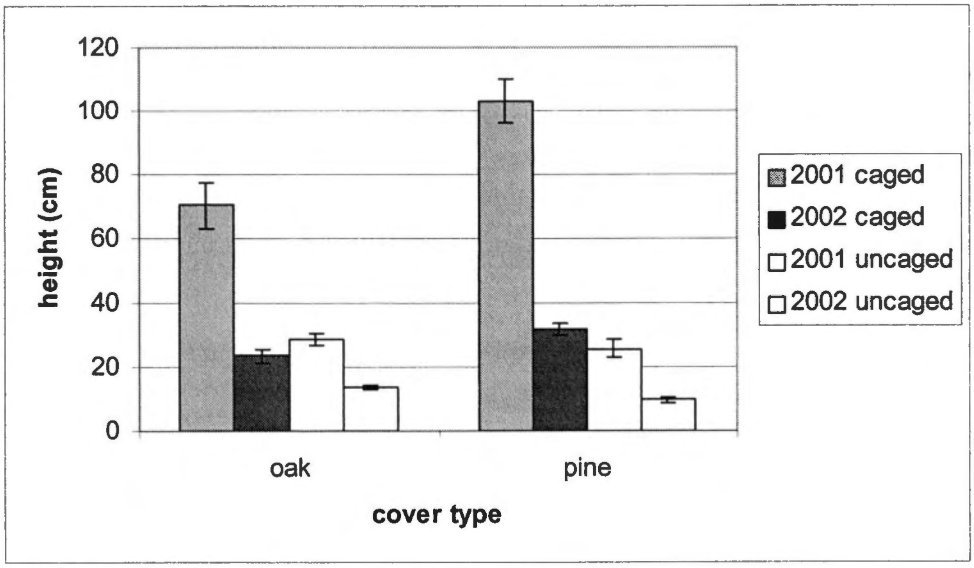
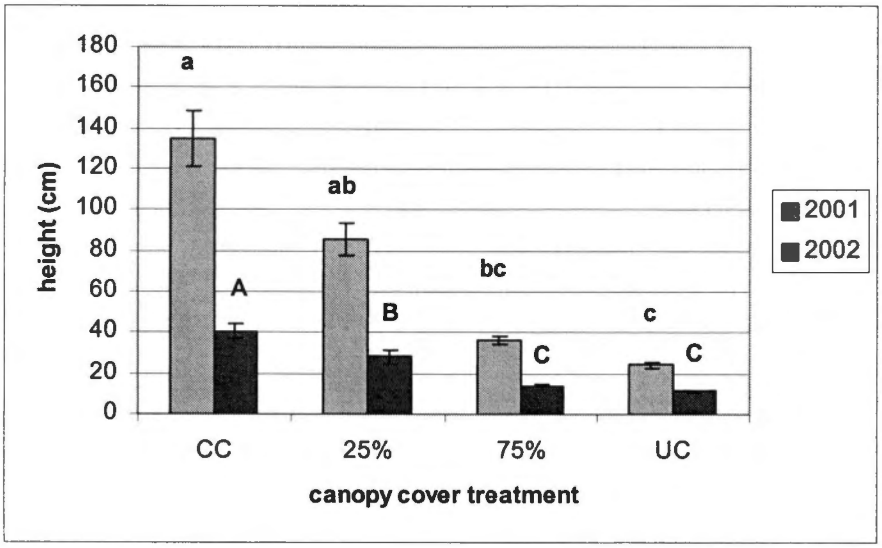


Figure 26. Mean caged and uncaged planted oak heights by cover type. Analysis conducted within groups of seedlings protected and unprotected from deer browsing within oak and pine stands before and after prescribed fire. There were no statistical differences between oak and pine cover types using $\alpha = .05$.

a) Oak



b) Pine

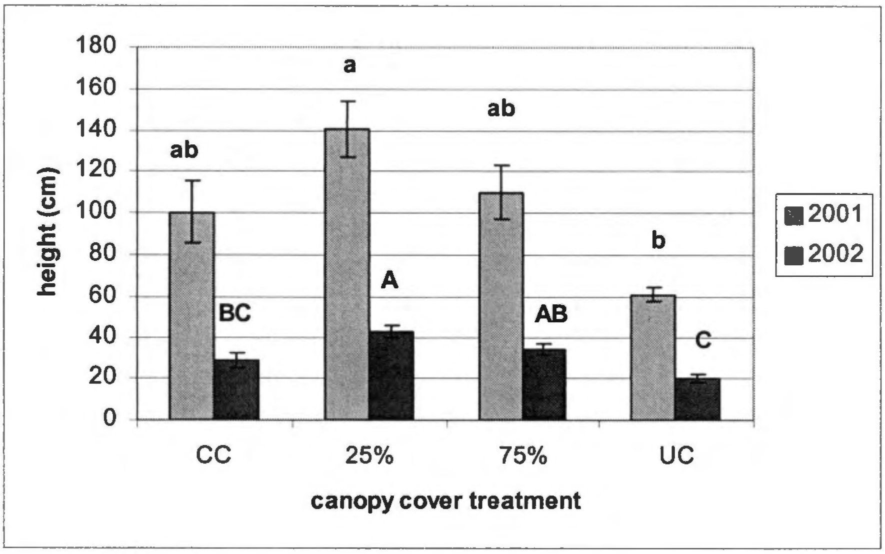


Figure 27. Caged planted oak mean heights. Analysis conducted before and after prescribed burning within a) oak and b) pine stands. Treatment codes and significance as in Figure 5.

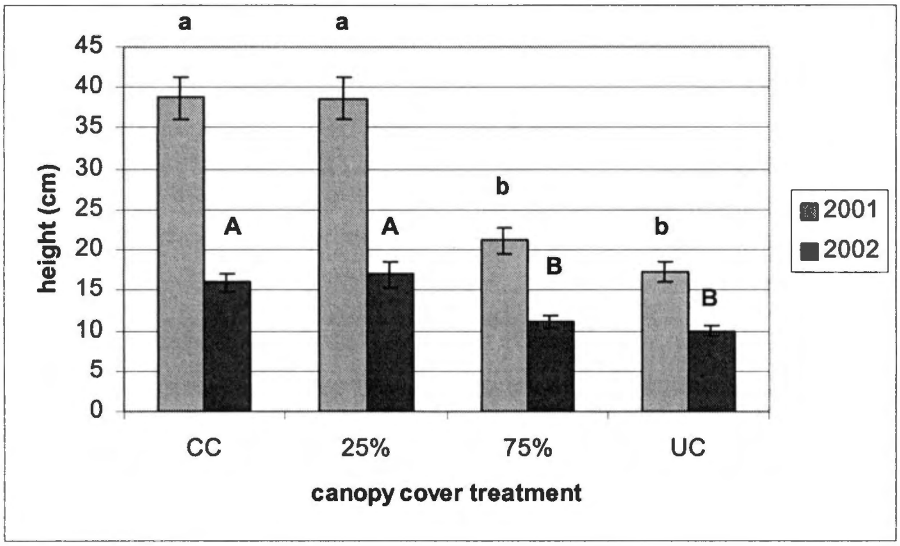
in 25% canopy cover treatments, within oak stands. In contrast, within pine stands, seedling and sprout height was not significantly different between 75% canopy cover treatments and 25% or clear-cut treatments (Figure 27). Oak clear-cuts and pine 25% canopy cover treatments contained the greatest mean caged mean seedling (140 cm) and sprout (40 cm) heights, and these values were nearly equal (Figure 27).

Generally, mean uncaged seedling height and sprout height had growth patterns similar to caged seedlings across levels of canopy cover, with a few exceptions. In oak stands, uncaged seedlings and sprout heights were not different between clear-cut and 25% canopy cover treatments and, in pine stands, uncaged seedling and sprout heights were not different between 25% and 75% canopy cover treatments (Figure 28).

Pre-burn seedling size and post-burn sprout growth relationship

Planted oak pre-burn height and basal diameter were significantly related to sprout growth when tested across all treatments ($P<.0001$). Simple linear regressions were run to establish predicted lines and develop equations for each canopy cover treatment. A comparison of regression results for pre-burn height and pre-burn basal diameter as predictors of sprout growth are located in table 4. The only regression that did not exhibit a significant relationship between pre-burn size and post-burn height was the regression involving uncaged seedling pre-burn height as the x variable in pine clear-cuts where very few seedlings were still alive ten years following planting (Table 4, Figure 33b). The strongest relationship between pre-burn size and post-burn sprout height was revealed

a) Oak



b) Pine

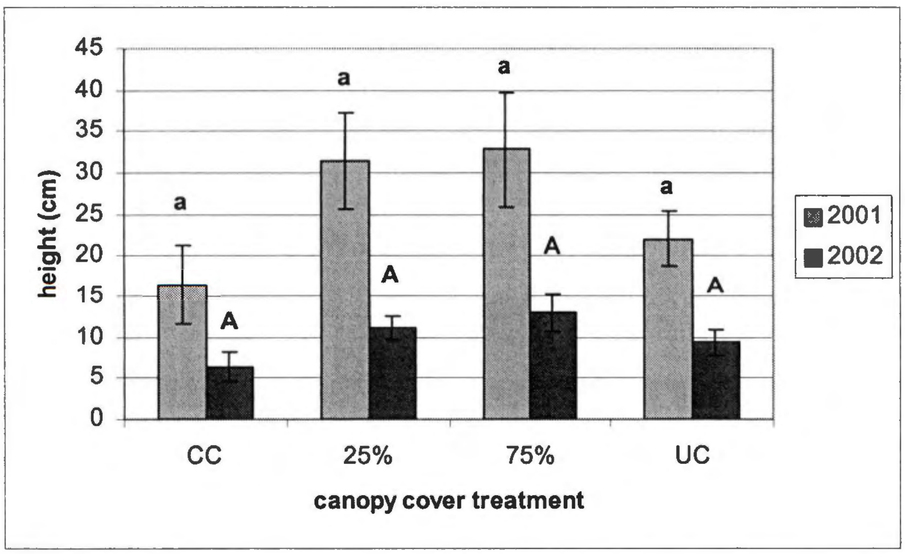


Figure 28. Uncaged planted oak mean heights. Analysis conducted before and after prescribed burning within a) oak and b) pine stands. Treatment codes and significance as in Figure 5.

using pre-burn basal diameter as the independent variable in 25% cover treatments within oak stands and 75% cover within pine stands (Table 4a).However, pre-burn height r^2 values were greater than pre-burn basal diameter r^2 values in all regressions except for caged seedlings in canopy removal treatments within oak stands and caged seedlings in pine clear-cuts (Table 4). The relationships between oak sprout height and pre-burn height, within each level of initial canopy cover, within oak and pine stands, are shown in figures 29-36.

Sprout growth was least predictable using pre-burn height for caged seedlings within uncut pine stands (r^2= .07) and uncaged seedlings within clear-cut oak stands (r^2=.06) (Figures 32b and 33a). Predictability of sprout growth using pre-burn height was also low in pine clear-cuts for both caged (r^2=.13) and uncaged (r^2=.12) seedlings (Figures 29b and 33a).

Table 4: Post-burn sprout growth regression results using: a) pre-burn basal diameter and b) pre-burn height as independent variables.

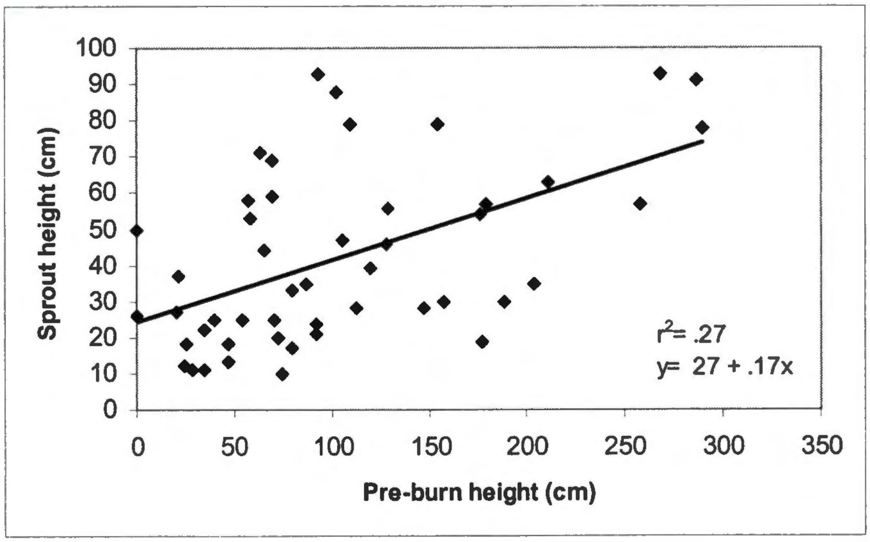
a)

	R-square	slope	Pr > F
Caged			
oak stands			
CC	0.32	18	0.0001
25%	0.44	35	0.0001
75%	0.27	17	0.0001
UC	0.18	11	0.0001
Caged			
pine stands			
CC	0.16	10	0.012
25%	0.08	10	0.0056
75%	0.33	22	0.0001
UC	0.06	15	0.0075
Uncaged			
oak stands			
CC	0.13	9	0.001
25%	0.23	20	0.0001
75%	0.35	24	0.0001
UC	0.11	12	0.001
Uncaged			
pine stands			
CC	0.17	8	0.0283
25%	0.25	12	0.0001
75%	0.49	25	0.0001
UC	0.35	30	0.0001

b)

	R-square	slope	Pr > F
Caged			
oak stands			
CC	0.27	.17	0.0002
25%	0.26	.22	0.0001
75%	0.21	.16	0.0001
UC	0.28	.23	0.0001
Caged			
pine stands			
CC	0.13	.08	0.0208
25%	0.25	.17	0.0001
75%	0.33	.17	0.0001
UC	0.07	.1	0.0021
Uncaged			
oak stands			
CC	0.06	.08	0.0247
25%	0.31	.27	0.0001
75%	0.5	.4	0.0001
UC	0.28	.3	0.0001
Uncaged			
pine stands			
CC	0.12	.07	0.07
25%	0.32	.11	0.0001
75%	0.52	.3	0.0001
UC	0.45	.31	0.0001

a) Oak



b) Pine

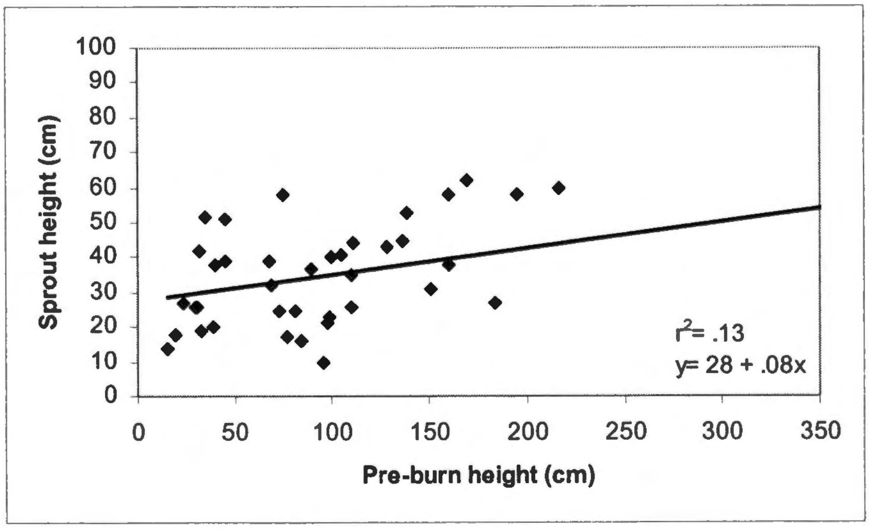
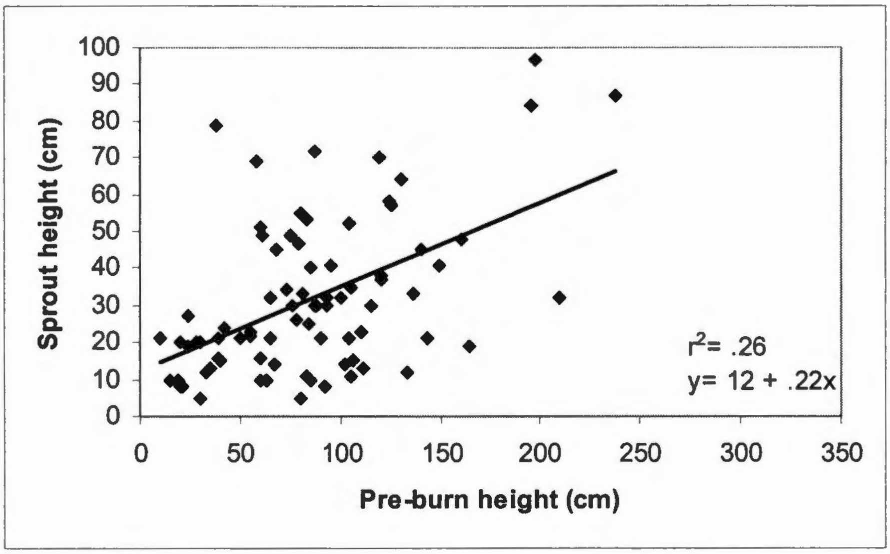


Figure 29. Relationship between post-burn sprout height and pre-burn height for **caged** oak seedlings in **clear-cuts.** Analysis conducted within a) oak and b) pine stands.

a) Oak



b) Pine

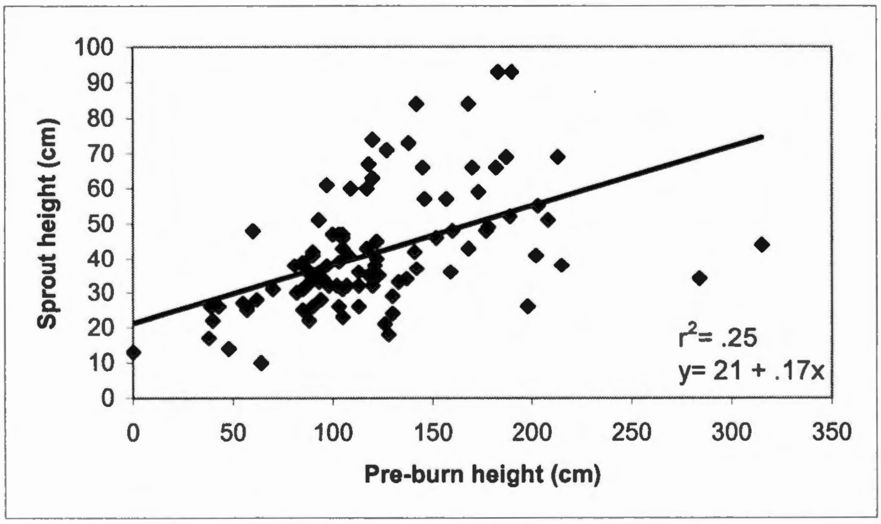
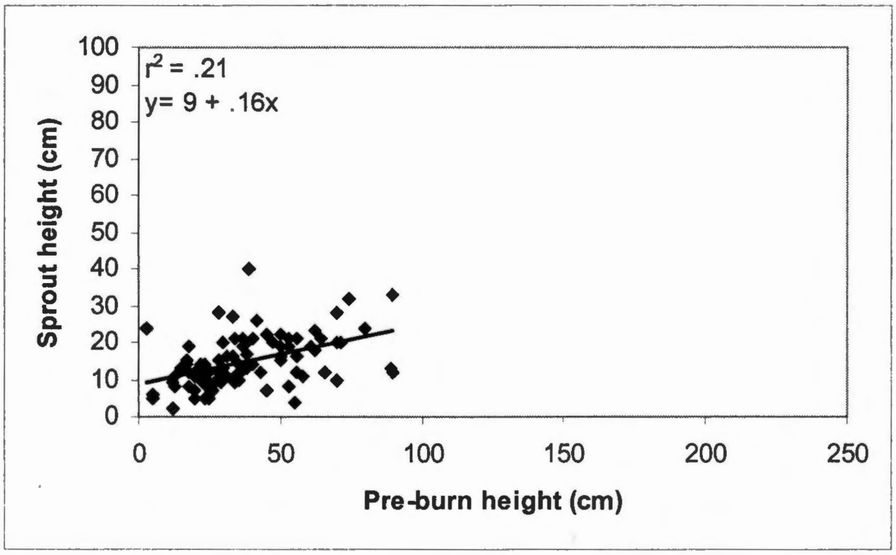


Figure 30. Relationship between post-burn sprout height and pre-burn height for **caged** oak seedlings in **25%** canopy cover plots. Analysis conducted within a) oak and b) pine stands.

a) Oak



b) Pine

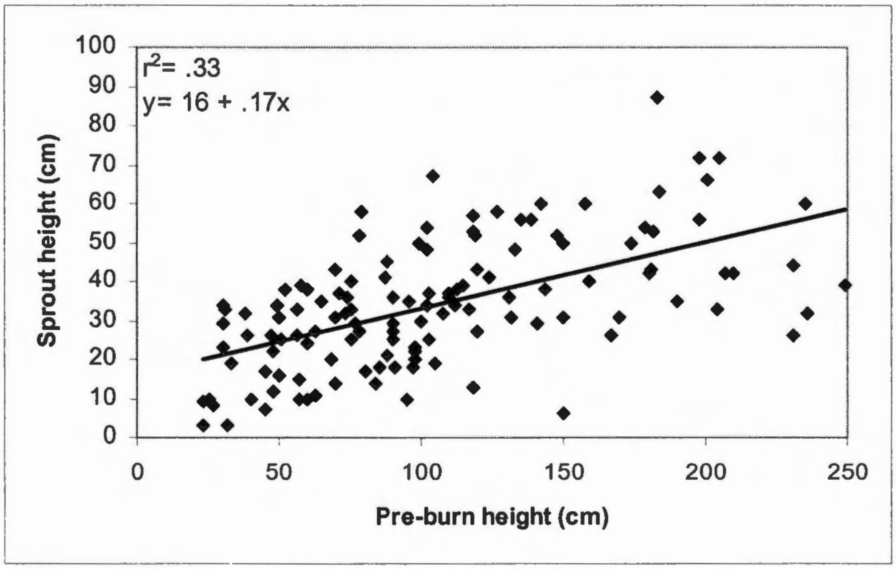
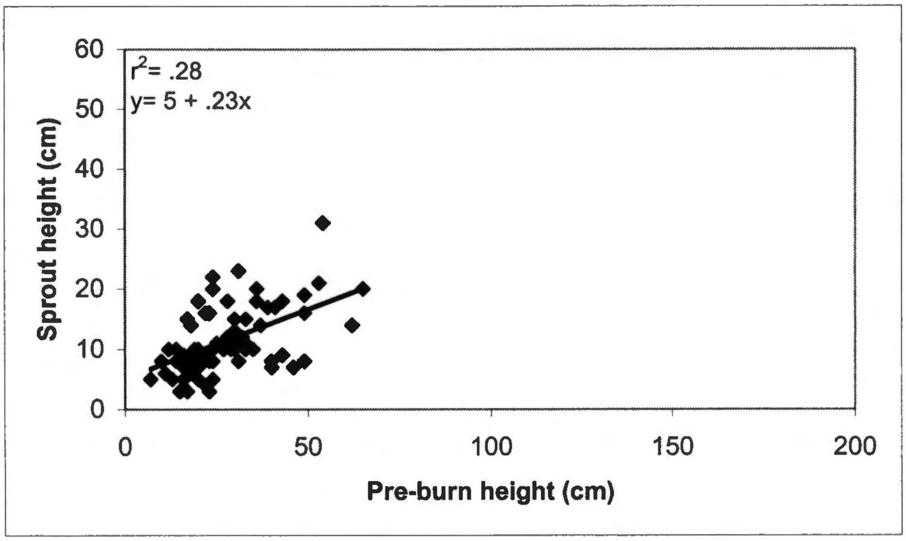


Figure 31. Relationship between post-burn sprout height and pre-burn height for **caged** oak seedlings in **75%** canopy cover plots. Analysis conducted within a) oak and b) pine stands.

a) Oak



b) Pine

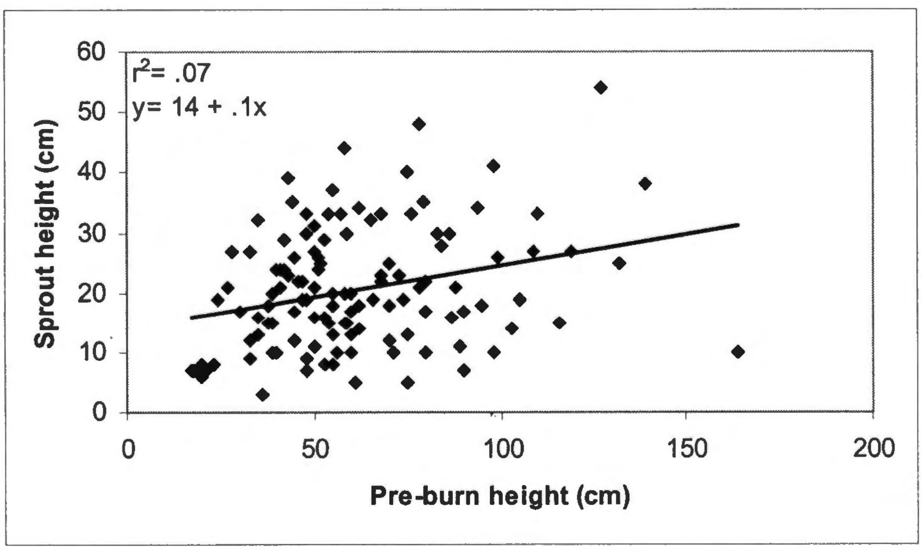
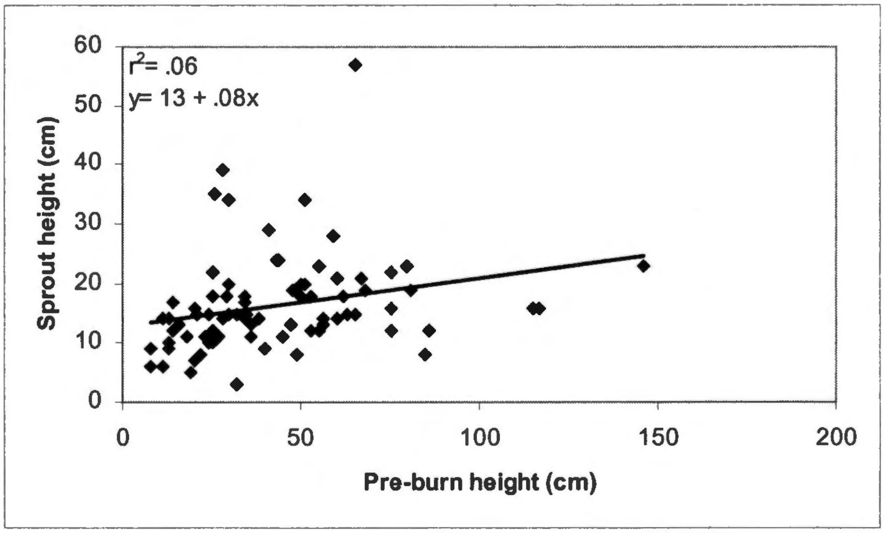


Figure 32. Relationship between post-burn sprout height and pre-burn height for **caged** oak seedlings in **uncut** plots. Analysis conducted within a) oak and b) pine stands.

a) Oak



b) Pine

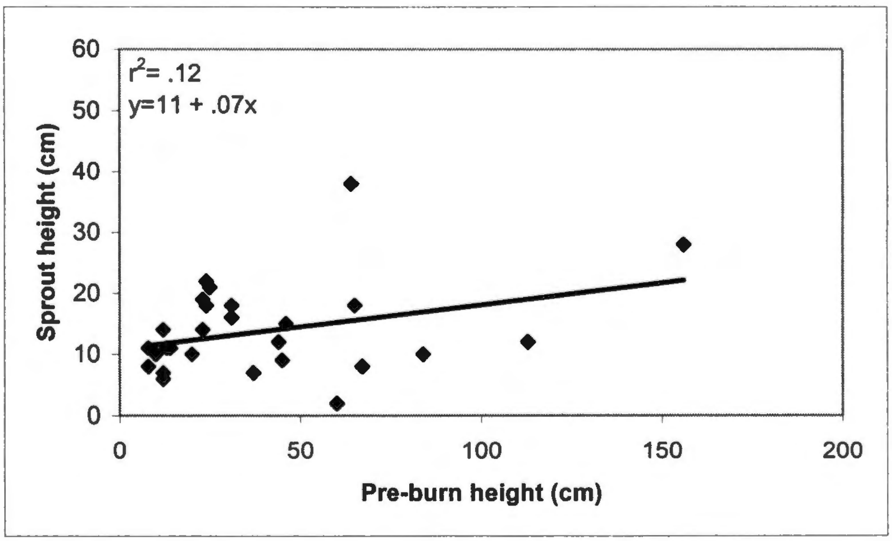
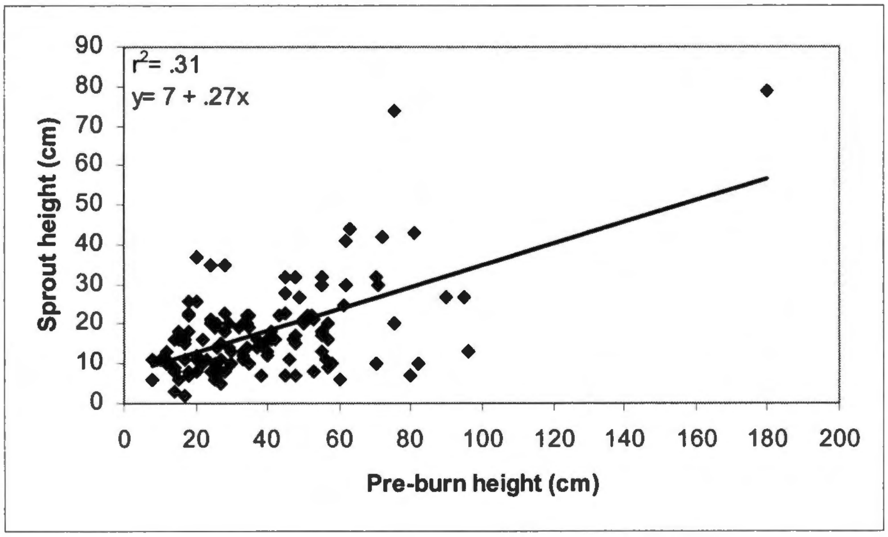


Figure 33. Relationship between post-burn sprout height and pre-burn height for **uncaged** oak seedlings in **clear-cut** plots. Analysis conducted within a) oak and b) pine stands.

a) Oak



b) Pine

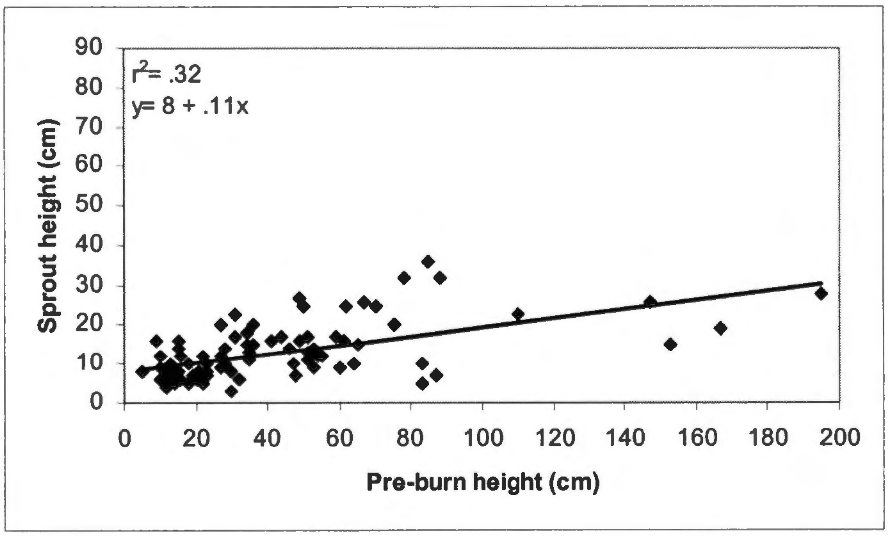
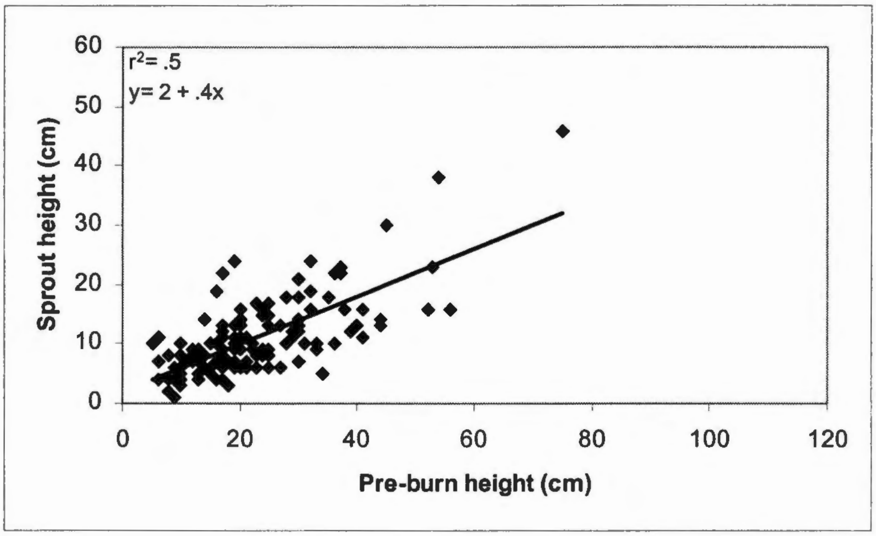


Figure 34. Relationship between post-burn sprout height and pre-burn height for **uncaged** oak seedlings in **25%** canopy cover plots. Analysis conducted within a) oak and b) pine stands.

a) Oak



b) Pine

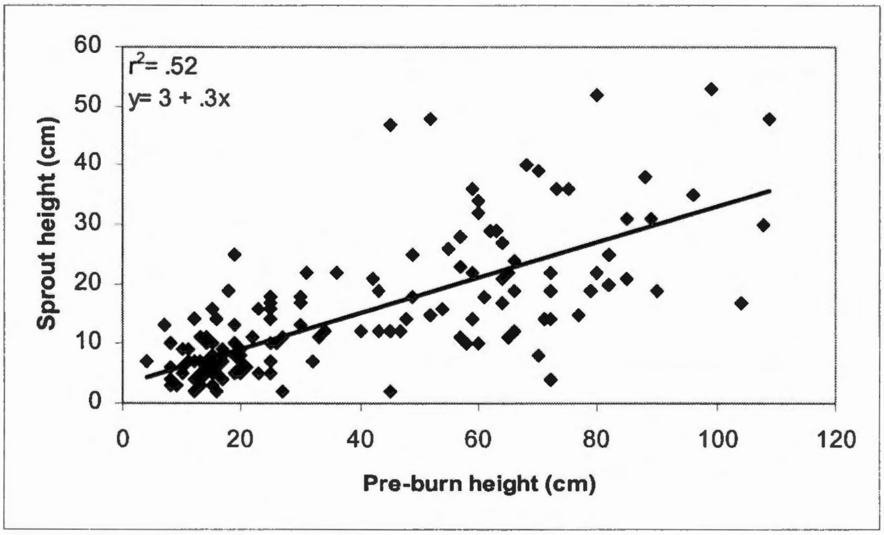
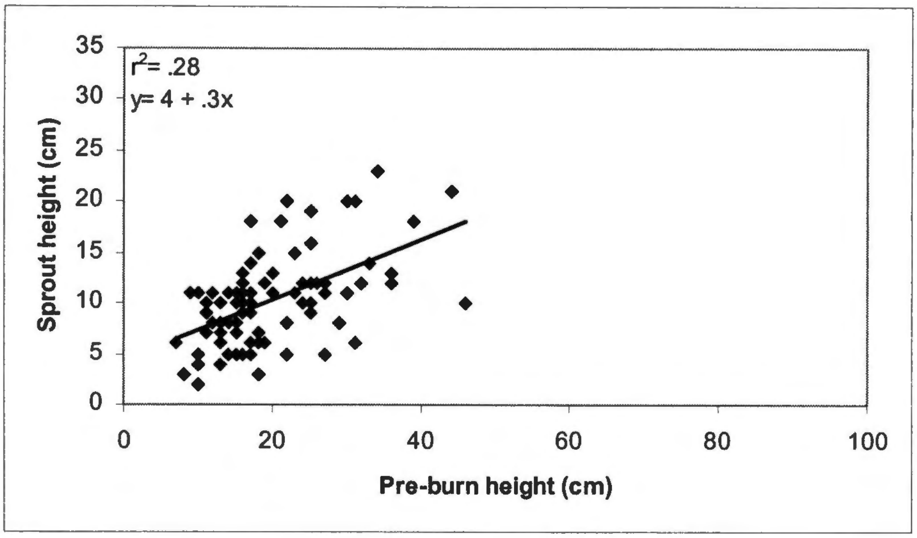


Figure 35. Relationship between post-burn sprout height and pre-burn height for **uncaged** oak seedlings in **75%** canopy cover plots. Analysis conducted within a) oak and b) pine stands.

a) Oak



b) Pine

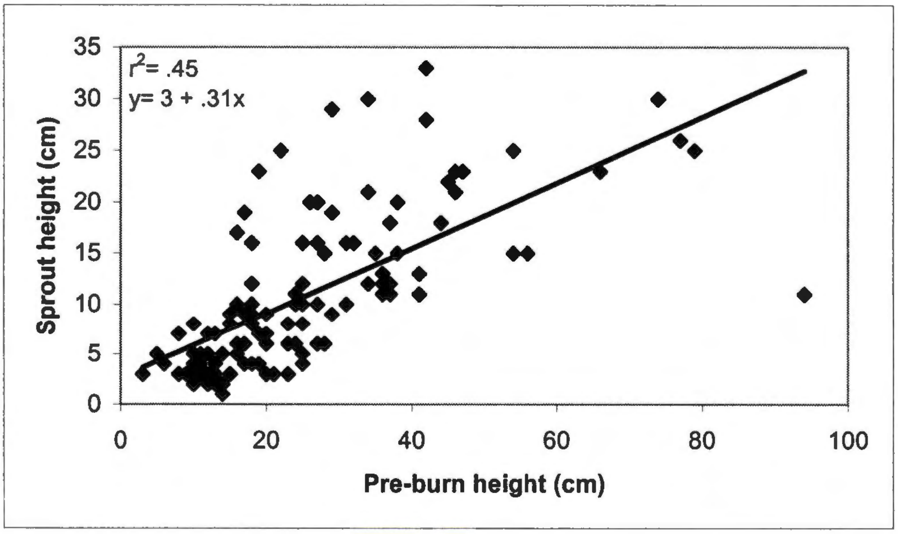


Figure 36. Relationship between post-burn sprout height and pre-burn height for **uncaged** oak seedlings in **uncut** plots. Analysis conducted within a) oak and b) pine stands.

Chapter 6: Discussion

Long-term effects of mechanical competitor removal 1990-2001

Tall understory red maple regeneration that resulted from initial mechanical treatments clearly affected 2002 measurements of both photosynthetically active radiation and canopy cover. Canopy cover increased and PAR decreased in clear-cut and 25% canopy cover treatments within oak stands due to the development of red maple saplings. Slightly greater measurements of PAR within pine stands than oak stands at the same levels of canopy cover may have had positive effects on oak establishment and survival. Greater PAR in pine stands was mostly due to a lack of red maple regeneration in pine plots with less overstory cover, and greater PAR penetration through pine than oak canopies in plots with greater overstory cover. While working on these same study sites, Buckley et al. (1999) concluded that the difference in the relationship between basal area and canopy cover between oak and pine stands was likely due to differences in crown architecture. Differences in PAR and other resources caused by differential effects of pine and oak overstory trees likely produced many of the interactions revealed in this research.

Overstory density and understory resources

As expected, overstory red pine and northern red oak responded to thinning in 1990. Canopy closure occurred in pine and oak plots that were originally thinned to 75%

and 25% canopy cover. However, the response in terms of increased bole volume was different between oak and pine stands, most noticeably in 75% cover plots. In 75% canopy cover treatments, residual oak stem basal area did not significantly increase as it did within pine stands. Throughout a decade of growth, volume increased along with canopy closure in pine plots that were originally thinned to 75% canopy cover, while canopy closure without substantial basal area growth occurred in oak plots where the same canopy treatment was applied. This result indicated physiologic and/or resource uptake differences between oak and pine residual trees.

Differences in the availability of below-ground resources resulting from greater overstory tree volume in pine than oak stands may have been a determining factor affecting the significant differences in red maple density between oak and pine stands. Soil moisture measurements were similar across all treatments in 2002, which indicated that the responding understory competition, in oak stands, and overstory crown expansion, in both oak and pine stands, may have caused soil moisture levels to become increasingly similar between stand types. While working on the same sites 1-3 years after treatments were first established, Kim et al. (1996) found significantly lower nitrogen mineralization in pine than in oak stands across all levels of canopy cover and Buckley et al. (1998) suggested that lower soil moisture resulting from greater basal area in pine stands may have contributed to lower initial success of oak regeneration in pine than in oak stands. Red maple domination in the regeneration cohort within oak stands throughout the last decade may have reduced these initial differences.

Red pine tends to have greater growth rates than northern red oak, which may explain the significant volume increase in plots originally thinned to 75% canopy cover within pine and not oak stands. However, lower density of hardwood regeneration in pine stands may have also contributed to increased residual pine diameter growth following thinning. Abundant understory red maple regeneration may have competed for increased resources produced by similar treatments within oak stands, and therefore did not allow a similar volume increase in residual oaks.

Red pine and red maple interaction

Red maple regeneration was nearly absent in pine stands. This result may have been due, in part, to greater litter depths in closed canopy pine stands, which may have had a negative effect on red maple recruitment. Red maple samaras are among the lightest maple fruits and are efficiently dispersed by wind (Walters and Yawney 1990). However, their light weight is also accompanied by relatively small amounts of seed reserves, which could have prevented red maple seedling radicles from penetrating the litter in pine stands and reaching mineral soil. There were also far fewer overstory red maple within pine than within oak stands, which likely affected the abundance of red maple seed and consequently may have had an impact on the density of red maple regeneration. However, the decreased ability of red maple to establish and/or compete on these red pine sites throughout the last century suggested that red maple may be at a disadvantage in pine stands regardless of the proximity of seed sources. The pine stands may have negatively impacted red maple recruitment and growth at the outset when red pines were first planted.

The absence of red maple in nearby jack pine plains, which have a relatively thin litter layer compared to red pine plantations, suggests that factors other than litter depth may have resulted in the lower density of red maple regeneration observed in the red pine stands studied. In the past, frequent fires kept red maple from establishing amongst jack pine, but after decades of fire suppression red maple has still not exhibited the ability to compete on the jack pine plains. The soils in jack pine communities are generally extremely well-drained outwash sands with high acidity levels. Udvig (1986) suggested that conversion of oak sites to red pine increased soil acidity. This suggests that a possible similar effect in the red pine stands studied may have negatively affected red maple regeneration. Walters and Yawney (1990) suggested that red maple exists on soils with a wide range of soil pH levels. However, red maple may have threshold of tolerance to acidity, and perhaps drought.

On intermediate quality sites, red pine may inhibit establishment and growth of species more suited to moist environments. On high quality sites, this inhibition may not be as strong because below-ground resource availability would not be as easily reduced by red pine. Normally, limited resources would be viewed as suboptimal for regeneration. However, in the case of oaks, which exhibit slow juvenile growth, lower levels of available resources for species such as red maple may favor long-term oak seedling survival into larger size classes, because density of species that would compete for light would be reduced.

Planted oak survival and growth

Greatest survival of planted oaks in 75% cover plots within pine stands suggested that oak seedling establishment may have been more successful in pine stands because growth conditions were not favorable for competitors such as red maple. Lower mortality in 75% than 25% cover plots in both stand types illustrated the importance of greater canopy cover for long-term survival. Reduced exposure to frost damage and deer browsing may have benefited oak survival in these treatments. In contrast, clear-cut and 25% cover treatments resulted in resource levels suitable for optimal oak seedling growth. The different benefits of 25% and 75% shelterwood treatments indicated that oak regeneration success may depend on a changing balance between exposure and competition at different oak seedling life stages. The balance of these effects on oak seedlings over time may have been more important than initial resource abundance. Greater survival in clear-cut oak stands than clear-cut pine stands indicated that oak competitors may have had positive effects on short-term survival by reducing frost and deer damage. In most clear-cut and 25% cover plots, there were one or two planted oak individuals that were substantially larger than the others. The fact that greatest mean heights and mortality of planted oaks occurred in clear-cuts indicates that microenvironment can strongly influence an individual oak seedling's chances of survival and ability to become dominant.

Natural oak regeneration

Average natural sapling (2.54 cm dbh-10 cm dbh) oak regeneration density, in oak and pine stands, did not approach Sander's (1976) requirement for a fully stocked oak stand of approximately 1070 stems per hectare. All measured natural oak saplings (2.54 cm dbh-10 cm dbh) within oak stands were coppice stems growing from two stumps that bordered sampling plots. However, in pine plots originally thinned to 25% canopy cover, natural oak saplings (2.54 cm dbh-10 cm dbh) were all independent genets and averaged approximately 250 stems per hectare. The standard deviation was larger than the overall mean because nearly all of these stems were located in pine block three. All oak saplings in pine block three were free to grow, and averaged 796 stems/ha.

The fact that the most abundant natural oak regeneration occurred in 25% canopy cover plots within oak stands indicated that 75% canopy cover of oak resulted in less light availability for oak regeneration establishment. In clear-cut and 25% cover plots within oak stands, substantially greater oak regeneration density and growth in shrub-layer removal understory plots suggested that oak release from red maple competition may have been most beneficial in 1996, 5 years after planting, when shrub-layer removal treatments were last applied.

Short-term effects of prescribed fire 2002

Physical effects of prescribed fire

Temperatures above 200° C (400° F) were not recorded. In future research, the use of paints that would measure temperature in smaller intervals, and within a narrower range, seems practical. Increased effective wind speed during pine stand prescribed fires did not affect heat per unit area projections. According to fire behavior nomograms (National Wildfire Coordinating Group 1992), this would have been the case comparing any two fires burning with equal weather parameters where the same fuel model applies. Projected heat per unit area was not different between oak and pine stands because relative humidity measurements were very similar across all replications. Equal projections of heat per unit area suggested red maple mortality should have been similar in oak and pine stands. However, nearly all red maple in the one pine overstory plot where they were well represented did not sprout back following the fire, which indicated that another factor affected the killing effects of fire in pine stands. Average fire temperature measured at .6 m (2 ft.) above the ground averaged 149-204° C (300-400° F) in the single pine overstory plot where red maple was present and did not sprout back following burning, while fire temperature in oak canopy cover plots averaged 79-93° C (175-200° F). Increased rate of spread and flame length in pine stands resulted from wind speed that averaged 1mph faster. This effect increased the amount of heat present at one time (fireline intensity, measured in btu/second/ft), which would have affected the temperature increase. However, the differences in chemical composition and continuity between pine and oak litter likely had a greater impact on significantly different fire temperature between oak and pine stands than the minute wind speed increase during pine stand prescribed fires. This effect was not accounted for because fuel models did not distinguish between oak and pine litter.

Prescribed fire treatment reduced a larger percentage of initial litter thickness in the oak than pine stands. This result suggested that increased depth of pine litter prevented moisture loss, while the needles on the surface may have exhibited fine dead fuel moisture levels consistent with other 1-hour timelag fuels. Reduced rate of spread in oak stands and greater air spaces in oak than pine litter may have also allowed the fire to burn more 1-hour timelag fuels, in the oak stands.

Bracken fern response

Increased levels of bracken fern coverage occurred following fire, which was an effect consistent with other prescribed fire research in northern Michigan red pine stands (Henning and Dickmann 1996). Substantial increases in bracken fern coverage occurred in clear-cuts and 25% cover plots within both oak and pine stands, but coverage was reduced in 75% cover plots and uncut stands. This result suggests a potential increase in competition between bracken fern and oak regeneration in treatments with little overstory cover. Since significant canopy closure occurred in plots originally thinned to 75% canopy cover, it is difficult to describe what levels of canopy cover can prevent fern domination following fire. However, since canopy cover in 25% shelterwood plots approached 50%, and fern coverage was extensive in these treatments, the ideal level of canopy cover to prevent fern domination may be greater than 50%. Overstory cover may also need to be greater in pine than oak stands due to the increased availability of PAR in pine stands previously discussed. In clear-cut and 25% canopy cover plots, bracken coverage exhibited greater expansion and was more vigorous within pine stands than oak stands. This result indicated that the lack of red maple saplings and lower density of red pine foliage may have increased the availability of light, thereby benefiting bracken fern growth.

Ferguson and Boyd (1988) suggested that accumulated phytotoxins secreted from dead bracken fronds, near the soil surface, caused extensive seedling mortality for conifer regeneration in Idaho. Consequently, they suggested a possible allelopathic effect of bracken fern. Their research also indicated that fire will enhance bracken fern abundance, and that adequate control would be most successful using herbicides, which directly penetrate bracken fern rhizomes. Future sampling would be needed in order to determine any direct negative effects that bracken fern had on oak regeneration. In the first year following burning, oak regeneration responded positively in the same treatments where bracken fern increased coverage.

Fire effects on natural regeneration

Natural oak sprout density was significantly most abundant in plots originally thinned to 25% oak canopy cover due to the significantly higher proportion of oak stems already present. The increased oak density in these plots was due to multiple oak sprouts originating from single, individual stems. New germinants following fire were not found in any plots within oak stands.

The best test of the shelterwood burn technique occurred in the shrub-layer removal treatments within 25% oak canopy cover plots because regeneration height was consistent with most shelterwood treatments where prescribed fires are used to reduce red maple competition in management situations. Within these understory treatments, red maple averaged 15 cm taller than oak before prescribed fire, but red maple and oak average heights were the same following burning. Equal heights of red maple and oak in the first growing season following prescribed fire illustrated that oak was not able to overtop red maple quickly, but red maple may have been set back more than oak. Future sampling will be needed in order to determine if subsequent oak sprout growth exceeds that of red maple.

Red maple density was reduced in uncut oak stands while density of live red maple stems in other oak canopy cover treatments was not reduced. This result suggests that prescribed burning to reduce red maple density may be more successful if applied when red maple stems are smaller prior to shelterwood cutting, or 3-5 years following shelterwood harvest as described by Brose et al (2001). Canopy treatment appeared to have very little influence on fire temperature, in oak stands. The most plausible explanation for reduced red maple density in the uncut oak stands is the fact that red maple regeneration was less abundant and smaller in uncut treatments before prescribed fire, compared to treatments where harvest released red maple a decade ago.

These tests of prescribed fire in oak stands, which would have been burned earlier under normal management situations, were valuable for documenting fire effects on specific size classes of red maple. The resulting heat per unit area (btu/ft^2) and fireline intensity (btu/second/ft), when relative humidity was 34% and mid-flame wind speed was 1-2 mph, did not top-kill red maple above two meters in height or above 2.54 cm dbh. Given the length of this research, it could not be determined if the heat capacity of this fire would eventually induce mortality of red maple saplings larger than 2.54 cm dbh, but positive identification of Verticillium wilt on two red maple saplings and apparent infection on most other individual stems larger than 2.54 cm dbh indicated that delayed mortality of these red maple stems may occur. Red maple coppice regeneration also developed signs of infection near the stump. However, they had not exhibited the same wilting and early color change as most individual saplings, as of August 2002.

The beneficial negative impact of *Verticillium* on red maple stems may be counteracted if *Trichoderma* expands at the expense of *Verticillium*, which was a possible explanation for the presence of *Trichoderma* on live red maple saplings in these research plots (Windham 2002). *Trichoderma* is a non-pathogenic fungus often found on firewood, but when it is attached to live stems it can exhibit pathogenic behavior on other fungi (Windham 2002). *Trichoderma* is currently sold in several forms as a biological control agent used to protect certain farm crops from fungal infestation (Harman 1996).

In southern pine stands, fires have been found to increase populations of *Trichoderma* species and reduce levels of *Heterobasidion annosum* (Annosus root rot) (Froelich 1978). In western pine forests, burned treatments caused *Trichoderma* to intensify it's negative impacts on *Armillaria*, leading researchers to believe that fire can help control certain fungal diseases (Reaves et al. 1990). Therefore, if the goal is to increase fungal infections of undesirable species such as red maple, *Trichoderma* may reduce the effectiveness of fire as a tool for inducing mortality through pathogen infection. However, increased abundance of suspected Verticillium wilt in red maple throughout August 2002 suggested that *Trichoderma* may not substantially reduce the impact of *Verticillium*. Several other factors may have contributed to *Trichoderma* spread, one of which may have been dead portions of cambium near the base of large red maple stems.

Fire effects on planted oaks

Compared with pre-burn browsing patterns, prescribed fire treatment reduced the percentage of uncaged planted oaks that were browsed in oak stands. This change may have been due to increased availability of overall browse in the oak stands, especially red maple, which was heavily browsed after, but not before, prescribed burning. Increased palatability of red maple following prescribed fire has also been documented in other research conducted in northern Michigan (Henning and Dickmann 1996).

Significantly greater mean planted oak sprout growth in oak stand clear-cuts than all other treatments could have several explanations, but the most likely reason sprout height was maximized in oak clear-cuts was greater oak seedling resources several years prior to prescribed burning. This difference may have been even more visible if prescribed fire treatment were conducted before or soon after red maple dominated the regeneration cohort.

The significant relationship between pre-burn planted oak seedling size and sprout height suggested that either pre-burn seedling height or pre-burn basal diameter could be used to predict oak sprout height, with nearly equal accuracy. Canopy cover treatments did not appear to have an effect on slope of the regression line, but sprout size was significantly related to pre-burn seedling size. These effects suggested that, in the first growing season following burning, pre-burn seedling size likely had a greater effect than level of canopy cover in determining sprout height growth.

Chapter 7: Conclusions

Prescribed fire did not reduce the overall density of red maple and other competitors relative to oak in the first post-fire growing season. The abundance of potential competitors of oak was not reduced because the small reduction in red maple density was countered by an increase in bracken fern coverage in clear-cuts and 25% cover treatments following burning. Survival of red maple stems greater than 2.54 cm dbh also substantially reduced the potential positive impacts of fire on oak seedlings. The conclusion that a majority of red maple stems were in fact negatively affected by prescribed fire could not be reached using data collected in the first growing season following prescribed fire. However, in 2002, prescribed fire did reduce red maple leaf area through the decreased average height of red maple between 25 cm ht and 2.54 cm dbh and scorching of the lower portion of the crown on larger red maple stems. Wounding and infection of large red maple saplings also occurred, which suggested that further monitoring of abundant live red maple is warranted. It will be important to compare growth rates of oak and red maple sprouts in subsequent years and then consider another prescribed fire.

Pre-burn height and basal diameter of oak seedlings were significantly related to post-burn sprout growth, but overall r-square values were low (average r^2=.25). Data transformations were not conducted, but could potentially improve the predictive value of these regression equations. Scatter plots suggested that pre-burn height and basal diameter had similar accuracy in predicting sprout growth, which may have positive implications for managers as pre-burn basal diameter measurements were tedious to collect.

The third objective of this research was to investigate the effects of interactions between fire and forest cover type (oak vs. pine), canopy cover, and deer browsing. Interactions between deer browsing and fire were most evident in oak stands where browsing of oaks was reduced and browsing of red maple increased, while a different effect was documented in pine shelterwoods, where browsing of oaks slightly increased. Browsing of oak sprouts in pine shelterwoods was likely due to a lack of alternate species that deer could utilize. Clear-cut and 25% canopy cover treatments interacted with prescribed fire to produce increased bracken fern abundance and a possible increase in competition between bracken fern and oak. Low understory sapling density in pine stands also interacted with prescribed fire to increase bracken fern coverage in these treatments.

An overall synthesis of the results suggests that after a decade of established treatments, an overstory composed of pine resulted in fewer potential competitors of oak than did a single prescribed fire. Analysis during the first growing season following fire indicated that the initial effects of a single prescribed fire on oak regeneration were more negative than positive on oak regeneration in pine canopy cover plots without a red maple component and/or less than 50% canopy cover. In oak stands, prescribed fire had positive and negative effects in plots with less than 50% canopy cover. In clear-cut and 25% cover plots within oak stands, any reduction in red maple vigor achieved through prescribed fire was countered by an increase in bracken fern coverage. In addition, even though prescribed fire set back most red maple below two meters and severely stressed most red maple saplings, the future development of competitive red maple in the oak stands may be inevitable without follow-up treatments. If competitor regeneration in oak shelterwood treatments is inevitable, repeated prescribed fire treatments combined with herbicide and/or mechanical bracken fern control may be necessary. However, these intensive treatments may also be economically unjustifiable. These results suggested that the most beneficial long-term oak management strategy may be very simple: focus on regenerating oak beneath pine.

Chapter 8: Management and Research Implications

This research examined several techniques with the potential to improve silvicultural prescriptions for oak using fire in combination with regeneration harvests. In order to meet the human and wildlife needs provided by vigorous oak trees, an important goal should be to design techniques that grow oak into productive stems as fast as possible while making improvements in the overall scheme of oak management. For this reason, the following management and research suggestions were separated into short-term and long-term implications.

Short-term implications

Overstory manipulation

Crown expansion in the oak stands without increased residual stem volume makes multiple harvest entries less practical for using mechanical treatments to reduce competition. In oak stands where advanced red maple regeneration exists, gradual thinning should be expected to increase red maple abundance if red maple remains uncontrolled between thinnings. Therefore, a potential short-term oak regeneration strategy may be to avoid areas where advanced red maple regeneration is abundant. However, these stands are likely few and far between, especially for the more productive sites that still qualify as having intermediate site indices. Avoiding their treatment may contribute to oak replacement through oak decline, gypsy moth, oak wilt, and other density-independent causes of mortality.

Gradual thinning of pine stands that have intermediate site indices may benefit oak recruitment and growth more than shelterwood treatments, which result in fairly rapid canopy closure. Instead of allowing an overload of resources to become instantly available, oak seedling physiological characteristics imply that they will benefit from slow and staggered improvements in resources. The problem with entering pine plantations at shorter intervals, while removing less volume during each entry, would be the marketability of each timber sale, and defining each harvest in terms of the objective. For instance, would this be considered a thinning or a regeneration harvest? In addition, this technique would have to be applied sparingly as most red pine plantations do not have an oak seed source, or are located on high quality sites and therefore contain a competitive understory. In Michigan, the CCC likely established several pine plantations in areas where deciduous regeneration potential was not strong due to the effects of late spring frosts. Also, red pine is often planted on sites that are higher in quality than those where it originally occurred. These patterns of reforestation may have impacted the proximity of many red pine plantations to an oak seed source. However, a few plantations with nearby oak stands may be encountered during inventories when descriptions of the species and density of advanced regeneration in pine plantations could establish a baseline for determining if oak has the potential to benefit from overstory pine thinning.

The literature suggests that suppressed white pine can be released through canopy reduction (Puettman and Sanders 2000) and pine canopies provide greater frost protection (Michigan Department of Natural Resources 2000). In stands where suppressed pole-sized white pine are present in the mid-story, selective harvesting could be used to create a stand with three distinct size classes, while avoiding the effects of heavy shade resulting from balanced uneven-aged, single-tree selection techniques. According to this research, litter produced by overstory pines may open the window for prescribed burning opportunities, increase fire temperature, and provide other indirect oak regeneration benefits. Future research on uneven-aged distributions within mixed oak/pine stands could yield some interesting results regarding oak and pine interactions and affect management decisions in areas where the public has expressed opinions opposing even-aged silviculture. Combinations of longer lived oak and pine species with greater shade tolerance and different soil resource needs may work especially well in this situation (e.g., white oak and white pine).

Desired fire behavior

The relationships between heat per unit area (btu/ft^2) and fire temperature, and between fireline intensity (btu/second/ft) and fire temperature, will need to be established in order to determine the specific levels of relative humidity and wind speed for achieving complete red maple mortality within a given size class. Increased temperature in pine stand prescribed fires that had very similar wind speed to oak stand prescribed fires suggested that separate regression equations for oak and pine stands would be required due to the differences in litter chemical composition and continuity. Established relationships between fire temperature, fine fuel heat capacity, and rate of release may increase the predictability of red maple mortality success, before prescribed fires are conducted. Fire tests in controlled environments that generate data on several fires of varying intensity and fire weather would be needed in order to establish this relationship, which was beyond the scope of this research project. However, a few valuable associations between fire temperature and projected fire behavior outputs were discernible.

Prescriptions for controlled fires are often written according to a suggested flame length. Flame length is most directly affected by effective wind speed, which is a combination of slope and mid-flame wind speed (National Wildfire Coordinating Group 1992). Indirectly, this research provided insight into what any other fire could have also suggested: wind speed and consequently flame length did not have an impact on the total amount of heat produced by each fire (heat per unit area - btu/ft^2). However, greater wind speed did affect the rate of heat release (fireline intensity - btu/second/ft), which produced greater temperature for a shorter period of time. Greater fire intensity may top-kill larger red maple, but also induce more vigorous red maple sprouting. Maintaining a fire temperature .6 m above the ground between 149-204° C (300-400° F), which was the temperature in the pine canopy cover plot where red maple did not sprout back, for as long as possible, may provide the red maple mortality desired. Burning when relative humidity is low using a firing pattern that counteracts the effective wind speed may create these effects. In the oak stands researched, drip torch fire strips spread in both directions due to low overall wind speed and burning on a north-facing slope with southwest winds. Increased backing fire behavior may have had beneficial impacts on expected red maple sapling mortality through reduced rate of spread and increased residence time, which distributed heat slowly and caused greater injury to red maple at the base of each stem. This insight indicated that writing prescriptions based on flame length and applying the strip head fire method may not be the most successful approach for using fire to reduce red maple abundance.

Firing pattern

Temperature and fuel load have been found to affect hardwood mortality during prescribed fire (Rouse 1988, Huddle 1999). Adjustments in firing patterns within certain types of regeneration treatments may distribute heat more efficiently by using a technique similar to the tree-centered spot-firing technique described by Weatherspoon (1989). In this type of prescribed fire, ignition around the base of leave trees causes fire to spread away from the stems instead of towards them. This technique also decreases the rate of spread allowing the fire to back and/or run into areas with more fuel where it can smolder and increase residence time, thereby releasing heat slowly. The prescription would employ more perimeter ignition characteristics normally used in burning slash because strips would need to be used to backfire along the perimeter soon after fire is lit around the base of residual trees within the interior. Increased fire behavior variability would be expected. Therefore, low effective wind speed would be ideal in this type of treatment, and it may only be efficient in seed-tree harvests where little overstory cover exists.

Applications of the shelterwood-burn technique

This research supported the viability of the shelterwood-burn technique (Brose et al 2001) with certain considerations and/or modifications. A practical addition to this prescription may include alternating repeated harvests and fire treatments, which would in effect combine the pre-determined definition of a harvest as being either a regeneration cut or an overstory thinning, previously discussed. This effect may have positive implications as it could be to the silviculturists' advantage to have a plan for dealing with regeneration in any harvest situation, especially where undesirable regeneration (i.e., red maple) would benefit from crop-tree methods.

Following prescribed fire treatment, greatest red maple density reductions and increased planted oak mortality occurred in uncut stands. This result suggested that if the goal during the first burn is primarily red maple control, and advanced oak regeneration "release" is not inherently important, prescribed fire application before overstory thinning, or shelterwood cutting, may be beneficial. Conducting all understory burns well after shelterwood harvest and before complete overstory removal also would not account for the effects of canopy closure, which, in this research, had measurable effects over a time period when repeated shelterwood burns are suggested.

In this experiment, measurements of canopy cover in shrub-layer removal treatments within 25% cover plots averaged 48% in 2002. Oak and red maple height in shrub-layer removal treatments within these canopy cover plots were similar to the average regeneration height when most understory prescribed fires are applied in management situations. Oak density was already abundant in these treatments before prescribed fire, due to red maple mechanical removal and twelve years of oak seed-fall. Oak density increased significantly following fire because oak regeneration was already present. The fact that no oak seedlings were new individuals following fire indicated that fire will not stimulate new oak regeneration from seed.

Several cohorts of oak regeneration are likely needed in order to meet full stocking (Larsen and Johnson 1998). Therefore, using mechanical treatments to gradually stimulate new oak regeneration followed by prescribed fire to "release" it from red maple competition more than once within each regeneration harvest seems practical and may be achieved by alternating prescribed fires with overstory thinning. Intermittent mechanical treatments may provide greater chances for oak germination through increased seedbed disturbance. Controlling canopy cover throughout oak thinnings/regeneration harvests may also provide the optimal balance between controlling bracken fern and making resources available for oak survival and growth. Alternating prescribed fires with overstory thinning seems to be the most practical application of the shelterwood-burn technique in northern Michigan.

Managers may find themselves wanting to use fire to reduce red maple dominance in oak shelterwood regeneration treatments that failed in the past. Expected future mortality of red maple saplings suggested that managers may be able to use low intensity fires to wound the base of individual red maple saplings, causing infections and structural damage. This technique would cause red maple to die slowly, instead of top-killing them and producing vigorous coppice regeneration. Positive identification of Verticillium wilt suggested that top-killing large individual saplings may not be the most beneficial impact of prescribed fire use. It may be to the managers' advantage that these stems die slowly.

Long-term implications

The basis for using pine to regenerate oak stands

Larsen and Johnson (1998) suggested that full stocking of natural oak regeneration could take two or more decades. The inevitability of variable oak seed production may make oak regeneration techniques a very long-term process. Therefore, why use techniques that take place before the optimum amount of natural oak seed can be disseminated into environments suitable for germination? The overall establishment of oaks is inherently a long-term strategy, and most likely, any short-term method would eventually become a long-term project as repeated understory control treatments become necessary. This research suggested that a long-term approach of re-incorporating red pine into oak dominated stands may be more conducive to eventual oak regeneration success. The efficiency of this type of management may be most effective in regions where managers have to plan treatments across large landholdings, and cannot afford to repeatedly treat single regeneration harvests over long periods of time.

The Forest Inventory Analysis database (1993) was used to estimate the acreage of oak and red pine forest types in the Highplains subsection of northern Lower Michigan. Estimated oak stand area was 214,038 ha (528,900 acres) compared to 122,863 ha (303,600 acres) of red pine. Only 9,470 ha (23,400 acres) of small diameter red pine were estimated (see appendix). Using red pine to regenerate oak on sites where oak is currently dominant may fulfill the economic benefits of supplementing the red pine resource through increased planting.

Two-aged red pine and oak management

A practical and testable silvicultural technique to regenerate oak, on a long-term basis, involves oak seed-tree regeneration harvests, prescribed fire, and pine reforestation. Prescribed fire could be applied during the first spring fire season following a seed-tree regeneration harvest using firing patterns previously discussed to induce greater complete red maple mortality and increase browsing of red maple that still produces sprouts. While bracken fern is green, site preparation treatments could be applied to reduce bracken fern abundance and provide a mineral seed bed. The following spring, red pine could be planted with wide spacings avoiding areas where oak sprouts exhibit the potential to be dominants among the pines. However, pines would still need to be planted close enough together to increase litter depths, inhibit oak competitors (i.e., red maple), and make thinning commercially viable when oak regeneration from seed reaches advanced regeneration status. Several different combinations of site preparation techniques could be applied, one of which could include herbicide application for releasing pines and oaks and/or for bracken fern control. By planting pine on a site with an oak seed source, the bulk of oak recruitment would be less dependent on the existence of advanced oak regeneration under the initial oak canopy. An early commercial thinning could be used to remove unwanted red maple and release advanced oak regeneration that may establish beneath and amongst planted red pines. The thinning could be economically justified through pine pulpwood harvest.

Oak seed trees could be left throughout the process to provide mast, aesthetic value, and avoid the misinterpreted categorization of the treatment as site conversion.

Slightly more than a century ago, red pine overstory density was greater than that of any other species on sites similar to the stands researched (Whitney 1986). Using red pine to increase oak recruitment re-incorporates red pine into present day oak-dominated stands, where it is not regenerating naturally. The technique would meet the objective of more closely replicating the pre-settlement forest species composition on intermediate quality sites in northern Lower Michigan. Planting red pine on sites currently dominated by oak while leaving a remaining oak seed source may, most importantly, contribute to the objective of long-term northern red oak sustainability.

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Acreage for the oak-hickory and red pine species groups according to Forest Inventory Analysis data (1993)

		Oak		
sub-subsection	total	large	med.	small
Vanderbilt	104100	75400	22900	5800
Grayling Outwash Plain	306700	153100	107000	46600
Cadillac	118100	76300	30800	11000
Highplains	528900	304800	160700	63400

		Red pine		
sub-subsection	total	large	med.	small
Vanderbilt	37600	15600	22000	0
Grayling Outwash Plain	185000	71700	95100	18200
Cadillac	81000	30700	45100	5200
Highplains	303600	118000	162200	23400

Descriptions of fuel models used in analysis according to Anderson (1982)

Fuel model 2: "Fire is spread primarily through the fine herbaceous fuels, either curing or dead. These are surface fires where the herbaceous material, in addition to litter and dead-downed stemwood from the open shrub or timber overstory contribute to fire intensity. Open shrub lands and pine stands or scrub oak stands that cover one-third to two-thirds of the area may generally fit this model; such stands may include clumps of fuels that generate higher intensities and that may produce firebrands."

Fuel model 9: "Fires run through the surface litter faster than model 8 and have longer flame height. Both long-needle conifer stands and hardwood stands, especially the oak-hickory types are typical. Fall fires in hardwoods are predictable, but high winds will actually cause higher rates of spread than predicted because of spotting caused by rolling and blowing leaves. Closed stands of long-needled pine like ponderosa, Jeffrey, and red pines, or southern pine plantations are grouped in this model. Concentrations of dead-down woody material will contribute to possible torching out of trees, spotting, and crowning."

Vita

Jason Paul Hartman was born in Saginaw, MI on February 27, 1979. In 1996, he graduated from Heritage High School, of Saginaw.

In May of 2000, Jason received a Bachelor of Science degree from Northern Michigan University with a major in Conservation and a minor in Biology. He became interested in fire research while collecting data for an ongoing fire history project at NMU, and began seasonal on-call wildfire work for the Michigan Department of Natural Resources while completing his undergraduate degree. Following college, he moved to Roscommon, MI, where he took a position as a Forest Health Aid for the MDNR. Before starting graduate school, he also worked as a Forest Technician for a private consulting forester.

In April of 2001, Jason accepted a position as a Graduate Research Assistant and part time Teaching Assistant within the Department of Forestry, Wildlife, and Fisheries at the University of Tennessee. While working and taking forestry classes at UT, he researched fire impacts on oak regeneration and taught dendrology labs. His career goals include a management-oriented position that combines forestry and wildland fire.