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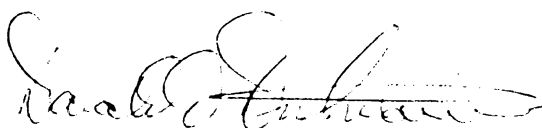
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THE LONG-TERM EFFECTS OF LOW INTENSITY FIRES IN A MATURE RED
PINE (*PINUS RESINOSA* AIT.) PLANTATION

By

Shailendra N. Adhikary

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ABSTRACT

THE LONG-TERM EFFECTS OF LOW INTENSITY FIRES IN A MATURE RED PINE (*PINUS RESINOSA* AIT.) PLANTATION

By

Shailendra N. Adhikary

This study focuses on the long-term effects of one- to two-decade-old prescribed low-intensity fires at varying intervals on the vegetation dynamics of a red pine plantation in northern Lower Michigan. One-burn, two-burns at a five-year interval, four-burns at two-year intervals, and unburned control plots were organized in a randomized complete block design during 1985 to 1991 and measured in the summers of 2001 and 2003. Overall, the effects of fire were apparent two decades after cessation of burning.

The fires had no effect on basal area, volume and mean annual increment (MAI) of the overstory (>10 cm dbh); species richness, diversity and density of the woody understory (>1.4m tall and < 10cm dbh); and percent cover of ground vegetation (< 1.4m tall). However, when compared to unburned controls, burnings decreased overstory tree density. The dominant overstory (>42cm dbh) and small understory (0-2 cm dbh) woody density were higher in burned plots, especially those repeatedly burned; whereas, sub-canopy (10-32 cm dbh) and large understory (6.1 to 10 cm dbh) woody densities were lowest in four-burn treatments. The more frequent the fires, the smaller were the diameters of understory woody plants.

Ground vegetation (<1.4 m tall) species diversity was highest in repeatedly burned plots. Bracken fern, *Rubus* spp., wild lily-of-the-valley, and red pine seedlings

had highest coverage. The consistent increase in importance values of overstory and the understory red pine in burned plots as well as suppression of red maple and other hardwoods indicated a shift in composition towards highly fire-adapted red pine, which in the long run will dominate the future canopy. Red maple, beech and white ash will also persist through new recruits.

The above data were projected 100 years into the future with and without a series of thinnings via the Forest Vegetation Simulator (FVS). Compared to unburned controls the key features of projected burned stands were extremely dense post-fire regeneration, higher inequality in size-classes, higher mortality/self thinning, and a sharper decline in density. At the end of no-management, unburned controls had grown slower and retained the densest understory and lowest overstory density. High red pine sub-canopy density produced by one- and two-burns indicates that low-intensity burns were sufficient to kill competing low vegetation and stimulate red pine reproduction, which grew into the mid-canopy layer of four-burn plots.

Burning, especially if repeated and followed by thinning, slowed down mortality, enhanced recruitment, stimulated growth of larger trees, extended the growth culmination age, and increased MAI and cumulative volume production. Four-burn treatments, particularly after the second thinning, produced the highest cumulative volume and the most uniform stand structure across tree size classes. Thus, frequent burning in mid-rotation, especially if combined with subsequent thinning, could be the basis of long-term sustainability, high productivity, and increases in biodiversity of red pine stands.

In the deep recollection of my ever loving father, Bodh N. Adhikary, a great source of inspiration.

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Chapter 1: Literature Review

1.1 Disturbance theory

1.1.1 Definitions/Disturbance regime

Traditionally, ecologists have considered disturbance to be a periodic event or a force (such as hurricanes, fire, etc.) that originates from outside the system (exogenous or allogenic) and causes sudden changes in species composition and the structure of communities or ecosystems (Borman and Likens 1979, White 1979, White 1985, Rykiel Jr 1985). Pickett and White (1985) define a disturbance as a relatively discrete event in time that disrupts community or population structure and ecosystem processes, changing resources, substrate availability or the physical environment. Such natural disturbances are considered normal phenomena of community maintenance and repair (Marks and Bormann 1972). In addition to physical or abiotic disturbances (fire, wind, flooding etc.), biological disturbances such as intense grazing, predation, insect-pathogen outbreaks, and the like can affect a system. Anthropogenic disturbances (construction, land conversions etc.) often break up habitats into smaller fragments that lose connectivity and diminish heterozygosity via loss of species (Baker 1989) and lower global biological diversity (Wu and Levin 1994). Similarly, indirect effects of anthropogenic activities—such as acid rain—affect ecosystems adversely (Likens and Lambert 1998). Disturbances are called autogenic or endogenous when the changes originate from within the system; for example, the death of bamboo forests after flowering, the decline and death of mature aspen stands (White 1979, Gilliam and Turrill 1993).

Natural disturbances range in magnitude, occurrence (frequency), severity (intensity), behavior (predictability) and duration, and their effects are relative to the size, life-history characteristics and life span of organisms. Together, these constitute disturbance regimes, which in turn are also affected by communities (Connell 1978, White 1979, Rykiel Jr 1985, White and Pickett 1985, Reice 1994, Menges and Hawkes 1998). Fires are often distinct from other physical disturbances such as hurricanes, volcano, flood and the like, which can happen in the absence of living beings or their remains. However, barring man-made flammable materials, fire needs living beings or their remains for its propagation; thus, fires are under partial or complete biotic control (Pyne 2004). Disturbances open the canopy, alter the availability of resources for recolonization and growth, and reduce the dominance of few species (Canham and Marks 1985). They create a pattern of spatio-temporal heterogeneity (Levin and Paine 1974). Small-scale disturbances are more frequent than large-scale disturbances (Sousa 1984; Bormmann and Likens 1979, Foster 1988, Merrens and Peart 1992, Heinzelman 1973, White 1979, Arno 1980, Romme 1982, Christensen 1985) and the magnitude of disturbances vary according to site or location. For example, in southern Canada the islands in Lake Duparquet are characterized by more frequent smaller-scale fires, than those on adjacent mainland (Gauthier et al. 1996).

Forest communities are exposed to one or more different types of disturbances that sometimes act in synergism and may be correlated (White 1979). Such disturbances set the stage for additional disturbances to prevail. The susceptibility of a tree to wind storms depends on the tree attributes, site, surrounding forest structure, and the prevailing

storm systems (Canham and Loucks 1984). Once trees become exposed to some exogenous disturbances, such as wind, they become more susceptible to other types of disturbances, such as fire (Bormann and Likens 1979, Schowalter 1985, Foster 1988). For example, in the Pisgaha old growth forest (New England), a series of different disturbances—lightning, windstorms, pathogens, and fire—occurred during different periods and had synergistic effects (Foster 1988). Chestnut blight entered the Pisgaha old growth forest in about 1913 and by 1915 the mortality was already extensive. Later, small windstorms hit the region a number of times, followed by an *Armillaria mellea* attack, and then small fires during 1924 to 1930. Later the forest was logged extensively, and in 1938 it was hit by a hurricane, which devastated the whole forest.

The southern pine beetle's attack on southeastern pines, which reestablish only after fire, is another good example of synergistic effect of natural disturbances (Schowalter 1985, Aber and Melillo 1991). The beetles slowly build up their population and are without much effect if their number is less than 100,000. However, if the population increases beyond 100,000 (threshold level) by June, then the attack is massive with the beetles forming galleries, excavating and girdling live trees (Aber and Melillo 1991). Furthermore, through their root feeding, the beetles infest the pines with a blue stain fungus that blocks their xylem, which causes the trees to further weaken and predisposes them further to beetle attack. The overall result is the killing of pine trees, which dry quickly during summer. Under these conditions, all stems including hardwoods, are susceptible to lightning-caused fire, which consumes almost all the fuel and makes the site suitable for southern pine regeneration again. Similarly, in the

Northern Rockies at Yellowstone there is a high mortality due to the mountain pine beetles and such mortality favors stand replacing fires (Wellner 1970 in Arno 1980, Loope and Gruell 1973, Arno 1980).

Benkman and Siepielski (2004) detail a good example of the disturbance effect of animals. They found that squirrels in the Rocky Mountains have the potential to alter the early stages of seedling establishment and succession. Whereas the forests without squirrels had consistently a 100% frequency of serotiny, those with squirrels had only about 50% frequency. Serotiny is the ability of conifers to produce seeds in closed cones that release seeds after getting exposed to fire. Serotiny is also the life-history traits of plants that experience stand replacing fires (Benkman and Siepielski 2004).

1.1.2 Climatic climax or Monoclimax theory

‘Climatic climax’ or ‘Clemential Monoclimax theory’ predicts that if there are no human disturbances, ecological communities will eventually reach a climatic climax; i.e., species interactions with a stable environment lead to a relatively stable state of species abundance and composition (Clements 1936 and 1938). This idea supports the equilibrium, balance of nature, steady state or homeostatic views of community dynamics. Further, Clements (1916) viewed communities themselves as organisms and the organisms within them as their parts. This led to the “Gaian hypothesis” in which the Earth is seen as a ‘super organism.’ Later, ‘polyclimax theory’ (Tansley 1939 in Selleck 1960) and ‘Climax pattern hypothesis’ (Whittaker 1953 and 1956) evolved to point out limitations of climatic climax. Others (Whittaker 1953, Selleck 1960) disagreed with the

‘Monoclimax concept,’ which was vague and lacked precision in terms of the geological time scale that affects ecosystems.

Since disturbances are random and ecosystems are dynamic (Wu and Loucks 1995), the climatic climax must be referenced to some environmental conditions or context, otherwise it loses its meaning (White 1979). Both the disturbances and ecosystems are then described in terms of heterogeneity along soil, aspect, temperature, moisture, light availability and other gradients that influence the disturbances and their effects on species occurrences and community attributes (Whittaker 1953 and 1956, Marks 1974, Bormmann and Likens 1979, White 1979, Sousa 1984, Foster 1988, Reice 1994). Grime (1977 and 1979) categorized the environment into productive, stressed and disturbed sites, which harbor competitor (C), stress-tolerant (S) and ruderal (R) species, respectively. However, Huston and Smith (1987) differ with Grime’s three discrete strategies and envision a continuum across those three strategies and their combinations. Additionally, the perturbations (effects) (Connell and Sousa 1983) and successions also form continua across different communities (Selleck 1960, White 1979, Hollings 1973, Wu and Loucks 1995). These gradients or continua across different systems/levels and their interactions are the basis for the dynamic nature of ecosystems. This view is in line with Sir Charles Elton’s claim in 1930 that “the balance of nature does not exist and perhaps never has existed.”

1.1.3 Modern theories

1.1.3.1 Non-equilibrium

The non-equilibrium model assumes frequent unpredictable disturbances (Connell 1978, Reice 1994) that cause random death of organisms/communities that never reach equilibrium. Such disturbances create patches or openings (Pickett 1980). Thus, ecosystems are always in a state of recovery from past disturbances (Merrens and Peart 1992, Reice 1994). The Intermediate Disturbance Hypothesis (IDH) as well as modern theories of disturbances such as patch dynamics and hierarchical patch dynamics provide important insight into mechanisms responsible for species migration and colonization, species abundance, niche differentiation, species diversity and their maintenance (Watt 1947, MacArthur and Wilson 1967, Connell 1978, Grubb 1977, Sousa 1979, Huston 1979, Pickett and White 1985, Reice 1994) and will be discussed further.

IDH postulates that if the disturbance regime is intermediate (i.e., neither frequent nor rare) both early and late successional species persist because of reduced competition (Connell 1978). Superior competitors remain dominant if disturbances are not frequent, whereas inferior competitors (good dispersers) persist and dominate the system if disturbances are frequent enough to prevent competitive exclusion (Connell 1978, Huston 1979, Connell and Sousa 1983, Roxburgh et al. 2004). However, species diversity will decline if disturbances are too frequent. For any system, the problem lies in finding out how intermediate is intermediate, which may vary in different systems as well. Therefore, the parameters of responses in any system should be defined precisely (Pickett and White 1985). IDH does not explain the coexistence of species that are at the top of the trophic

level or mobile invertebrates (Huston 1979, Wootton 1998; Roxburgh et al. 2004) and may not apply to all terrestrial systems. For example, IDH does not explain increased richness and diversity in the arid (low resource) Chamise shrub habitat where there is low competition for resources (Christensen 1985).

1.1.3.2 Patch dynamics

Disturbances create patches of different shapes, sizes, ages and stages of succession that vary in structure and composition of species in space and time. Environmental gradients within and outside the patches create the heterogeneity that is important in maintaining the mosaic structure of ecosystems (White and Pickett 1985, Forman and Godron 1981, Collins et al. 1985, Reice 1994). Thus, landscapes are mosaics of patches (Forman and Godron 1981, Dunning et al. 1992) and their widespread occurrences and dynamism is called patch dynamics (Watt 1947). For example, about one to two percent of old growth forests are under new patches or gaps at any time (Runkle 1981, Runkle 1985).

Gap size in forest ecosystems depends on the number and type of trees that fall and how they fall (Brokaw 1985b). Patch size affects temperature fluctuations, nutrient and water dynamics, timing and type of propagules reaching the patch, as well as recolonization, overall species diversity, and productivity of the patch (Forman and Godron 1981, Sousa 1984, Runkle 1985, Phillips and Shure 1990, Roberts and Gilliam 1995). Multiple tree fall forms large-sized gaps (Sousa 1984), which are brighter, hotter, and drier than smaller size gaps formed from the fall of a single or few trees (Denslow

1980). Large patches favor large numbers of early successional species (ruderals or R), whereas, small patches favor late successional species (competitors or C) (Marks 1974, Grime 1977, Bormann and Likens 1979, Denslow 1980, Gilliam et al. 1995). The intermediate size patches can harbor both types of species (Connell 1978). Mesic patches exhibit highest species diversity as compared to xeric and hydric patches (Roberts and Gilliam, 1995). Patch shapes and their edge-area, numbers, configuration and the networking of patches, and connectivity or corridors between patches are important for species migration and diversity (Formann and Gordon 1981, Sousa 1984, Dunning et al. 1992).

Reproduction explains the ‘non-equilibrium theory’ through patch dynamism, i.e., patch creation and filling (Pickett 1980). Gap-phase reproduction or gap recovery occurs through two types of models of vegetation recruitment (Egler 1954): initial floristic (reaching the site first) or relay floristic (making the site suitable for others). The recovery and succession of patches or success of species are determined by the following: good seed years; seed migration (Marks 1974); species life-history traits such as, size, tolerance to light, dispersability and growth (Grime 1977, Huston and Smith 1987); environmental and resource gradient across patches (Watt 1947); time setting of patches for recruitment and patch closure (Halpern and Spies 1995); and patch availability (Horn and Mac Arthur 1972). Gaps or patches recruit through regrowth (vegetative), migration from adjacent stock and recruitment from outside the proximate system (Reice 1994). Gap-filling can be due to germination of seeds (buried and transported), growth of preexisting seedlings and saplings, growth and expansion of clones and sprouts,

principally of pioneer species (Spurr 1956, Marks 1974, Likens et al. 1978) or the growth of epicormic branches (Runkle 1985) and occurs until resources become limiting (Nicholson and Monk 1975). In the tropics, ruderals (R) grow in disturbed sites, maximize seed production over vegetative growth and are density independent (r-selection) (Grime 1977, Brokaw 1985a, Brokaw 1985b). On the other hand, competitors (C) grow in productive sites, maximize vegetative growth over seed production, are density dependent (K-selection), and are later replaced by stress tolerants (S). Further, species are either competitor or ruderal but not both (Grime 1977, Roberts and Gilliam 1995).

Regeneration, the path of succession, future structure and composition of forests depend on the availability of species and the temporal pattern of disturbances (Abugov 1982, Glitzenstein et al. 1986, Peterson and Pickett 1995). Early arrivals are important especially in the subsequent establishment of light-intolerant woody species in the gaps (Bormann and Likens 1979, Canham and Marks 1985). In the Boundary Waters Canoe Area Wilderness, canopy openings are filled with one or more species. If more than one species invade a gap, patches of each dominant species are usually formed in the gaps (Frelich and Rich 1995).

If disturbances are too frequent, succession is shortened or takes a different course (Cornell and Slatyer 1977, Frelich and Reich 1995), whereas if the disturbance is catastrophic, then succession starts again (Reice 1994). However, all disturbances do not start succession; they may rather alter successional changes (Glitzenstein et al. 1986,

Abrams and Scott 1989). Sometimes even disturbances of the same magnitude and type initiate different or multiple pathways of succession (Abrams et al. 1985).

1.1.3.3 Hierarchical patch dynamics

In Wu and Loucks's (1995) view, 'disturbance theory' is best explained by a hierarchy of patch dynamics, non-equilibrium and stochastic patterns and processes. Patch dynamics and hierarchical ('hierarchical patch paradigm') theory together consider patches as structural and functional units of ecosystems working at multiple scales. After disturbances, patch formation and its recovery across a landscape and the interactions of patches with each other at multiple scales (spatial, temporal and organizational) create, maintain and destroy patterns at various levels and form a hierarchical mosaics of patches or patchiness. Changes in this mosaic occur due to interactions among vegetative, disturbance and geomorphological processes (Watt 1947, Borman and Likens 1979, Brokaw 1985b, Holling 1992, Wu and Levin 1994, Wu and Loucks 1995). Thus, there are patches within patches within patches, creating a hierarchical system that absorbs small disturbances when looked at through a larger level or resolution of a landscape. For example, the disturbance at one level (death of a tree) may not be a disturbance at other levels (stands, landscape or ecosystem); i.e., the effect is absorbed as we go from a lower to a higher level (Rykiel Jr 1985).

Northern New Hampshire forests are characterized by such hierarchical mosaics of different-aged patches of communities, which Bormann and Likens (1979) called a 'shifting-mosaic-steady-state.' Their system basically is a shifting of standing biomass of

even-aged stands produced by clearcutting. According to Wu and Loucks (1995), shifting of such hierarchical mosaics of patches at lower level transforms to a shifting-mosaic-steady-state at a higher level and constitutes a kind of equilibrium that has a range of some lower and higher bounds or limits. After disturbances in old forests, trees fall and as the canopy closes slowly, the standing biomass changes slightly over the mean; however, the biomass on any small plot in the stands/watershed may vary at any time. For instance, old growth forests of Douglas-fir show shifting mosaics of resources and environments that support a diversity of species (Halpern and Spies 1995). However, Baker (1989) did not find any such temporally stable patch-mosaic at any scale while studying a ca. 404,000 ha patch mosaic created by fire in the Boundary Waters Canoe Area in Minnesota. He suggested that this situation could be due to heterogeneity between fire regimes and environment or mismatching of the scale of patches and the environment. Frelich and Lorimer (1991) found that in upper Michigan hemlock hard-wood forests the age distribution in two fairly large areas (14500 and 6073 ha) were nearly in equilibrium.

In Wu and Loucks's (1995) view, in a homeorhetic state, the stochastic non-equilibrium patch processes at a smaller level are dynamic and translate to a quasi-equilibrium state at higher levels; i.e., a shifting-mosaic steady state (Bormann and Likens 1979). Such a state is congruent with the 'hierarchical patch paradigm' or 'hierarchy theory.' After perturbation, such a system returns back to the pre-perturbation trajectory rate of change but not to the pre-perturbation steady state. For example, in southern Wisconsin forests, fires with intervals of 50 to 200 years were found to destabilize in the short-term but stabilize (steady state) on a long-term scale; i.e., a

periodic wave of high and low diversity is maintained by periodic perturbations of 50-200 years (Loucks 1970). Similarly, in a gopher mound study by Wu and Levin (1994), local populations of certain species at the patch (or local population) level became extinct frequently, but metapopulations showed little fluctuation. Thus, forest composition may be relatively stable or in a dynamic equilibrium with local changes canceling out over the whole under the influence of fire (Heinselman and Wright 1973). Further, several patches at equilibria or multiple equilibrium patches and their shifting during disturbances have also been suggested (Holling 1973 and 1992, Levin 1976).

1.2. Fire effects on ecosystems—general

1.2.1 Fire regimes

Fire plays an important role in establishing, shaping and modifying the structure and composition and thus the successional pathways of north-temperate and boreal forest, grassland and prairie ecosystems (Larsen 1929, Little and Moore 1949, Cooper 1960, Bormann and Likens 1979, Vogl 1969, Van Wagner 1970, Heinselman 1973, Heinselman and Wright 1973, Rowe and Scotter 1973, Kilgore 1973, Wright 1976, Arno 1980, Pyne 1982, Romme 1982, Whitney 1986 and 1987, Hulbert 1988, Aber and Melilo 1991, Abrams 1992, Agee 1993, Arno 1993, Covington and Moore 1994b, Howe 1995, Feeney et al. 1998, Arthur et al. 1998, Veblen et al. 2000). Impacts of fire are better understood in terms of ‘fire regime,’ which includes ignition source, its seasonality and predictability; mosaic nature of landscapes; fire intensity and its spread; wind speed; relative humidity; local weather conditions; climate; the past history of fire on vegetation; and the impact of vegetation on the fire regime itself (Sousa 1984, White and Pickett 1985, Gill and Groves 1981 in Veblen 1985, Agee 1998). Depending on its intensity and

periodicity, fire alters availability of light, water, nutrients, microclimate and the availability of propagules and their regeneration (Harmon 1984, Sousa 1984). Flammability of vegetation or communities also affects the fire regime (Mutch 1970). Fire affects the quality and quantity of fuel available (Reice 1994), which controls fire frequency to some extent (Romme 1982). All of these factors vary over space and time and their interactions create heterogeneity (patchiness) in ecosystems, which in turn affects local fire regimes (Sousa 1984, Veblen 1985). Topography and location also are important; e.g., mountain tops are more vulnerable to severe and frequent fires because of low water and windy conditions (Reice 1994, Taylor and Solem 2001) than the bottom or valley (Romme 1982). Frequent fires favor shrub and herb establishment rather than trees (Runkle 1985). Fires are thus used in the managements of grasses and shrubs (Raison 1979). Fire regimes as they incorporate most aspects of ecosystem patterns and processes have implications in maintaining forest health and managing forests (Cleland et al. 2004). Fire regimes of some important vegetation types and their locations are summarized in Table 1.1.

Table 1.1 A summary of fire return intervals (FRI) in different locations and vegetation types.

Location/Site/vegetation types	Fire return intervals -- in years	References
Northern MI during prelogging era, FRI	ranged from <100 to >1000	Cleland et al. (2004)
In Michigan, FRI changed from	250 (in the past) to 3000 (present)	Cleland et al. (2004)
Scrub oak forests in northern, MI after 1920	9 or less	Kittredge and Chittenden 1929
Jack pine	25 to 60 or even 80 (crown fires)	Whitney 1986
Red pine (natural)	5 to 30 or even 80 (low intensity fires)	Van Wagner 1970; Bergeron and Brisson 1990; Englestrom and Mann 1991
Red pine (natural)	150 to 200 (stand replacing fires)	Bergeron and Brisson 1990
Forests in upland areas	130 to 260	Whitney 1987
Mixed moist NHW	400 to 500	Whitney 1986
Subalpine forests in Maine/ NHW	800	Lorimer 1977; Bormann and Likens 1979; Foster et al. 1985
Hemlock-white pine type in NHW	even up to 1200	Whitney 1986
New Brunswick, Canada	650 to 2000	Bormann and Likens 1979
Boudry Waters Canoe Area, northern MN	50 to 350	Heinselman 1973
Northern Rocky Mountains (MO, IA and Alberta)	22 to 153	Arno 1980
Sub-alpine forests, Yellowstone National Park, WY	300 to 400	Romme, 1982
Southern Cascades, CA		
Before and during European settlements were	76 and 177	Taylor and Solem 2001
Red-white fir forests	41	Taylor and Solem 2001
White fir-Jeffery pine, lodgepole pine, lodgepole	59 to 70	Taylor and Solem 2001
pine-red fir and red fir-western white pine forests		
New Jersey Pine Barrens	15 to 65	Little and Moore 1945 and 1949; Formann and Boerner 1981
Longleaf pine forests in the Southeast	3 to 10	Chapman 1932
Great Smoky Mountain National Park	10	Harmon 1984
Ponderosa pine forests, Southwest	2 to 12	Feeney et al. 1998
Long grass prairie	1 to 10	Axelrod 1985 (in Abrams 1992)
Arid Chamise shrub habitat, California	25 to 50	Christensen 1985

Note: NHW, northern hardwoods.

1.2.2 Forest fire suppression and effects of fire

In the US, human interventions have changed the fire regimes throughout major ecosystems as a result of activities such as logging, clearcutting, burning slash, grazing, land conversions and development activities including fire suppression that occurred during the nineteenth and twentieth centuries (Heyward 1939, Cooper 1960, White 1985, Arno 1993, Fule et al. 1997, Abrams 1992, Covington and Moore 1994b, Heinselman 1973, Dickmann and Leefers 2003, Cleland et al. 2004). Heavy loads of slash left in unburned stands after extensive logging operations during the nineteenth and early twentieth centuries were followed by unprecedented catastrophic fires throughout this country, including Great Lakes States (Dickmann and Leefers 2003). This situation led to the implementation of a fire suppression policy that mandated fire exclusion. This policy began during early 1900s and was strictly implemented within a couple of decades throughout the country (Kilburn 1960, Whitney 1987, Arno 1993). The eventual result was an accumulation of huge loads of forest fuel and many large-scale catastrophic wild fires compared to the pre-logging and pre-settlement era (Larsen 1929, Vogl 1969, Van Wagner 1970, Heinselman 1973, Wright 1976, Romme 1982, Whitney 1986 and 1987, Abrams 1992, Arno 1993, Feeney et al. 1998, Arthur et al. 1998, Veblen et al. 2000). These modern fire regimes have changed the structure and composition of fire-adapted forest and grassland ecosystems and reduced overall species diversity (Heyward 1939, Little and Moore 1945 and 1949, Buell and Cantlon 1953, Kilburn 1960, Mutch 1970, White 1979, Romme 1982, Whitney 1986 and 1987, Taylor and Solem 2001).

Before fire suppression was common in Michigan, fires frequently occurred after logging, consuming many of the remaining pine seed trees and seedlings and favoring oak, maple, birch and aspen establishment, which, changed the composition and structure of forests, as evident today (Heinselman 1973, Whitney 1987). Under current conditions, however, oaks have not regenerated under oak shade (Hartman et al. 2005) but have yielded to more shade tolerant red maple and white pine that need only small gaps (Arthur et al. 1998; Abrams 1992). Oaks are not adapted to low light and decline under shade of other species (Abrams 1992; Lorimer et al. 1994; Arthur et al., 1998). Due to lack of fire and other disturbances needed for their perpetuation, the area occupied by aspen-birch forest has also declined markedly since the 1930s (Cleland et al. 2001).

When burned, thick bark and sprouting ability of oaks favor them as compared to non-oak species (Abrams 1992, Lorimer et al. 1994, Arthur et al. 1998). Oaks are resistant to fire even in sapling stages. In the Cumberland Plateau northern hardwood ecosystem, burning killed 67 to 100% of the black cherry, paper birch and large-toothed aspen whereas none of the oak saplings were killed (Reich et al. 1990). Likewise, White (1983) found that large oak trees ($\geq 25\text{cm}$) in Minnesota were affected very little by annual burning of oak-savanna forest for 13 years and that the density and basal area of overstory oak trees were significantly higher in burned than unburned areas. In the Great Smoky Mountain National Park, vegetation changed in dominance from fast-growing, thick-barked early successional trees to slow-growing thin-barked late successional trees after fire suppression since 1940 (Harmon 1984).

In subalpine forests of Yellowstone National Park, as a result of fire suppression, older trees at late successional stages dominated the landscape rather than younger trees at post-fire early successional stages, and landscape diversity was less than that of natural fire regime (Romme 1982). Arno (1993) suspected that “the wild fire problems will worsen...in the Western North America.” Similarly, fire suppression has changed vegetation from fire-dependent lodgepole pines to vegetation similar to those found in lower montane forests (i.e., fir) in the southern Cascades (Caribou Wilderness), California (Taylor and Solem 2001) and also in Alberta’s Rocky Mountains (Day 1972). Douglas-fir thickets have increased in the sub-alpine forests of Yellowstone National Park in the recent past because of fire suppression and grazing, and these conditions render lodge pole pine forest prone to intense fire. In Colorado Front Ranges, both the fir and spruce were replaced by lodgepole pine where fire was frequent (Moir 1969).

In the Southwest, fire suppression for decades has changed the open park-like ponderosa pine forests with clusters of old pines and lush green grassy areas to dense thickets of saplings and shrubs, which suppress grass growth and increase vulnerability to stand-replacing wildfires and insect outbreaks (Dickman 1978, Cooper 1960, Moir 1966, Feeney et al. 1998, Allen et al. 2002). Yeaton (1983) have suggested that ponderosa pine and sugar pine co-exist because of disturbance that opens up space and microsites for them to establish in Sierra Nevada, California.

The absence of fire that used to occur every two to three years before fire exclusions caused long-leaf pine dominated forests (sandhill vegetation) to convert to

oak-hickory forests in the southeastern coastal plain from Florida to North Carolina (Quarterman and Keever 1962; Abrams 1992). Also, grass-sedge bogs are changed to forest areas when protected from fires (Garren 1943). In the absence of fire, long leaf pine forests are taken over by loblolly pines in the drier regions and by slash pines along the coastal areas (Walker 1980). These southern pines are shade intolerant and they germinate and establish in exposed mineral soil and in the absence of fire are encroached by hardwood species, mainly oaks (Walker 1980). In the Cumberland Plateau and other forests, oaks declined, whereas other fire sensitive species became abundant due to fire suppression during the latter part of the twentieth century (Arthur et al. 1998). However, in the New Jersey Pine Barrens, fire suppression increased fire-sensitive hardwood species, including oaks which replaced swamp cedar. The area burned each year was reduced to about 10% of the total area (Forman and Boerner 1981).

Oaks invaded and dominated the tall grass prairies after fire exclusion as well as during European settlement, during which time construction, land conversion and development activities acted as barriers for fire to expand (Abrams 1992). In the Midwest, the total area of oak savanna, which used to be 11 million ha, has now been reduced by >98% (Abella et al. 2004). In an oak-savanna study in Wisconsin, openings were found to be filled with woody trees and shrubs in 10 years and completely converted to a dense oak forest in 30 years of fire exclusion (Curtis 1959 in White 1983). In Minnesota oak-savanna, fire suppression was found to double the amount of carbon storage (220 mg/ha) in woody biomass and the forest floor as compared to carbon amount of presettlement; however, there was no effect in soil (Tilman et al. 2000).

1.2.3 Effects of fire on Boreal forest

The boreal forest is well adapted to frequent fires (Rowe 1961, Heinselman 1973, Rowe and Scotter 1973). Frequent fires account for the occurrence of young communities that determine future structure and composition of boreal forests (Zoladeski and Maycock 1990). In Taiga (Interior Alaska), intense fire is needed to release the system by getting rid of feather and sphagnum mosses covering the forest floor and starting succession. Fire opens up space, consumes the thick litter layer, exposes mineral soil completely and melts the permafrost and thus basically determines the type of forest (Aber and Melillo 1991). Black spruce forest inhabits the colder northern and less steep slopes with poor drainage that develop thicker permafrost layer unlike the southern slopes which are inhabited by white spruce. Poplar forests may develop in the less steep areas that lack permafrost. Post-fire recruitment and species retained depends on time lapsed since fire (Johnstone et al. 2004). In Yukon, British Columbia, the post-fire spruce population remained constant after the first decade, whereas both aspen and lodgepole pine declined due to density-dependent mortality (self-thinning process). The highest post-fire recruitment occurred in the first five years. Also, forests undisturbed for a long time act as refugia from where plants and animals can spread and recolonize the burned areas (Rowe and Scotter 1973).

1.2.4 Effects of fire on grassland and prairie

Fire stimulates grass coverage and flowering guilds and suppresses woody vegetation and forbs. If the prairies are not burned, cut or grazed, they convert to forest slowly in the long run (Niering et al. 1970, Bragg and Hulbert 1976, Hulbert 1988, Howe

1995). Tall bluestem prairie grasses grow earlier and faster in burned than unburned areas (Hulbert 1969 and 1988, Niering et al. 1970, D' Antonio and Vitousek 1992). For example, after 17 years of burning, standing biomass of *Andropogon* spp. increased to 364 g/m² as compared to 252 g/m² in unburned prairie (Niering and Dreyer 1989). All fire regimes (not just a single burn) are critical in determining the community response in long-grass prairies (Hobbs and Huenekke 1992). High surface/volume ratio, dead standing biomass that can easily catch fire and spread, and highly photosynthetic new tissues with luxuriant growth are all fire adaptive characteristics of grasses (D' Antonio and Vitousek 1992). Following high-intensity burns, closed canopy forests, because of their high fuel loading, had a tendency to change to prairies (Anderson and Brown 1986). Thus burning destabilizes the closed canopy system. In the case of prairies, however, fires help to stabilize the system. Vogl (1969) found alternations of floods during wet periods and fires during drought maintained pristine open marsh, sedge meadow, and wet prairie in lowland areas in southeastern Wisconsin (1836 to 1966). Recurring fires perpetuated the sucker-sprouting aspen, whereas burning decadent aspen forests could originate true prairie. Also, if burned with high intensity fires, pure even-aged aspen forests could originate from seeds. Alien grasses in the seasonal submontane zone of Hawaii are due to fire which favors more exotic grasses thus changing the overall vegetation dynamics in ecosystems that did not have fire adapted species (Hughes et al. 1991, D' Antonio and Vitousek 1992). This is also true in many prairie ecosystems in the western U.S. states; e.g., the exotic cheat grass (Covington et al. 1994).

1.2.5 Effects of fire on nitrogen fixing plants and nutrient cycling

Fire volatilizes carbon, nitrogen and sulfur but mineralizes phosphorous, potassium, calcium, magnesium and certain micronutrients (Ahlgren 1960, Alban 1977, Vitousek 1985, DeBano et al. 1998). Fire redistributes nutrients in the soil (Ahlgren and Ahlgren 1960, Raison 1979) and most sodium, potassium and calcium leach during the first three months after burning (Smith 1970, Raison 1979). Microbial activities as well as nitrogen fixation decline immediately after burning but they resume soon because of increased ash, nutrients and soil pH (Alban 1977, Raison 1979). Such increases in nutrients, particularly phosphorous and pH, also occur in peat burns (Vogl 1969) and favor soil microorganisms and nitrogen-fixing bacteria which increase soil nitrogen (Christensen and Muller 1975, Spurr and Barnes 1980, Barbour et al. 1999). For example, in grasslands in Connecticut, *Baptisia tictoria*, a fire increaser and nitrogen fixer increased by 2- and 3.5-fold after 17 years of annual and biennial prescribed burning (Niering and Dreyer 1989). In the frequently burned (every 1-3 years) plots of longleaf pine, burning increased establishment of legumes in the understory (Hains et al. 1999). However, ectomycorrhizal hyphal densities decreased following fire in the New Jersey Plains in contrast to the expected increase (Buchholz and Gallagher 1982).

Among different nutrients, nitrogen and phosphorous are most limiting to plant growth in most forests (Vitousek 1985). However, the loss of nitrogen during fires is usually low, although losses may be severe with intense burns (Binkley et al. 1992). Fire consumes surface litter, reduces C/N ratio, reduces microbial immobilization and releases nutrients. Fire may either increase or decrease nitrogen (Binkley et al. 1992). Nitrogen

uptake and immobilization by growing vegetation are important processes that are responsible for nitrogen retention after harvest and decomposition (Vitousek et al. 1979). Nitrogen and phosphorous availability increases immediately after fire due to decreased immobilization and increased soil temperature and moisture (Raison 1979, Vitousek 1985), despite the losses due to volatilization (Christensen 1985, Christensen and Miller 1975). Such increases have been found in the pine-oak forest in the nutrient poor spodosols of the New Jersey Pine Barren, where oaks showed rapid growth after burning (Burns 1952 in Boerner et al. 1988, Boerner et al. 1988). However, because of the nutrient poor sandy soil the nutrient availability was higher only for a period of about four months after burning. Also, there was a very small loss of phosphorous and calcium (Boerner et al. 1988).

In reviewing 87 studies carried out between 1955-1999, Wan et al. (2001) found nitrogen in fuel wood to decrease significantly (by 58%) and soil ammonium and soil nitrate pools to increase significantly by 94% and 152%, respectively, after fire, but such changes depended on fuel type as well as fire time. None of the variables—vegetation type, fire type, fuel type, fuel consumption type, fuel consumption percent, time after fire, and soil sampling depth—affected soil nitrogen amount. Soil ammonium pool increased by two folds immediately after fire and then gradually declined to pre-fire level after one year. Similarly, the soil nitrate pool increased less (only 24%) immediately after fire but increased to three fold after about 0.5- to 1-year after fire and then decreased.

In a disturbed forest, nutrient increase is apparent until the forest grows back and the canopy closes and then nutrient decreases later (Vitousek 1985). Resources in disturbed gaps are under-utilized as they are released from decaying plant organic matter and there is low uptake during the recruitment process (Marks 1974). In the absence of fire, dense thickets of trees are formed in the understory of ponderosa forests and such thickets intercept more light, which increases the soil organic matter. Increase in soil organic matter leads to nitrogen immobilization by microbes causing nitrogen deficiency, which affects herbaceous growth (Moir 1966). In loblolly pines in low productive soil (SI 27 m at 50 years), net nitrogen immobilization was highest in unburned than in two- and four-year burn interval plots. Carbon and nitrogen were very high in the forest floor in unburned than in once-burned areas in loblolly and long-leaf pine forests in North Carolina (Binkley et al. 1992). Covington and Sackett (1986) also reported an increase in nitrogen after burning in ponderosa pine forests.

In Chaparral, only 146 kg ha⁻¹ and 49 kg ha⁻¹ of nitrogen and potassium, respectively, were lost after burning, but there were additional nutrient losses due to erosion during the first rainy season (Debano and Conrad 1978). This nitrogen loss represented about 11% of the nitrogen in the plants, litter, and upper 10cm of soil before burning. Two years after the Little Sioux forest fire in BWCA in northern Minnesota, potassium and phosphorous increased by 265% and 93%, respectively, in Meander Lake that received down-stream flow from burned plots and Dogfish Lake that was down-stream from unburned plots (Wright 1976).

In general, the loss from the forest due to burning has been considered to be small when compared to the total nutrient balance of forest ecosystems, which retain most of their nutrients even after a major fire.

1.3 Fire effects on pine dominated ecosystems

Pine forests are maintained by fire and adapted to low and high intensity fires (Burdon 2002, Richardson 1998). In the US, high-valued pines such as, longleaf and ponderosa pine are adapted to frequent surface fires (Chapman 1932, Cooper 1961, Moir 1966, Burdon 2002). Red pine and white pine are resistant to low intensity fires; but they establish readily by seed following stand-replacing fires (Ahlgren 1976, Van Wagner 1970, Dickmann 1993). Jack pine and lodgepole pine have thin bark and have little fire resistance; however, they are prolific seed producers with serotinous cones that open when burned by a stand-replacing crown fire (Arno 1980, Burdon 2002, Schoennagel et al. 2003). Pitch pine sprouts after burning and is found along with shortleaf pine in the New Jersey Pine Barrens (Little and Moore 1949). Loblolly pine and slash pine are two other high-valued and fire-adapted pines of the South. In general, pines with thick bark, protected buds, serotinous cones and sprouting are considered fire-adapted (Little and Moore 1949, Van Wagner 1970, Dickmann 1993).

1.3.1 Ponderosa pine

Historically, mature ponderosa pine forests were open savannah-like monocultures with some cover of grass and herbs and were maintained by periodic low intensity natural surface fires. This regime, however, was disrupted during Euro-

American settlement (Cooper 1960, Cooper 1961, Moir 1966, Arno 1980, Covington and Moore 1994b). Historically, low intensity fires occurred between 3 to 30 years (Cooper 1960, Covington et al. 1997, Arno 1980, Feeney et al. 1998) and varied from place to place. Ponderosa pine is a shade intolerant but drought tolerant high-valued timber adapted to fire, with thick bark, insulated buds, and tolerance to crown scorch (Agee 1998). Periodic low intensity natural fires used to kill groups of trees here and there and formed gaps that transformed into patches of young even-aged pine trees, forming a mosaic of patches of different ages over the landscape (Cooper 1961). At high altitude (~ 2800 m) in the Colorado Front Range, ponderosa pine mixes with Douglas-fir and lodgepole pine forming stands that are not open and park-like. As the altitude increases aspen and limber pine increase (Veblen et al. 2000). In the absence of fire, stands shift to less fire resistant trees such as white fir, Douglas-fir and junipers (Allen et al. 2002).

One century of human activities—fire suppression, overgrazing, logging and introduction of exotic species—have changed the structure and function of ponderosa pine forests from park-like savannas to dense thickets of sapling and shrub growth (Cooper 1961, White 1985, Covington and Moore 1994b, Fule et al. 1997, Feeney et al. 1998, Kaye and Hart 1998, Mast et al. 1999, Allen et al. 2002). Large ponderosa pine density used to be 47 to 49 trees ha⁻¹, in Flagstaff, Arizona (Covington and Moore 1994a). Tree density was 148 trees ha⁻¹ in 1883 and after fire exclusion it increased to 1265 tpha in Navajo, Arizona (Fule et al. 1997). Similarly, fire exclusion increased ponderosa pine density to >3000 tpha in Arizona in 1992 (Mast et al. 1999). Currently, the conditions of many ponderosa pine forests are considered unhealthy because of the

thickets of white fir and Douglas-fir (Mutch et al. 1993 in Covington et al. 1994, Covington et al. 1997, Fule et al. 1997, Covington 2000). Douglas-fir used to be kept at minimum before the fire exclusion policy (Dickman 1978). The forest fuel loads are well above the presettlement level and are prone to stand replacing wildfires and mountain beetle outbreaks (Startwell and Stevens 1975). It is likely that frequency and magnitude of wildfire will increase for many years (Covington 2000). Climatic oscillations (Covington and Moore 1994b) and elevated carbon dioxide have added to all these changes in ponderosa pine forests (Covington and Moore 1994a). Currently, high-intensity fire hazards have been linked with the Southern Oscillation events (ENSO)—El Nino and La Nino—every 2-5 years in the Colorado Front Range (Veblen et al. 2000). Warm-phase El Nino- Southern Oscillations events cause high fuel production, whereas dry phase La Nino events cause widespread fires.

Currently, scientists and resource managers have realized the problems related to a century-long fire exclusion in western ponderosa pine forests (Covington et al. 1997, Fule et al. 1997, Veblen et al. 2000, Allen et al. 2002). The major problems have been identified as the huge accumulation of fuel wood, dense thickets of seedlings and shrubs, and potential insect attack, all of which increase fire hazards. Therefore, to restore and improve the condition of these forests, wood reduction via thinning and burning has been recommended (Feeney et al. 1998; Veblen et al. 2000, Allen et al. 2002). The shade-intolerant ponderosa pines need not only open space but also exposed mineral soil for the seeds to germinate and develop. Thus if both the thinning and underburning is carried out, it is possible to maintain the healthy and low-fire hazard ponderosa forests. In a 80-

year-old forest at Bitterroot National Forest in Montana, Fiedler et al. (1992) found that different combinations of burning and thinning were able to reduce 60 to 65 % of litter and woody fuels (out of about 5 tons per ac). The main objective was to consume fuel by burning and let trees grow to an old growth condition under a shelterwood. In the mean time, burning was able to thin out 60% of the seedlings and saplings. Fule et al. (2001) found thinning followed by burning to lower density, lower crown basal area and enhance crown-fire resistance.

1.3.2 Lodgepole pine

Lodgepole pine is a shade intolerant species that bears serotinous cones (Baker 1949) and is a good example of pine adapted to stand replacing fire. It maintains a climax forest where there is sufficient light for them to grow (Despain 1983). It dominates both pioneer and climax forests in the sub-alpine zone of Yellowstone National Park, and it is mixed with sub-alpine fir, Engelmann spruce, and whitebark pine in the climax (Romme 1982). In Yellowstone, the vulnerability to fire depends on whether or not spruce and fir occupy the understory. If yes, the forest is susceptible to fire (Despain 1983) and if not, they become resistant to fire (Romme 1982), which gives lodgepole pine sufficient time (200-300 years) to establish as a climax (Despain 1983). Fire regimes vary as the habitats vary. Fire return intervals are around 300 years at higher elevations with stand replacing fires in the Northern Rockies at Yellowstone (Romme 1979 in Arno 1980, Schoennagel et al. 2003). Similarly, the fire return intervals are 25-50 years in the upper limit of Douglas-fir at Yellowstone and in the Bitterroot Mountains of Northern Idaho with low intensity fires (Romme 1982, Larsen 1929). Rugged terrain in the Northern Rockies

makes the fire regime more complex, resulting in establishment of one to many aged stands differing in composition and structure (Romme 1979 in Arno 1980, Arno 1980, Arno 1993). Similar fire regimes have been found in Oregon and Washington. In the Front Range of the Canadian Rockies, fire ensures regeneration and the long-term population dynamics of lodgepole pine and Englemann spruce (Johnson and Fryer 1989).

1.3.3 Southern pines - Longleaf pine (*Pinus palustris*)

The longleaf pine of the southern coastal plains forms monocultures with a natural ground cover of *Andropogon* or *Carex* spp. (Chapman 1932). Such vast tracts of forests (millions of ha) were possible only because of the fire resistance of longleaf pine and vulnerability of other species to fire (Heyward 1939). Longleaf pines produce thick, stout root (with a lot of food reserve) for the first five years, but they do not grow much in height and then shoot off when conditions are favorable. About 90% of longleaf pine used to be burned every 3-4 years and that maintained its open park-like nature with rare catastrophic fires (Heyward 1939). Longleaf pines are not damaged by low-intensity fires which usually occur every 3-10 years due to lightning during spring and summer months (Chapman 1932, Wahlenberg 1946 in Campbell 1955). Long leaves (20-46 cm) and scales covering the buds protect them from fire at the young or the grassy stage (Chapman 1947, Burdon 2002). Burnings kill seedlings; however, the ones that survive periodic winter burns become established (Garren 1943). Annual fires, however, are deleterious to pine seedlings in the long-run and give rise to persistently sprouting oaks and shrubs. One-year-old longleaf pine seedlings survive low-intensity fires but their height growths are reduced by 5 years compared to height growths of unburned seedlings

(Bruce 1947). However, after the seedlings from burned plots reach 3m tall, their height growths become similar to those of unburned ones. Effects of burning on seedling mortality depend on the season of burn and summer burns should be avoided (Garren 1943). Stands under long-term fire exclusion as well as annual burning in North Carolina showed an increase in hardwood sprouts in gaps between trees and decreased pine reproduction (Heyward 1939). Even 5-6 years of fire protection affected the seedlings negatively because of the competition with sedges and grasses (Chapman 1932). Longleaf pine seedlings failed to establish because of the buildup of organic matter if fire was excluded for >10 years, and stems up to 30 cm or so in diameter were killed if burning was re-introduced during the hot summer (Chapman 1932).

After extensive eighteenth and early nineteenth century logging, most of the longleaf pines failed to reestablish in the areas they once occupied; however, longleaf pines were replaced mostly by different types of oaks, slash pine and loblolly pines (Campbell 1955). The commercial southern pines, except longleaf pines, need to be about 3 to 4m high to resist even low intensity burns. Among its associates, slash pine is resistant, whereas loblolly pine is more susceptible to fire (Heyward 1939). Loblolly, slash and shortleaf pines grow quickly up to 10 years and develop thick bark to resist most low intensity fires; however, they cannot survive frequent fires unlike the longleaf pines (Chapman 1932). Loblolly, slash and shortleaf pines are similar to red pine in their fire ecology and are shade intolerant and need mineral soils for their germination and establishment. Shortleaf pines also can sprout after fire (Walker 1980). Among the two associates, longleaf pine is taken over by slash pine, and loblolly pine by shortleaf pine

during succession. Hardwoods (predominantly oaks and hickories) dominate the community in the absence of fire or other disturbances for a long time, as the pines cannot establish in the shade (Walker 1980). Also, intense burning, cutting or bark beetle attack that remove the canopy pine trees result growth of understory hardwoods to the canopy (Walker 1980).

Prescribed burning is an essential tool for natural regeneration of pines and also helps in decreasing brown spot needle blight (Westveld 1949). Prescribed burning was found to check hardwoods like scrubby oaks and shrubs like gallberry (Campbell 1955, Lemon 1949). However, shrubs sprouted more following dormant season fire than growing season fire (Drewa et al. 2002). Burning also increased grass forage—slender bluestem and native legume species such as *Lespedeza* and *Desmodium* spp. (Bruce 1947, Walker 1980). In a 32-year study, unburned plots produced only 37 kg ha⁻¹, whereas annually burned but ungrazed plots produced as much as 1120 kg ha⁻¹ of grass (Bruce 1947). Earlier studies suggested that the regeneration of longleaf pine and understory vegetation may be maximized by increasing gap size. Gap sizes as small as 0.1 ha are strongly correlated with seedling and understory vegetation growth (Mc Guire et al. 2001).

1.3.4 New Jersey Pine Barrens

The New Jersey Pine Barrens is the nations' first National Reserve. The highly drained upland forests are dependent on frequent fires and cover about 30% of New Jersey's land area and have scrub oaks and ericaceous shrubs— huckleberries and

lowbush blueberry—in the understory (Buell and Cantlon 1953, Boerner 1981, Forman and Boerner 1981). The Pine Barren occupies 550,000 ha in southern New Jersey with pitch pine or shortleaf pine, or both mixed with black, white, scarlet and chestnut oaks, hickory and red maple on sandy gravelly acidic coastal areas or abandoned fields (Little and Moore 1949, Forman and Boerner 1981, Good and Good 1984). Pitch pine is the most dominant canopy tree, constituting most of the volume in pine-oak upland forests. An average point today in the Barrens burns every 65 years which used to burn every 20 years. Such reduction in fire frequency favors non-fire adapted species. For example, hardwood swamps (red maple) are being replaced by cedar swamp (Forman and Boerner 1981, Good and Good 1984). Extensive areas of very dense dwarf pine-oak forests (<3m height) called ‘Plains’ also occur (Lutz 1934, Boerner 1981, Buchholz and Gallagher 1982, Buchholz and Good 1982, Forman 1998). These ‘Plains’ are pigmy forests formed by fire in large areas which lack fire barriers (Givnish 1980). Dwarf trees are serotinous, precocious and predominant in vegetative reproduction. Among the two pines, pitch pines are of high importance as compared to shortleaf pines and are usually succeeded by hardwood (Westveld 1949). Because of their thick bark and sprouting capabilities, pines are persistent (Lutz 1934). Hardwoods can never replace pines completely as fires are so frequent, formerly about 1100 fires per year (Lutz 1934, Forman and Boerner 1981, Forman 1998, Barbour et al. 1999). The most frequent fires produced pigmy vegetation of scrub oaks and pitch pines, whereas less frequent fires produced oak-pine forests which shift to oaks after some time (Boerner 1981, Little 1998). Currently, the total area burned every year has been reduced from 22,000 ha to 8,000 ha.

Cutting and burning suppresses the growth of mixed hardwoods and promotes pine seedlings and are profitable in such sandy soils. Both pine species sprout when damaged by fire (Westveld 1949, Little 1974). Because of frequent fires occurring every 15-40 years (Little and Moore 1945), all the hardwoods are of sprout origin as they are killed back if they are <0.6 m; however, light winter fires do not kill well established pines >5 cm dbh (Buell and Cantlon 1953). The oaks also sprout from underground buds and grow faster and have a large root crown development after a series of frequent fires. The sprouting is so dense that germination and establishment from seeds would be difficult for new species (Westveld 1949, Little 1998). Such high production (density, biomass, net annual above ground productivity) increases flammability by increasing fire frequency and severity in the Barrens (Buchholz and Good 1982). Old oak pine stands (40-60 years old) are easy to convert to pine-dominant stands by periodic burning every 4 or 5 years because of the decreased sprouting capacity of old trees (Westveld 1949).

1.3.5 Great Lake States pines (red, white and jack pine)

Red pine is often associated with jack and white pine in the Lake States. Red pine is distributed widely in the U.S. from Maine to Minnesota and the southern parts of Canada (Engstrom and Mann 1991, Van Wagner 1970). The range of white pine is similar but extends farther south than red pine. Both red pine and white pine are important timber species of the Great Lakes region; however, the importance of red pine as a timber resource has increased because of damage to the jack pine by the jack pine budworm and to the white pine by white pine weevil and blister rust (Burns and Honkala 1990).

White and jack pine are more frequent seed producers than red pine. Seed production starts later (20-25 years) in red pine than in jack pine (5-10 years) and white pine (<20 years) (Van Wagner 1970, Lancaster and Leak 1978, Rouse 1988). Additionally, jack pine produces abundant seeds (>4 million seeds ha⁻¹) that have higher viability than those of red pine. Red pine cones are destroyed immediately if burned (Rouse 1988), whereas serotinous jack pine cones need fire to open. Jack pine cone temperatures have been found to reach as high as 300 °C for 60 seconds while burning; however, the seeds remain viable in soil until favorable conditions set in (Van Wagner 1970, Whitney 1987). The serotinous cones of jack pine sometimes open even with intense summer heat if they are near ground surface. Thus, jack pine regenerates and establishes better than red pine. White pine is a more frequent seed producer than red pine (Ahlgren 1976) with a good seed year every 3 to 5 years, and it is much more capable of establishing in stands after fires, under the canopy in undisturbed stands (Van Wagner 1970; Lancaster and Leak 1978), or in steep eroded slopes and along low river banks (Maissurow 1935). Red pine seeds are also highly self-fertile and thus even a single mature tree left in the stand can provide sufficient seeds for reestablishment (Spurr and Barnes 1980). Red pine has sporadic seed production, and a good seed year (seed mast) occurs every 5 to 10 years (Van Wagner 1970). Both jack pine and white pine can tolerate a layer of ash during germination whereas red pine germination is inhibited by a thick ash layer (Ahlgren 1976).

Red pine seedlings have to compete with hardwood associates, such as aspen, red maple and white birch, which are prolific annual seeders and successful sprouters (Van Wagner, 1970). Red pine seedlings cannot survive competition with the quick flush of herb growth that follows fire (Ahlgren 1976). Because of the competing associates and the organic matter accumulated on the soil, red pine seeds cannot reach mineral soil that is essential for regeneration and, thus, they have difficulty establishing in new stand (Metheven and Murray 1974, Ahlgren and Ahlgren 1981, Rouse 1988). Red pine is a species that cannot regenerate and establish in the forest floor with thick duff. Thus, fire is needed to consume duff, expose mineral soils, clear the understory shrubs, and prepare a suitable seed bed (Ahlgren 1976, Bergeron and Brisson 1990). In a simulation study using 'LANDIS' to look at the effect of presence or absence of fire, Schellar et al. (2005), found that red pine regenerates in fire rotation periods of 50, 100 and 300 years, and large fires were needed for red pine regeneration.

Among the two differently fire adapted species, red pine survives low-intensity fires but jack pine is usually killed; however, they co-exist (Clark 1991). Similarly, despite the fire adaptability, fire kills almost all red and white pine <6 m in height or 15 cm in dbh immediately and larger trees may also die; however, a crown fire is less likely after they reach >18 m in height (McConkey and Gedeny 1951, Van Wagner 1970). In red pines, branches in mature trees are well above the ground and such branchless tall boles also save trees from crown scorching and crown fire. Mature pine trees, however may be affected badly or even die if crown scorch is >75% (Van Wagner 1970, McConkey and Gedeny 1951), and intense fires might enhance bark beetle attack as well

(Dickmann 1993). Survival of red pine stands is due to thick bark which at the same age is considered to be more resistant to heat transfer than white pine (Van Wagner 1970).

Both red and white pines do not regenerate well in the heavy shade of natural stands or in severely burnt, extensively logged and fire-suppressed areas (Reich et al. 2001, Van Wagner 1970, Heinzelman 1973, Lancaster and Leak 1978). However, red pine stands are maintained by localized fires that are not so severe (Bergeron and Gagnon 1987). High intensity fires have been found to create scattered and mixed white pine stands along Alleghany Plateau, Pennsylvania (Runkle 1985). Metheven and Murray (1974) concluded that mature red and white pines are not damaged by low intensity prescribed burns and excellent regeneration can be obtained but periodic fires may be detrimental to established regeneration (Van Wagner 1970). Inability of red and white pine to regenerate in their own stands is well known and Kittredge (1934), in Star Island in Minnesota, found jack pine, red pine and white pine to fully occupy a site for 100, 300 and 250 years, respectively, with succession ultimately to maple-basswood in 650 years, but only in the absence of fire.

1.4 Disturbance, fire suppression and restoration management

1.4.1 Fire suppression and fuel reduction management

As discussed earlier, natural disturbances occur in forest ecosystems and create heterogeneity (mosaic structure) and a state of non-equilibrium with patches at different stages of succession in space and time. To manage an ecosystem, it is necessary to realize its ever-changing and dynamic nature and to understand the role of disturbance regimes,

patchiness, heterogeneity, and its patterns and processes. Such disturbances may also alter or degrade natural communities by invasion and thus is to be considered as an important problem to conservation management (Hobbs and Huenekke 1992). Therefore, active management is needed and must be informed by a better knowledge of disturbance regimes and the species to be discarded or favored (Hobbs and Huenneke 1992). Since recolonization is the outcome of interactions between heterogeneity and disturbances, disturbances should get proper appreciation from managers and policy makers as they are beneficial to biodiversity (Reice 1994). Nature reserves should be designed on the basis of minimum dynamic area and such areas must be guided by disturbance theory and patch dynamism regulated by gap formation to gap filling (Pickett and Thompson 1978). The smallest area in nature reserve should have natural disturbance regime that maintains internal recolonization and hence minimizes extinctions. Traditional successional and climax concepts may not be advantageous to sound vegetation management (Niering 1987). Such considerations are also needed because almost all management plans involve decisions that alter landscapes (Turner 1989).

In the US, fire suppression carried out for almost a century has caused unique ecological problems across landscapes and ecosystems, including the buildup of fuels that cause more intense and uncontrollable fires (Mutch, 1970); vulnerability to insects, pests and diseases; loss of fire dependent species from sites that are not allowed to burn (White 1979); loss of biodiversity (Christensen 1985); and ultimately an alteration of the natural disturbance regime (Sousa 1984). Such problems have led to increased use of low intensity fire or prescribed burning in forest, natural areas, and national park management

(Kilgore 1973, Kilgore 1976, Mutch 1976 in Romme 1982, Christensen et al. 1989, Feeney et al. 1998, Veblen et al. 2000). For example, Yellowstone National Park has adopted a let-burn policy for some lightning-caused fire since 1975, but only if human life, property, or other values are not threatened by such fires (Romme 1982). Landscape diversity was found to increase following two small fires and a mountain pine beetle outbreak in Yellowstone National Park, a non-steady state subalpine ecosystem, and such disturbances may significantly influence wildlife habitat, stream flow, nutrient cycling, and other ecological processes and characteristics within the park (Romme 1982). The USDA Forest Service has also increased prescribed burning since 1989 (Arthur et al. 1998). Christensen et al. (1989) suggested that different forms of fire suppression as well as prescribed burning should be included in management of wilderness areas, but there is not a single cook-book recipe to manage ecosystems that are so complex. As discussed earlier, to restore and improve the condition of ponderosa pine forests, reduction of wood as well as thinning and burning have been recommended (Feeney et al. 1998, Arno and Fiedler 2005, Veblen et al. 2000, Allen et al. 2002).

1.4.2 Low intensity prescribed fires

Lemon (1949) described prescribed burning as a “purposeful and planwise use of fire under strict control.” It is used as a silvicultural tool to manage forests and wildlife. Fire prepares a suitable seed bed by consuming litter/duff, clearing understory shrubs and competing associates, opening the canopy, and exposing mineral soil for the establishment of pines in the Great Lakes as well as other regions (Lemon 1949, Buell and Cantlon 1953, Van Wagner 1970; Metheven and Murray 1974, Kilgore 1973,

Ahlgren 1976, Alban 1977, Lancaster and Leak 1978, Thomas and Wein 1985; Dickmann 1993). The reduction in depth of organic matter with fire increases establishment because seedlings are closer to the constant water supply of more decomposed organic layers and mineral soils (Thomas and Wein, 1985). Also, the mineral soils have higher moisture content and do not dry quickly (unlike the litter). Mallik and Roberts (1994) found red pine regeneration to increase with a decrease in duff thickness. The openings created by burning allow sunlight to reach to the forest floor. Burning decrease competition by killing the existing vegetation; however the extent of killing depends on the type, duration and intensity of the burn and also on the vegetation itself. Such killings modify the soil micro-environment (Raison 1979). Fire affects species diversity (Reich et al. 2001) as well as soil organic matter, partially or wholly (Debano and Conrad 1978) and re-establishes the pioneer condition. Regeneration of red and white pine has failed in pine and hardwood mixed stands under different management systems, and thus there is alarming loss of areas containing these species (McRae 1994). Therefore, fire is needed to perpetuate natural pine ecosystems (Maissurow 1935, Van Wagner 1970, Dickmann 1993).

Low-intensity (200-500 Btu/sec-ft) prescribed burns are sufficient to control understory herbs and shrubs in red and white pine stands (Van Wagner 1970). In the New Jersey Pine Barrens the density of pine seedlings was found to increase as much as three times after burning (Little and Moore 1949, Buell and Cantlon 1953) but was unfavorable to oaks, as their seeds were exposed to sun and bird and mammal predators (Boerner et al. 1988). Additionally, in the case of longleaf pine, fire consumes the mat of dead wire

grass, which otherwise would not decay, increasing fire hazard. Fire also reduces damage from pests and diseases, especially brown spot needle blight (Chapman 1932, Feeney et al. 1998) and red pine cone beetle (see ref. in Dickmann 1993). Such reduction in pest and diseases following prescribed fire has been found in ponderosa pine (Covington et al. 1997).

Prescribed fire also reduces the heights of understory vegetation and provides browse for wildlife, improving habitat and thus increasing hunting and recreation scope in the Great Lakes States (Little and Moore 1949, Rouse 1988, Dickmann 1993, Bender et al. 1997). Niering and Dreyer (1989) have highlighted fire's potential in the management of wildlife and restoration of grass-dominating areas within oak forests. Further, the reduction of hazardous forest fuels by prescribed burning helps to prevent forest fires and makes suppression of them easier. For example, prescribed fire is used to remove slash from about 10% of all clear cuts in Canada and 20-25% in British Columbia (Sullivan et al. 1999). Prescribed fire is also useful in managing grasslands, prairies and wild flowers and maintaining park-like vistas with high visual qualities in stands; e.g., Sequoia National Park (Biswell 1989).

Burning forests may have adverse effects as well. Fire is not selective in killing vegetation and their size classes, and thus it may be difficult to save desired plants or the desired size classes. Moreover, the fire controls vegetation only for a short time. Further, negative effects of prescribed burning on the physiological condition, growth, and survival of ponderosa pines have also been reported in studies where fuel loads were not

reduced prior to burning (Sutherland et al. 1991). Also, small mammal diversity and abundance was reduced after burning clearcuts occupied by spruce-fir (Sullivan et al. 1999). Prescribed burning also has risks of escape and produces blackened charred stems, smoke and other particulate matter and several radiatively active gases (CO₂, NO_x, SO_x and others), which add to pollution and the greenhouse effect. Thus, prescribed fire may prove unacceptable in some environments. In any case, it needs to be done correctly (Dickmann 1993) and its use depends on clearly defined objectives.

Fire risks should be understood for conflict resolution and sustainable management (Cleland et al. 2004). Risks of fire escape are also because of lack of proper training in the use of prescribed burning (McRae et al. 1994). But there will be fire regardless of whether we burn or not. Prescribed fire should be highly desirable as long as its goal is the betterment of human beings without irreversibly changing the ecosystem or vegetation.

1.4.3 Red pine density management

Red pine is one of the most widely planted and intensively managed species in the Great Lake States (Michigan, Minnesota and Wisconsin) with a very high economic as well as ecological importance in the region (Lundren 1965, Benzie 1977, Bassett 1984). Because of its faster growth, higher productivity and ability to grow well in infertile soil, compared to its hardwood and other conifer associates in the region, it has been planted throughout these states since the early part of the last century (Gilmore and Palik 2006). Currently, it occupies about 0.4 million ha in the Great Lakes states alone (Benzie 1977,

Lundgren 1983, Parker et al 2001). Red pine grows well in clayey, loamy and sandy acidic soils (Bassett 1984) and site indices ranging between 13.7 to 22.9 m at 50 years (Gilmore and Palik 2006). The products obtained vary with management or the silvicultural technique applied to red pine plantations and its growth and yield depends on stand age, site quality and stand density. For example, high-density management produces small poles and sawlogs, whereas low density management produces large utility poles and sawlogs (Buckman 1962, Lundgren 1965). Red pine grows fast, provides better yield than other native pines, has good form and is relatively free from defects and diseases (Buckman 1962, Lundgren 1965, Burgess and Robinson 1998, Penner et al. 2001).

Because they had such a high value, most of the pristine natural red pine forests in the region were deforested by the turn of the last century. This situation demanded that extensive research and management be carried out, and various aspects of research started as early as the beginning of the last century in both the US and Canada (Burgess and Robinson 1998). Numerous studies carried out in the Lake States as well as in adjacent provinces of Canada have examined density management, thinning, growth and yield and other aspects of management including succession, wildlife habitat and browse availability (Rouse 1988, Bassett 1984, Lundgren 1981, Dickmann et al. 1987, Dickmann 1993, Bender et al. 1997, Burgess and Robinson 1998, Penner et al. 2001). In the last 50 years or so, US and Canadian research has explored the effects of current and historical wildfire on vegetation composition, structure and succession and their role in the management of red pine forests (Mutch 1970, Heinselman 1973, Benzie 1977, Whitney

1986, Bergeron and Gagnon 1987, Engstrom and Mann 1991, Dickmann 1993, McRae et al 1994, Henning and Dickmann 1996, Newmann and Dickmann 2001, Cleland et al. 2004).

Red pine is a shade intolerant (light demanding) species (Benzie, 1977) and is recommended for even-aged management. Red pine can also be managed as uneven-aged stands with a selection system; however, this becomes expensive because thinning must be carried out across different size-classes (Benzie 1977, Parker et al. 2001). If the management objective is related to some research questions or obtaining sawtimber, then uneven-aged management could be justified and applied. For maximum productivity of red pine it is necessary to thin it periodically (Day and Rudolph 1972). Red pine response to thinning is very quick. Stephens and Spurr (1947), for example, observed daily and weekly increases in growth rates of red pine after thinning and pruning. Thus, thinning is one of the most important management tools for this species.

Thinning has a variety of well-understood effects on tree stands, so the type of thinning undertaken depends upon the management objectives. Artificial thinning usually involves cutting or removal of suppressed or overtopped trees, which cannot perform well and would eventually die if left unattended during stand development. In a study at Petawawa Research Station in Ontario, Canada, Burgess and Robinson (1998) found that unthinned natural stands of white and red pine had mortality as high as 10 times that in thinned stands. Thinning can enhance the diameter growth but not the gross (overall) productivity (Haberland and Wilde 1961). The growth potential of the

remaining trees can be increased by removing suppressed, diseased, deformed and dying trees and concentrating the growth in fewer larger trees that are retained (Spurr et al. 1957, Althen and Stiel 1990). Such removal does not decrease the potential unit-area volume growth of the stands (Nyland 1996). Even if released, suppressed trees do not grow well due to their physiological deficiencies and are less productive of unit area biomass than the uniformly distributed large ones that are retained (Smith 2003). According to Kozlowski and Peterson (1962), dominant red pines have early growth initiation, faster growth and longer growing season than the intermediate and suppressed trees. Crown touching and friction leads to deterioration and decreased average growth of diameter in unthinned stands (Spurr et al. 1957). All of these factors result in growth inhibition in suppressed trees. Further, if the stands are too dense and grown for a long time without any treatment, there is loss of volume growth due to suppression (Buckman 1962). Thus, thinning is needed to maximize the net productivity of the stands.

In the Lake States in 15 to 20 years-old stands, if the tree density was more than 2500 trees ha⁻¹, there was stagnation; yield and MAI varied with the intensity of management (Rudolph 1957). Coffmann (1976) also found that the gross as well as net volume growth in red pine plantations decreases if unthinned for a longer period and it is caused by mortality due to self-thinning. Stiel et al. (1994) in an overstory release experiment in a 80-year old white pine mixed wood, found 80% increase in saw log volume after 20 years of thinning by bringing back the stands to residual BA of 16 m² ha⁻¹. The greatest growth was 159 m³ ha⁻¹. Smith (2003) found that the larger trees reserved during the thinning improved production of board foot volume.

The removal of suppressed or overtopped trees provides extra space and resources to the trees retained, increases rates of diameter and volume growth, shortens the time to grow to a given diameter, shortens rotation time, and increases yield (net production) by removing trees through early harvests that otherwise would die (Spurr et al. 1957, Smith 1986, Nyland 1996, Lundgren 1981, Parker et al 2001). So long as the gaps created by thinning are fully occupied or covered by green vegetation, gross productivity does not change whether thinned or not (Bassett 1984). However, if there is any vacancy in growing space, productivity is reduced and will take some time to recover (Day and Rudolf 1972, Gilmore et al. 2005). If there are fewer trees they tend to become larger and if there are many trees they tend to be smaller; however, the total basal area growth rate does not change. Such increase in diameter affects net increase in volume growth (Assman 1970, Nyland 1996). Burgess and Robinson (1998) found an increase in diameter growth in both white and red pine stands after thinning. Residual saw log volumes were concentrated in the fewer and larger natural white and red pine trees (40 years old) after a series of six thinnings over 71 years at Petawawa Research Forest, Ontario Canada. Such volume accumulation in large sized trees makes them more valuable as well.

Thinning has some disadvantages too. For example, if red pine stands are thinned heavily, wind susceptibility might increase, although red pine is considered to be a relatively wind firm species (Buckman 1962). If only the inferior and suppressed understory or overtopped co-dominants are removed from below, there could be very small or even no increase in net growth as their removal might not stimulate additional

growth in larger trees (Smith 1986, Nyland 1996). Other disadvantages of thinning are: i) the high cost involved during harvesting; ii) formation of large openings that stimulate hardwood invasion (Burgess and Robinson, 1998); iii) damage to residuals during felling and skidding; iv) fungal (rot) invasion through cut stumps; and v) increased fuel loading.

If the stands are too dense, they might also need a precommercial thinning (Benzie 1977). Buckman (1962) advises that thinning start early at a stand age of 25 years. Further, early thinning to a lower residual density than recommended for maximum volume production will promote understory succession of woody and herbaceous plant species thus increasing the flora and fauna diversity and improving the visual appearance of red pine monocultures (Dickmann et al. 1987, Dickmann 1993). Again, whether it is advantageous or not to do so depends upon the objective of management.

Lundgren (1965) showed that a 25-year-old red pine stand regularly thinned (from below and above) every 10 years to residual BA of $20.6 \text{ m}^2 \text{ ha}^{-1}$ had the highest investment returns when compared to other regimes. Similarly, Benzie (1977) also recommended for the basal area to be retained as low as $20.6 \text{ m}^2 \text{ ha}^{-1}$ for better yield. In the growth projection study by Buckman (1962), red pine growth and yield with three schedules of thinning to 20.6, 27.5, $34.4 \text{ m}^2 \text{ ha}^{-1}$ were not significantly different; however, he found out that the radial growth could be increased at lower residual density.

In a study using a growth and yield simulator program called REDPINE, Lundgren (1981) found that either thinning to low densities or planting fewer trees would accelerate diameter growth and provide larger trees at a given age. Lundgren recommended the best tree density to be 494 tpha for sawtimber (with initial density 123 to 3954 tpha); below this density the mean annual increment (MAI) declined. Similarly at the higher densities (2965 to 3954 trees ha⁻¹), the total cubic volume production was found to level off. Therefore, both the initial tree density (trees ha⁻¹) and residual stand density following thinning strongly influenced diameter growth, although there were fewer larger trees at the time of harvesting when fewer trees were retained. This effect was more pronounced in the better sites. He also showed that site index, timing of thinning, and rotation length affect volume of wood produced. Total cubic volume MAI was found to be affected more by site index than length of rotation. In a productivity study of red pine in Lake States using another growth model (STEMS), Lundgren (1983) found that the merchantable volume from unthinned stands to be 18% higher and that from the thinned stands to be 32% higher than current estimates in the Lake States. Average yield in thinned stands was found to increase from 6.4 to 7.1 m³ ha⁻¹ per year after thinning and the culmination of mean annual increment increased from 55 years (in unthinned stands at 18.3 site index) to 80 years.

Gilmore et al. (2005) in their simulation study of a 46-year-old red pine plantation tried to test the Langsaeter Hypothesis, which stated that “the total production of cubic volume by a stand of given age and composition on a given site is, for all practical purposes, constant and optimum for a wide range of density stocking. It can be decreased

but not increased by altering the amount of growing stock to levels outside this range.” In their study with stand level production equations and growth projection models, there was a difference of only about 10% of actual volumes on average. They did not have strong evidence to support this hypothesis. The low thinning with $32.1 \text{ m}^2 \text{ ha}^{-1}$ of BA retained had 30% more volume than unthinned. This volume was lower than the geometric and crown thinning set at $28.7 \text{ m}^2 \text{ ha}^{-1}$ BA, which had a volume increase of 35% over the unthinned control. The unthinned plantation grew in volume by only about 22% at the end of the 10-year projection.

Well-spaced stands use more resources (sunlight, water and nutrients) as they occupy the site more uniformly (Buckman 1962). In a 27-year-old spacing study, Marty (1988) found that 39% of red pine trees in the thinned stands with 494 tpha reached their threshold of sawtimber size (23 cm dbh) much earlier than in densely planted stands, showing that wide spacing in red pine plantation lowers the per unit area planting cost. Penner et al. (2001) in an initial spacing trial of red pine established in 1953, thinned in 1982 and sampled in 1998, found that both the initial lower spacing (that is, higher densities) of 1.2 and 1.5 m had higher mortality rates than the higher (i.e., less dense) initial spacing of 1.8 to 2.4 m. In terms of total volume production, thinning was found to reduce the total time needed to reach utility pole size with little mortality. Although the lower initial spacing helped to produce more poles, it required thinning to prevent mortality and maintain good diameter growth.

Following an improvement cut (set BA to 6.9, 11.5 and 16.1 m² ha⁻¹) in a 80-year-old mixed hardwood forest in Canada, Stiehl et al. (1994) found highly significant growth responses in white and red pine 20 years after release. There was about an 80% increase in sawlog volume in the treated stands, and also mortality and rotation age for red pine was significantly reduced, increasing the natural rate of succession.

To summarize, disturbances are sources of heterogeneity that create patchiness (mosaics of patches) in the environment of plant/forest communities in time and space. At any time such disturbances not only create patches of different sizes, shapes and ages but also different stages of patch development or successional stages in forest ecosystems. Looking at the fire regimes throughout the temperate North America, it is revealed that fire could play an important role in the restoration and management of forest ecosystems. Further, learning from the past experience of fire suppression in the US, prescribed fire or controlled burning is being used more and more as a tool in the management and restoration of forests, national parks and reserves. Fire could also be important in restoring pine forests in the Lake States, as red and white pines sometimes have problems in regenerating and establishing in natural stands, as these pines need exposed mineral soils with clear forest floor and reduction in competing hardwoods for their successful establishment.

I studied long-term effects of fire in a red pine plantation in northern Lower Michigan, since conventional thinning or other silvicultural systems alone may not be sufficient to create a suitable environment for these species. Also, there is lack of

information on long-term effects of low-intensity fires on red pine forests. Effects of single and multiple fires at different intervals after one to two decades of burning on the structure, composition and overall vegetation dynamics of a red pine plantation were studied and are presented in Chapter 2. Further, longer term effects of such burnings were studied in relation to no-management and different thinning regimes projected for 100 years into the future with the use of the Forest Vegetation Simulator and are presented in Chapter 3.

Chapter 2: Effects of Low-Intensity Fires on the Vegetation of Northern Michigan Red Pine (*Pinus resinosa* Ait.) Plantation.

2.1 Introduction

Red pine was a prominent species in the forests and barrens of the Lake States before European settlement. However, it declined in natural stands in the nineteenth and early twentieth centuries due to harvesting and slash burning (Heinselman 1973). Before European settlement, low to medium intensity fires occurred every 5-50 years or even 70-80 years in natural red pine stands (Bergeron and Brisson 1990, Englestrom and Mann 1991, Van Wagner 1970) and occasional intense stand replacing fires occurred at intervals of 150-200 years (Bergeron and Brisson 1990). Such occasional intense fires were ideal for red pine regeneration and establishment because they consume litter, decrease duff thickness, expose mineral soil and prepare seed beds (Van Wagner 1970, Alban 1977, Engstrom and Mann 1991, Dickmann 1993, Mallik and Roberts 1994). However, the exclusion or suppression of fire after the 1920s has disrupted the natural regeneration and establishment of red pine, which does not regenerate well in fire suppressed areas (Reich et al. 2001).

Prescribed burning is being used as a potential tool for red pine regeneration (Alban 1977). Mature red pine trees are tolerant of low-intensity understory fires, and the species is considered to be fire adapted because of its very thick and insulated bark which protects the cambium from fire damage (Van Wagner 1970, Metheven and Murray 1974, Whitney 1986 and 1987, Rouse 1988, Dickmann, 1993). Its bark is considered to be even

more resistant than of white pine (Van Wagner 1970). Branch free boles up to 5 m also help red pines withstand fire.

Multiple prescribed fires remove unwanted vegetation such as maples, hazelnut and balsam fir and are useful in red pine regeneration (Alban 1977; Metheven and Murray 1974; Van Wagner 1970; Mallik and Roberts 1994) and also alter post-fire vegetation cover by consuming some buried seeds and rhizomes (Thomas and Wein, 1985). However, burning at frequent intervals also reduces the number of red pine seedlings or even kills them (Henning and Dickmann 1996; Van Wagner 1970), so burning should be done only as needed.

Short-term effects of single and periodic prescribed burns in red pine ecosystems in Michigan have been studied (Dickmann 1993; Henning and Dickmann 1996; Neumann and Dickmann 2001). However, the long-term effects (>10 years), as well as the effects of different growing periods (or length of time) after the last fire, have not been documented. The overall goal of my research is to broaden the understanding of the long-term effects of prescribed burning on species diversity, regeneration and establishment of red pine in northern Lower Michigan. The specific objectives are to: a) examine the long-term effects of both short and long interval low intensity prescribed fires on the vegetation dynamics of overstory red pine trees, herbaceous ground flora and understory woody vegetation in mature red pine ecosystems; b) explore the relationship between fire and red pine ecosystems by quantifying plant species diversity of various sites burned with low intensity prescribed fires; and c) determine the effects of low

intensity prescribed fires on regeneration and age distribution of saplings of red pine and its associates.

2.1.1 Global research hypothesis

A disturbance is any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment (Pickett and White, 1985). Also, disturbances are different in their magnitude, frequency and size and their physical and biological effects are different at different layers, species and size classes (White 1985). A low-intensity fire affects ecosystems in different ways. First, it affects the vegetation dynamics of a stand by consuming duff, reducing competition, changing resource availability and altering the seedbed and seedling establishment. Second, it alters the understory vegetation by selectively killing woody stems of smaller diameter classes, especially conifers. Third, it affects small-sized sub-canopy trees by selectively killing them and promoting the growth of large-sized mature overstory trees. Thus, fire ultimately changes a red pine ecosystem as a whole, by killing or altering the growth and development of community components.

This study focused on how red pine forest changes during the course of succession following different burning regimes. The following working hypotheses were tested:

- a. Low intensity fires cause changes in community structure, species composition, and diversity of a red pine ecosystem and such changes are evident even 10 or more years following burning.

- b. Compared to total fire exclusion, red pine ecosystems with a history of one or more low intensity fires (discontinued for more than 10 years) will have:
 - i) higher species richness, diversity and coverage of understory vegetation, especially with more frequent burning.
 - ii) a decrease in density and diameter of larger understory woody vegetation but an increase in density of smaller understory woody vegetation, especially with more frequent burning.
 - iii) a decrease in density but an increase in growth and yield of mature overstory trees.
 - iv) shifted from a hardwood dominated to a red pine dominated understory.

2.2 Materials and Methods

2.2.1 Study site

The study was carried out on experimental plots established in the 1980s in the Pigeon River Country State Forest Management Unit in northern Lower Michigan (Figure 2.1). My study gave continuity to established on-going research (Henning and Dickmann 1996), which was nearing two decades in duration when I began.

The study area, located along Clark Bridge Road, is a 61 ha-pine plantation established in 1931 with red, white and jack pines. In 1970, all the white and jack pines were harvested, leaving a variable residual basal area (mean $10 \text{ m}^2 \text{ ha}^{-1}$), much of it in an under-stocked condition. The site is very productive; the Emmett Sandy loam soil

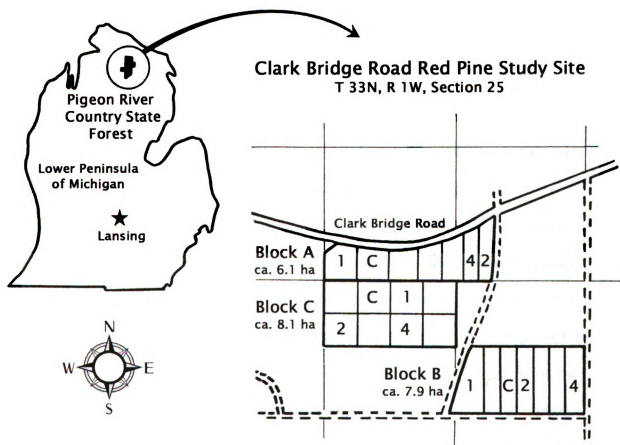
Figure 2.1: Location of Pigeon River Country State Forest in the Lower Peninsula of Michigan and Red Pine Study Site experimental plots along Clark Bridge Road. Unused plots in each block were designated for fall burns, which never occurred because of lack of suitable weather.

C= Unburned control

1 = One spring burn (1985)

2 = Two spring burns (1985 and 1990; 5-year burn interval)

4 = Four spring burns (1985, 1987, 1989 and 1991; 2-year burn intervals)



(Coarse-loamy mixed frigid, Alfic haplorthods) produces an average site index for red pine of 20m (65 ft) at 50 years.

The experiment I used was set up in a randomized complete block design (RCBD). The study site had three blocks (A, B & C), each of which had four treatments (Figure 2.1). The experimental plots (0.86 to 1.0 ha) were burned beginning in 1985 during spring with low-intensity prescribed fires with planned intervals between successive burns of two (four fires completed), five (two fires completed), and 10 (one fire completed) years. Thus, the study site provided plots with a mix of fire frequencies and intervals and different growing periods after the last fire ranging from 10 to 18 years.

The study plots were measured in the summer of 2001 and 2003 and analyzed to test the long-term effects of different prescribed fire regimes. The blocks (A, B & C) were within few minutes walking distance but not adjacent to each other. Each plot in the three blocks was divided by two north-south running transects. Four points along each transect were chosen randomly and served as the center of subplots. Thus, there were a total of eight subplots in each plot within a particular treatment. However, only five subplots were taken in the one-burn plot of block A because an intense flare up during the first burning killed many of the overstory trees and the understory woody and ground vegetation looked quite different than other plots. The center of each subplot was marked and also a nearby large tree was selected as a witness tree for each of the points, marked with paint, the direction and distance from the point was recorded and marked, and GPS coordinates logged to relocate the points.

Vegetation data were collected as follows:

- Overstory tree measurements were taken in variable radii plots using a 20 BAF (English) prism at each of the sample points along each north-south running transect. Diameter at breast height (DBH) was measured using a diameter tape and tree height using a clinometer. Tree density, basal area, volume and mean annual increment were computed from these data and used for further analysis.
- All trees and shrubs >1.4m tall and < 10cm DBH were categorized as woody understory and measured at the same sample points as above using 100 m² rectangular sub-plots. DBH of individual plants of each species was measured. The age of red pine, red maple, black cherry, beech and white ash seedlings >1.4m in height and <10cm in dbh were determined from a total of 218 sample cross-sections cut at the base of the understory woody vegetation to establish the relationship of their establishment with the fires.
- All plants < 1.4m tall were categorized as herbaceous ground vegetation and were measured in 1 m² quadrats. Three such quadrats were taken in each 100 m² plot, one at the center and the other two on the outer sides (i.e., 24 subplots per plot). Percent cover of all species was estimated in each of the 1 m² subplots. Also, number of individuals of each species except grasses, mosses and lichens were counted in those plots.
- Species area curves for the woody understory and herbaceous ground vegetation were constructed in all of the three blocks to see if the sampling was adequate.

2.2.2 Data analysis

Species diversity; vegetation composition of the tree, understory woody and herbaceous ground vegetation components and their density, frequency, growth and yield were evaluated for each of the burned and unburned study treatments. Different indices of species diversity—species richness, Simpson’s Index, Reciprocal of Simpson’s Index, Shanon’s index, and Evenness index—were used to examine biodiversity in the understory woody and herbaceous ground vegetation (Magurran 1988). Relative Value Index or Importance Value (IV) also was determined for overstory trees and woody understory trees as the magnitude of this value gives a better indication of species importance as compared to just density, frequency or basal area alone (Curtis and McIntosh 1951). IV is the sum of relative density, relative frequency and relative basal areas.

The Mixed Linear Model (ProcMix in SAS) was used to analyze the data for treatment effects. Normality of the data was checked and natural log or other appropriate transformations were done. Arcsine transformation was done in case of ground vegetation cover. A binomial test (Proc Glimmix in SAS) was used to test if the proportions of one species and the remaining others were significantly different across treatments. Such tests were repeated with all of the species or groups of species in the overstory tree, understory woody and the herbaceous ground vegetation groups. Similarly, binomial tests were also done to examine the proportions of different size classes of overstory and understory trees. Goodness of fit or chi-square tests were used to compare the observed and expected number of species in different treatments as well as to see if the diameter classes and

species under different treatments had some associations. Least Square Difference (LSD) was carried out to compare among treatments. Because of the low number of replicates and heterogeneous nature of the experimental blocks, a standard p-value (<0.1) was set for examining the rejection or failure of hypotheses.

If an F-test was significant ($P < 0.1$), means were contrasted using a two sided t-test in three different ways: 1) unburned plot against all of the burns, 2) unburned and one-burn plots against two and four-burn plots, 3) one-burn against two and four burn plots. Biodiversity indices were tested in the Mixed Linear Model using ProcMIX. Microsoft SAS was run for all of the analysis. JMP (a SAS product) and Excel were also used for summarizing data. Images in this dissertation are presented in color and used for discussion.

2.3 Results and Discussion

2.3.1 Overstory trees (>10 cm dbh)

The overstory trees in the Clark Bridge Road plantation consisted mostly of red pine, with *Acer rubrum*, *A. sachharum* and *Pinus banksiana* as minor tree species (relative frequencies respectively of 94, 2, 2 and 1 percent of a total of 414 trees inventoried in all of the plots). The remaining one percent consisted of *Fraxinus americana*, *Pinus strobus*, and *Tilia americana*. The dominance of red pine in the plots is clearly shown by the Importance Value (IV) (Table 2.1). IV of red pine overstory trees was highest in the four-burn plots and lowest in unburned control plots. Block A had the highest density of red pine trees followed by block C and block B. Block B contained only red pine trees with no other overstory tree species in the sample.

Table 2.1: Stand characteristics of the overstory (>10 cm dbh) in experimental red pine plantation under four burn treatments (n=12; df=6).

under four burn treatments (n = 12, df = 9).						
Treatments	Number of observations	Tree Density tree ha ⁻¹	Basal Area m ² ha ⁻¹	Volume m ³ ha ⁻¹	MAI m ³ ha ⁻¹ yr ⁻¹	Red pine IV
Control	3	281 a (90.2)	19.3 a (3.2)	203.9 a (38.9)	2.9 a (.5)	186
One Burns	3	128 b (42.5)	17.9 a (1.6)	193.5 a (39.61)	2.7 a (.6)	267
Two Burns	3	146 b (48.3)	21.4 a (3.2)	227.0 a (38.9)	3.2 a (.5)	278
Four Burns	3	148 b (49.1)	23.3 a (3.2)	261.8 a (38.9)	3.7 a (.5)	285
Contrasts		Tree Density				
Control vs All Burns		s				
C & 1B vs 2B & 4B		s				
1B vs 2B & 4B		ns				
The tree density are the log back transformed values.						
MAI = Mean Annual Increment						
IV = Importance Value (sum of relative frequencies, density and basal areas)						
The means used above are the Least Square Means (LSM).						
LSM in each column followed by the same letters are not significantly different at p ≤ 0.1						
s and ns indicate significant and non-significant respectively						
Standard errors of means (±) are given in parentheses						
C, Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns						

The effects of the prescribed burning treatments on stand and tree characteristics of the 70-year-old red pine plantation were analyzed statistically for both the sub-plot and plot level means, and significant treatment effects were detected only for overstory tree density (Table 2.1 and 2.2). Among different treatments in my study, the overstory tree density was significantly higher in unburned controls than in burned plots and approximately double in control (281 trees ha⁻¹) than in burn treatments (Table 2.1). Unburned controls were significantly different in overstory density than all of the burned plots together. Also, overstory tree density in unburned controls combined with one-burn treatments were significantly different than in both of the repeatedly burned plots combined. Here, the higher density in unburned controls as compared to burned plots was both due to ingrowth in the sub-canopy layer of the unburned controls as well as removal of substantial number of sub-canopy trees during repeated burnings. However, since the prescribed burns were of low intensity, mature overstory red pine growth and yield were not affected adversely (cf. Mc Conkey and Gedney 1951, Van Wagner 1970, Dickmann

Table 2.2: Mean characteristics of overstory trees (>10 cm dbh) in experimental red pine plantation under four burn treatments (n= 414; df=6).

Treatments	DBH cm	Height m	Crown Ratio %
Control	41.2 a (1.8)	25.6 a (2.0)	4.5 a (0.5)
One Burn	44.7 a (1.8)	26.5 a (2.0)	4.5 a (0.5)
Two Burns	45.7 a (1.8)	25.9 a (2.0)	4.8 a (0.5)
Four Burns	45.2 a (1.8)	27.1 a (2.0)	4.0 a (0.5)

dbh = Diameter at breast height;
The means used above are the Least Square means.
LS Means of parameters followed by the same letters are not significantly different at $p \leq 0.1$.
Standard errors of means ($\pm$) are given in paranthesis
Note: Crown ratio 1 equals 10% of tree height

1993, Henning and Dickmann, 1996, Neuman and Dickmann 2001). In previous studies, a single low-intensity surface fire < 200 Btu/S/ft. (692 Kw/m) or repeated fires at two and five-year intervals neither caused significant pine overstory mortality (Henning and Dickmann, 1996) nor affected the basal area in a mature red pine stand (Neuman and Dickmann, 2001). There was a negative correlation between the density and the average diameter of the overstory trees in my study ($n = 93$; $p\text{-value} \leq 0.0001$, $r = -0.7827$). The control plots had the highest density of overstory trees and the lowest average diameter (41.2 cm); whereas, the burned plots had the lowest density of trees and larger average diameters (Table 2.2). Average tree height also was slightly lower in the control plots. The reduced average diameter and height of overstory trees in unburned controls was due to the presence of greater numbers of smaller trees compared to those in the burned plots, where most of the small-sized trees were killed or severely scorched during burning. Earlier, Lunt (1950 in Dickmann 1993) found 20 years of annual burning to increase height and volume of red pine in Connecticut and the increases were thought to be due to the increased pH as well as available phosphorous and exchangeable calcium. There was not much difference in crown ratios among the burned and unburned plots in my study, although they were lower in the four-burn plots.

There were no significant treatment effects on basal area, volume and mean annual increment (MAI) of the overstory trees (Table 2.1). Nonetheless, there was a trend of increasing stand values with more burning. Basal area, volume and MAI all increased as the number of burns increased from one- to two- to four-burns, with the highest growth occurring in the four-burn plots despite having less than half the density of trees than in

the unburned controls. Among the two and four-burn plots, the latter had the highest basal area, volume and MAI, even though both had the same tree density.

Fire as a disturbance agent not only works at a stand or community level, but also at different levels of species and their diameter classes (Pickett and White 1985). I tested the effects of burning on overstory tree characteristics and their size classes to see if the effects of fire were different at different levels. However, the effects on species were not tested as red pine was so dominant in the overstory. Overall, the contribution of red pine to total density, basal area, volume and MAI in four-burn plots were 95, 98, 99 and 98%, respectively, and were the lowest in one-burned plots among burned plots (Appendix 2.2). Unburned control plots, however, were clearly different than burned plots; red pine density, volume, basal area and MAI dropped to 35, 82, 89 and 95%, respectively, of the total. In unburned control plots, red maple (32% of total density), followed by sugar maple (22% of total density) and jack pine (8% of total density) were important members.

To examine the effects of fire on the overstory composition and structure, trees were grouped into three different diameter size classes: large (42 to 62 cm), medium (32 to 42 cm) and small (10 to 32 cm), which will be called dominant overstory, mid-canopy and sub-canopy trees, respectively, hereafter. Species richness across plots was very low among the dominant overstory trees, which had a total of only four red maple, sugar maple and jack pine trees besides red pine. Similarly, there was only one basswood tree besides red pine in the mid-canopy trees. However, the sub-canopy trees had relatively

higher species richness and abundance than other size classes, with a total of six species—four jack pines, seven red pines, eight red maple, six sugar maples, and one each of white ash and white pine. A binomial comparison revealed that there were no significant treatment effects on the proportions of any of the three size classes versus the remaining two classes across treatments. However, further statistical analysis with Mixed Linear Model (Proc MIX) revealed that there was a significant treatment effect on dominant overstory tree density (Table 2.3). The dominant overstory tree density in four-burn plots (103 trees ha⁻¹) was significantly higher than in both the unburned control and one-burn plots. When compared with two-burn plots, the dominant overstory density in one-burn were significantly lower. Further, when control and one-burn plots were contrasted with two- and four-burn plots, they also showed significant difference on dominant overstory density. Similarly, one-burn treatments were significantly different from two- and four-burn treatments together. However, control versus all burn treatments when contrasted did not show a significant effect. Thus, the analysis shows that there is some difference in the density of dominant overstory trees in repeatedly burned plots, although the effect was lesser in the two-burn than in four-burn plots.

The increase in density of dominant overstory trees in four-burn plots than in other treatments was probably due to faster diameter growth and shifting of some of the mid-canopy trees to dominant overstory class during the post-fire growing period. Such shifts to larger size classes have been reported in the New Jersey pine region by Stephenson (1965). Radial growth of western larch (*Larix occidentalis*) increased up to eight years after a single burn (Reinhardt and Ryan 1988b in Dickmann 1993).

Table 2.3: Effects of prescribed burning on dominant overstory (>36 cm dbh) , mid-canopy (32 to 36 cm dbh) and sub-canopy (10 to 32 cm dbh) trees¹ in experimental red pine plantation, summer 2001 (n=93).

Treatment effects	Tree Density trees ha ⁻¹	Basal Area m ² ha ⁻¹	Volume m ³ ha ⁻¹
Dominant overstory			
F-tests, p-value	0.0448	0.1208	0.1493
Chi-square tests, p-value	0.0055	0.0325	0.0726
Control	66 ac (8.4)	12.8 a (1.9)	138.5 a (19.6)
One Burn	62 a (8.6)	12.0 a (1.9)	122.5 a (19.2)
Two Burns	89 bc (9.8)	16.4 a (1.9)	170.7 a (21.8)
Four Burns	103 b (10.5)	18.2 a (1.9)	194.5 a (23.3)
Contrasts			
Control vs All Burns	ns	ns	ns
C & 1B vs 2B & 4B	s	ns	ns
1B vs 2B & 4B	s	ns	ns
Mid-canopy*			
Control	27 (19.8)	3.1 (2.2)	34.3 (25.3)
One Burn	42 (20.0)	4.9 (2.2)	56.2 (25.7)
Two Burns	40 (19.8)	4.4 (2.2)	47.0 (25.3)
Four Burns	42 (19.8)	5.0 (2.2)	55.7 (25.3)
Sub-canopy*			
Control	235 (65.5)	3.4 (1.3)	19.8 (5.3)
One Burn	30 (67.4)	0.96 (1.4)	6.1 (5.5)
Two Burns	25 (65.5)	0.6 (1.3)	3.7 (5.3)
Four Burns	5 (65.5)	0.2 (1.3)	2.0 (5.3)
Dominant overstory tree densities are back transformed values of square root.			
MAI = Mean Annual Increment			
The means used above are the Least Square means (LSM).			
LSM of parameters followed by the same letter are not significantly different at ≤ 0.1 .			
s and ns indicate significant and non-significant respectively.			
Standard errors of means ($\pm$) are in parentheses.			
C, Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns			
*Comparisons were not made for mid-canopy and sub-canopy trees because of insufficient data			
¹ Sub-canopy has approximately 25% red pine trees and the remaining are mainly red maple, sugar maple and jack pine, whereas, dominant overstory and mid-canopy layers have red pine trees only.			

There were no detectable treatment effects on basal area, volume or MAI of the dominant overstory trees, although values for the four-burn treatments were larger (Table

2.3). However, chi-square tests showed that there was some relationship between fire and the basal area of dominant overstory trees.

Unlike in the dominant overstory, sub-canopy tree density decreased due to burning and the decrease was more prominent as the number of burns increased. Even a single burn reduced the sub-canopy tree density drastically, agreeing with Van Wagner (1970) who stated that young recruitments cannot withstand even a low intensity fire. Consequently, the basal area, volume and MAI of sub-canopy trees in the unburned plots were all much higher than those in the burned plots and they decreased gradually as the frequency of burns increased. It seems that there was a lot of killing and scorching of sub-canopy trees due to the burning. Thus, there was an enhanced overall growth of dominant overstory red pine trees in the two- and four-burn plots due to the killing of competing bushy vegetation and the sub-canopy trees by repeated burnings. Further, the prescribed burning must have altered competition among the dominant overstory trees and mid-canopy trees, resulting in greater overall growth of mature trees. The removal of bushy vegetation and the sub-canopy trees create openings (extra-space) that reduced competition. The overall effect of burning on larger trees is similar to thinning from below, which helps to enhance diameter growth of fewer, larger and uniformly distributed trees that are retained during the process (Kozlowski and Peterson 1962, Lundgren 1981, Smith 1986, Nyland 1996, Burgess and Robinson 1998, Parker et al. 2001, Smith 2003). Such volume accumulation in large-sized trees makes them more valuable as well.

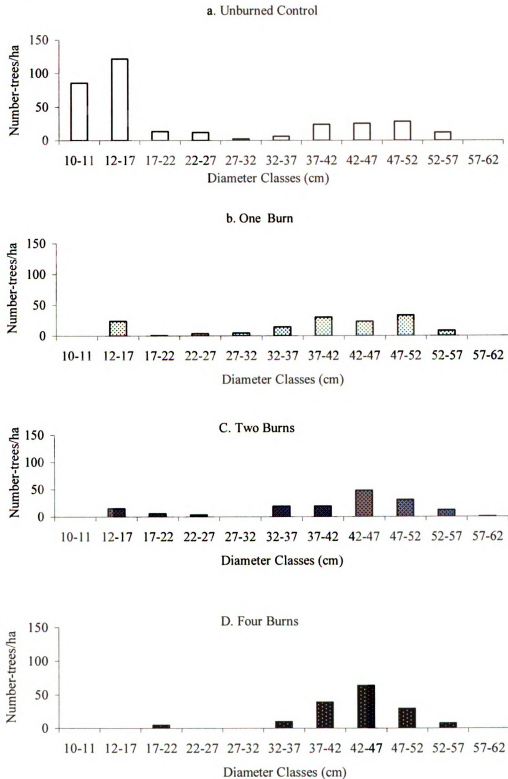
Higher growth in repeatedly burned plots must also be due to the increased availability of nutrients. Nutrients such as potassium, phosphorus, calcium and magnesium are released during burning and nitrogen fixation is enhanced. Release of nutrients is advantageous, as nitrogen and phosphorous are usually limiting in most forests (Vitousek 1985). Marks (1974) also suggested that immediately after disturbance nutrients are released from decomposition of organic matter and are in a state of under-utilization. Some of the nutrients such as nitrogen and potassium may even leach during the first few months of their release and get lost to the system (Ahlgren 1960, Deban and Conrad 1978, Wright 1976); however, they may become available to the trees (Ahlgren 1960) as competition gets reduced due to burning.

Sub-canopy trees were absent or very few in most of the burned plots and thus ANOVA could not be carried out (for example, the 10-11 cm diameter class was present only in the unburned control). No significant effect was found during binomial test of sub-canopy trees with others using Proc Glimmix in SAS. The reduction of species richness and abundance of the sub-canopy trees agrees with earlier studies (Dickmann 1993). Furthermore, there was no adverse effect of low intensity prescribed burnings on the overstory red pine trees as they are tolerant of low intensity understory fires and considered to be fire adapted because of their thick bark (VanWagner 1970). From the tree distribution pattern (Figure 2.2a-d), it seems that among the sub-canopy trees, the 22-27 and 27-32 cm classes might have escaped severe scorching during burning and grown into the mid-canopy stratum during the 10-16 year gap since the last fire. Sub-canopy trees in the 10-22 cm diameter class must have either been killed or severely scorched

during the low intensity burning. The species that were killed or affected mostly by the fire were saplings of red maple, sugar maple, jack pine and white pine. In unburned plots, overstory tree distribution was clearly a bimodal, but the distribution became increasingly unimodal as burning frequency increased (Figure 2.2; Appendix 2.3). In the repeatedly burned plots there were almost no sub-canopy trees at all and, thus, the mid-canopy and dominant overstory trees formed a unimodal or bell shaped structure. A similar shift from bimodal to unimodal was also observed for basal area, volumes and MAI of different diameter trees (Appendix 2.3), although the overall effect on them was not significantly different.

Therefore, my analysis reveals that low-intensity fires have a profound effect on tree density and species richness of sub-canopy trees. Repeated fires at an interval of two or five years essentially wiped out the sub-canopy and enhanced the diameter growth and yield of dominant overstory trees. The enhanced diameter growth was probably due to reduced competition and enhanced resource availability.

Figure 2.2: Average overstory tree density of different diameter size classes in a mature red pine plantation (n=3).

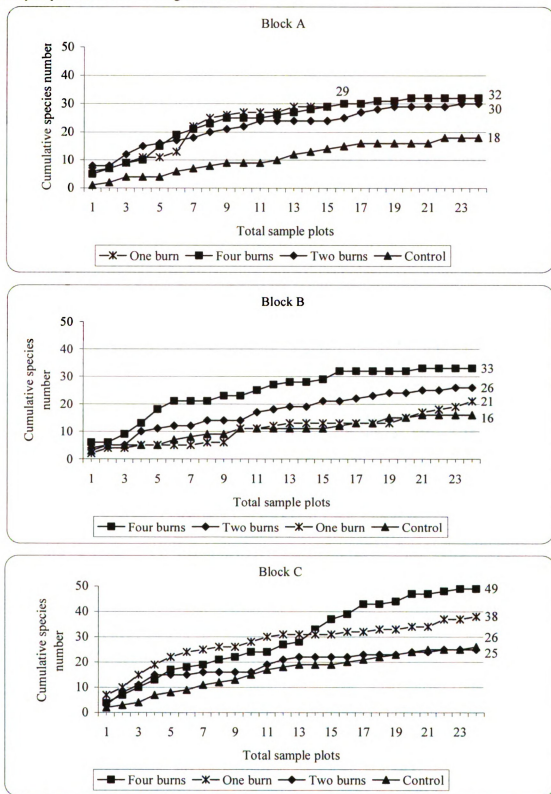


2.3.2 Ground vegetation

2.3.2.1 Species diversity

Species richness in all of the three blocks (A, B & C) tended to stabilize after sampling about 17 to 20 one-sq m quadrats out of a total of 24 quadrats sampled for each of the treatments in each block (Figure 2.3). Although not always universal, local species richness is positively correlated with the area over which they are recorded (Gaston and Lawton 1990). Total species richness of ground vegetation (all herbs, shrubs and trees <1.4 m in height) was always higher (32 to 49 species) in four-burn plots than in others. Conversely, the unburned plots always had the lowest species richness (16-26 species), except in block C where both unburned and two-burn plots were almost the same (25 species). Thus, burning increased total species richness which increased gradually from control to one- to two- to four-burn plots. All of the treatment plots in block C were higher in ground vegetation species richness than in other blocks (Figure 2.3). Among three blocks, block C had the lowest woody understory tree density and was thus more open; the openness, among other reasons, might have caused more herbaceous species to grow in this block than others. The openness in block C was also reported in earlier study by Henning and Dickmann (1996). In my study, generally, the species richness declined in all of the plots compared to Henning and Dickmann (1996), who measured the plots immediately after burning in 1991. However, both Henning and Dickmann (1996) and Neumann and Dickmann (2001) found species richness of herbaceous and woody ground flora (<1m in height) to be greater in periodically or once-burned areas compared to unburned areas.

Figure 2. 3: Species area curves by blocks for herbaceous ground vegetation in the 70-year-old red pine plantation under burning treatments.



Note: only 15 quadrats were used for one burn plot block A.

There were no significant effects of treatments on species richness on a per sample plot basis. However, the F-tests and chi-square tests showed significant treatment effect on Simpson's Index, Simpson's reciprocal and Shannon's Indices for ground vegetation (Table 2.4). Simpson's reciprocal and Shannon's indices were significantly lower in unburned controls whereas Simpson's diversity was significantly higher in unburned controls than in four-burn treatments. Simpson and Shannon's indices in unburned controls were all significantly different from one-burn treatments as well. These differences indicate that unburned controls had lower diversity of ground flora than four-times burned plots. The higher Simpson's diversity index in unburned controls

Table 2.4: Species diversity (per sample plot) of ground vegetation (<1.4 m height) in experimental red pine plantation, 2003 (n=12).

Treatments	Indices of Diversity				
	Species richness S	Simpson D	Simpsons' Reciprocal, 1/D	Shanon H'	Evenness ¹ J
Treatment Effects					
p>F-value	0.2544	0.0725	0.0983	0.081	...
p>Chi square	0.1524	0.0082	0.0189	0.0112	...
Control	2.3 a (0.9)	0.6 a (0.1)	2.3 a (0.3)	0.8 a (0.1)	0.7 (0.1)
One Burn	4.7 a (1.0)	0.4 b (0.1)	2.8 ab (0.3)	1.1 b (0.1)	0.7 (0.1)
Two Burn	6.7 a (0.9)	0.5 ab (0.1)	2.6 ab (0.3)	1.0 ab (0.1)	0.6 (0.1)
Four Burn	2.3 a (0.9)	0.4 b (0.1)	3.1 b (0.3)	1.2 b (0.1)	0.7 (0.1)
Contrasts					
Control vs All Burns		s	s	s	
C & 1B vs 2B & 4B		ns	ns	s	
1B vs 2B & 4B		ns	ns	ns	
F-tests p-values are given along with the chi-square values as treatment effects. C, Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns Values in the columns are the Least Square Means. Values with the same letter are not significantly different from one another at $p \leq 0.1$. s and ns signifies significance and non-significance, respectively, at $p \leq 0.1$. Standard error of means ($\pm$) are in parenthesis. ¹ Evenness index was not analyzed as it was not normal even after transformations					

suggests that the unburned plots had dominance (or abundance) of fewer species than in burned treatments. Evenness indices were not analyzed as they were not normal but their values were almost the same in all of the treatments. There was no difference in species diversity among the burned treatments. Unburned controls were significantly different than all of the burned plots combined for all of the Simpson, Simpsons's reciprocal and Shanon's indices. Unburned controls and one-burn treatments when contrasted with two- and four-burn plots were significantly different for Shanon Indices whereas similar contrasts for Simpson and Simpson's Reciprocal were not different. Control, one- and four-burn plots had high evenness (0.7), which means that 70% of the species had the same number of individuals in them. Two-burn plots had a somewhat lower evenness (0.6), suggesting that 60% of the species had the same number of individuals in them.

2.3.2.2 Percent cover

The response of ground vegetation to the burn treatments varied and depended on the type or form of the vegetation (tree, herb or shrub species). The overall average percent cover of ground vegetation increased from unburned control (27%) to burn (34 to 36 %) plots; although, there was no significant treatment effect (Tables 2.5 and 2.6). Similarly, Henning and Dickmann (1996) detected no differences in total percent cover in measurement of this same study in 1991. I categorized and analyzed the ground vegetation in two groups: 1) trees and 2) herbs and shrubs. A binomial test comparing the two groups shows that there was no significant difference between the proportions of

Table 2.5: Average cover and relative cover of trees (per sample plot) in descending order in the understory ground vegetation (<1.4 m) in a mature red pine plantation (n=279).

Species	Control			One Burn			Two Burns			Four Burns		
	Avg. Cov.	Rel. Cov.	Species	Avg. Cov.	Rel. Cov.	Species	Avg. Cov.	Rel. Cov.	Species	Avg. Cov.	Rel. Cov.	Species
<i>Pinus resinosa</i>	0.7	2.5	<i>Pinus resinosa</i>	1.4	3.8	<i>Acer rubrum</i>	2.5	7.0	<i>Pinus resinosa</i>	2.9	8.4	
<i>Amelanchier</i> sps	0.5	1.9	<i>Prunus virginiana</i>	1.3	3.5	<i>Acer saccharum</i>	0.9	2.6	<i>Prunus virginiana</i>	1.7	5.0	
<i>Fraxinus americana</i>	0.4	1.7	<i>Acer rubrum</i>	1.0	2.7	<i>Fraxinus americana</i>	0.5	1.5	<i>Prunus serotina</i>	1.3	3.7	
<i>Acer saccharum</i>	0.4	1.6	<i>Prunus serotina</i>	0.9	2.4	<i>Pinus virginiana</i>	0.5	1.4	<i>Acer rubrum</i>	0.6	1.9	
<i>Prunus virginiana</i>	0.4	1.5	<i>Fraxinus americana</i>	0.5	1.5	<i>Pinus resinosa</i>	0.3	0.9	<i>Acer saccharum</i>	0.4	1.3	
<i>Acer pensylvanicum</i>	0.2	0.9	<i>Acer saccharum</i>	0.4	1.1	<i>Ulmus americana</i>	0.2	0.6	<i>Quercus alba</i>	0.4	1.2	
<i>Tilia americana</i>	0.2	0.8	<i>Ostrya virginiana</i>	0.3	0.9	<i>Amelanchier</i> sps	0.2	0.5	<i>Acer pensylvanicum</i>	0.3	1.0	
<i>Acer rubrum</i>	0.2	0.7	<i>Quercus rubra</i>	0.2	0.7	<i>Prunus serotina</i>	0.2	0.5	<i>Amelanchier</i> sps	0.3	1.0	
			<i>Amelanchier</i> sps	0.2	0.5	<i>Acer pensylvanicum</i>	0.2	0.4				
Total Average cover	1.7 a (1.1)			3.5 a (1.7)			5.4 a (2.1)			3.1 a (1.6)		
Trees only	23.3 a (9.0)			36.3 a (10.47)			32.8 a (10.0)			29 a (9.6)		
Herbs, Shrubs & Trees												
Avg. Cov. = is the average cover; Rel. Cov. = relative cover												
The values for Total Average cover are the arcsin back transformed Least Square Mean (LSM) and the values with the same letter/s along the corresponding rows are not significantly different from one another at p<0.1.												
Standard error of means (±) are in parenthesis for totals only.												
Note: All species having average cover below 0.15 % have been omitted in this table whereas the total cover was calculated from all species												

trees or herbs and shrubs across the treatments. Further statistical analysis (F-tests) showed that there were no significant differences among treatments for either of the two groups (Tables 2.5 and 2.6). Nonetheless, for both groups the average coverage tended to be higher in all of the burned plots than in the control.

Thus, despite no significant differences, it is apparent that there are some distinct effects of burning on ground vegetation coverage. First, all the burn treatments had higher overall percent cover than the control. Second, the most frequently burned plots had lower overall species coverage than the least frequently burned plots. Third, burned plots had relatively more tree coverage than unburned plots, and among the burned plots the highest was in the two-burn plots and the lowest in the four-burn plots. Such increase in woody species in burned plots was suggested by Ahlgren (1960). Once-burned plots also were found to contain the greatest composition of woody ground flora than periodically burned plots by Neumann and Dickmann (2001) who measured the following season after burning. Fourth, herb and shrub coverage was the lowest in unburned control and generally decreased gradually as the number of burns increased. In central Appalachian forests, herbaceous species were found to play an important role in the recruitment, establishment and development of woody seedlings, which are always more as the stand becomes mature (Gilliam et al. 1995).

2.3.2.3 Tree species

Red pine, red maple, juneberry (*Amelanchier* spps.), choke cherry (*Prunus virginiana*), sugar maple, white ash and black cherry (*Prunus serotina*) were the seven

tree species that were most abundant in all of the treatments (Table 2.5). None of these species were statistically different in their coverage across treatments. However, red maple, black cherry, choke cherry, red pine and white ash showed substantial differences over control in their coverage after burning. Differences in post-fire establishment of red maple and black and choke cherry densities were also reported earlier (Henning and Dickmann 1996). These species were most favored by repeated fires in my site. Increase in these species improves wildlife habitat as forage and soft mast availability increases (Rouse 1988, Bender et al. 1997, Dickmann 1993). Black cherry had been found to densely seed in the openings after 1938 Hurricane in New England (Spurr 1956). The seeds of black and choke cherries can remain dormant in soil for long periods (Canham and Marks 1985) and they sprout vigorously from the root collar, which makes them aggressive post fire colonizers (Henning and Dickmann 1996). Despite the increase in tree species in the burned plots, the species coverage in our study was lower when compared with that of Henning and Dickmann (1996). Such a decrease of tree seedlings with time since disturbance was also found in Pennsylvania by Peterson and Pickett (1995). Likewise, in a boreal system in the Yukon in British Columbia, Canada, new regeneration occurred only in first five years after fire (Johnstone et al. 2004).

Red pine and red maple were the two most abundant tree species found in the ground vegetation for all the treatments. Red pine, a species considered to be shade intolerant, had the highest relative cover in four-burn plots, 334% higher than in the control. Apparently repeated burning prepared the seedbed by opening up space and exposing mineral soil, allowing seeds to germinate and seedlings to establish. Prescribed

burning improves seedbed for pines (Buell and Cantlon 1953). Red pine is highly adapted to such fire-prepared seed beds (Ahlgren 1976, VanWagner 1970). Also, since good seed years in red pine are every 5-10 years (VanWagner 1970, Rouse 1988), the four-burn plots provided a much longer window of optimum seedbed conditions. In repeatedly burned plots competing vegetation is killed or at least suppressed (Alban 1977, Metheven and Murray 1974, Van Wagner 1970) increasing the chance that red pine seedlings will become established. Henning and Dickmann (1996) found that red pine seedlings occurred less commonly in four-burn plots; however, they measured the plots immediately after the last burn. Therefore, my re-measurement showed that the 10-years gap since the last fire provided an appropriate environment for further recruitment of red pine seedlings in the ground vegetation layer. My results also show that shade tolerance is a relative concept; even in a shaded understory, an “intolerant” species like red pine can recruit if seedbeds are optimum and competition is suppressed.

Red maple, a moderately tolerant species with long lasting dormant seeds, had higher coverage in burned plots than in controls (Table 2.5). Sugar maple, the third highest ranking and a very shade tolerant species, showed highest coverage in the two-burn plots. Juneberry and bass wood coverage was less in the burned plots.

Red oak (*Quercus rubra*), black oak (*Quercus velutina*), white oak (*Quercus alba*), and American elm (*Ulmus americana*) were all absent in unburned plots but showed up in at least one burned plot. The relatively tolerant species American beech (*Fagus grandifolia*) and shade intolerant red oaks were very minor, with a relative cover

less than 0.1 percent. White pine and American elm also showed up in the burned plots even though their average coverage was very low. The sub-plot in block A which was burned once with an intense, hot fire causing complete overstory mortality were omitted from analysis in this study. They had mostly American elm, red raspberry and blackberry (*Rubus* spp.) in the ground vegetation layer.

2.3.2.4 Herbs and low shrubs

Bracken fern (*Pteridium aquilinum*), moss (*Sphagnum* spp.), wild-lily-of the valley (*Mianthemum canadense*), red raspberry, blackberry, sarsaparilla (*Aralia nudicaulis*) and grasses were the herbs and shrubs that occupied the top five positions or ranks based on their average percent cover and relative cover for all of the treatments (Table 2.6). Shrubs are killed back and are reduced in number and biomass (Little and Moore 1949). The overall species coverage was not significantly different across treatments and was consistent with the results of Henning and Dickmann (1996). However, in general, the herbaceous layer increases with increase in fire frequency (Buell and Cantlon 1953). There was an increase of herb and shrub species richness with a cover >0.15% from unburned (7) to once burned (11) to twice burned (12) to burned four times (14). Henning and Dickmann (1996) and Neumann and Dickmann (2001) also found that the species richness of herbaceous and woody ground flora (<1m in height) was greater in periodically or once-burned compared to unburned areas. Increased soil moisture and nutrients due to burning may stimulate some herbaceous plants, while increases in temperature in gaps that form may affect both herb growth and production (Collins et al. 1985). Chabot (1978) found variation in light to produce greatest change in growth of

strawberry plants as compared to other environmental factors. Growth of strawberries increased with an increase in light intensity, with a daily fluctuation of 10 °C, in gap edges. However, Bakelaar and Odum (1978), in an nutrient perturbation (added NPK fertilizer) experiment, found that a few species dominated others, which decreased in their importance value and thus decreased diversity or niche width.

The highest relative cover in my study was of bracken fern, which ranked top in all of the treatments except in the four-burn plots where wild-lily-of the valley had almost the same percent cover (Table 2.6). Bracken fern showed the least cover in the four-burn plots. Ahlgren (1960) found that bracken fern was more abundant in burned areas than in unburned areas. But it was found to have higher cover values in less frequently burned plots (Buell and Cantlon 1953). Bracken fern was found both in control and older burn plots but was highest in the most recent burns in New Jersey Pine Barrens (Boerner 1981). The rhizomes of bracken ferns are vigorous and sprout back after fire; its spores also germinate better in burned soil (Olinonen 1967a and 1967b in Henning and Dickmann 1996, Henning and Dickmann 1996). The decrease of bracken fern cover in my four-burn plots could be due to the repeated fires every two years or the increase in competing species. Besides killing unwanted vegetation, repeated fires also create more openness; bracken ferns are also susceptible to frost killing in more open conditions (Cody and Crompton 1975 in Abella et al., 2004).

Generally, the moss and lichen decreased as the frequency of burning increased, and this result is consistent with that of Henning and Dickmann (1996).

However, it is not consistent with findings of Buell and Cantlon (1953) in New Jersey pine region in which burning increased moss and lichen.

Rubus species coverage was negligible or absent in unburned control plots but higher in burned plots, especially those burned once or twice (Table 2.6). F-tests and Chi-square tests revealed that the number or count per square meter of red raspberry and red pine showed significant treatment effects (Table 2.7). Red raspberry was significantly lower in unburned controls than in four-burn plots, which were also higher than one-burn plots. Red pine counts were significantly higher in two-burn than in other burned and unburned plots. Both species in unburned control and one-burn treatments when contrasted with two- and four-burn treatments were significantly different. This shows that red pine regeneration is low in unburned controls and also four-burn plots because repeated fires every two years kill already regenerated and established red pine seedlings. Increases with burning were also observed by Henning & Dickmann (1996) for *Rubus* species in an earlier analysis of this study. Vigorous growth of *Rubus* spp. (after burning) in northeastern Minnesota was reported by Ahlgren (1960). The ability of *Rubus* seeds to remain in soil for a long period before they germinate (Marks 1974) and their sprouting and heavy fruiting after fire (Abrahamson 1984, Ahlgren 1979), were two main reasons for their success and increased growth in the burned sites. In northern hardwoods, pin cherry (*Prunus pensylvanicum*), a colonizing and exploitative species replaced *Rubus* spp. after three years from seeds that existed in the soil (Marks 1974; Bormann and Likens 1979).

Other species that were favored by fire were grasses, sarsaparilla and shinleaf, which did not show treatment effects. Stimulatory effects of burns on grass cover have also been reported by others (Buell and Cantlon 1953, Ahlgren 1979, White 1983, Howe 1995, Henning and Dickmann 1996). In tall prairies, vigorous clones of the dominant grass (*Andropogon gerardii*), dominant forb (*Solidago altissima*) and a less common forb (*Aster simplex*) increased steadily in all burn treatments (Howe 1995).

Common strawberry (*Fragaria virginiana*), fragrant bedstraw (*Galium triflorum*), wild lettuce (*Lactuca canadense*), shin leaf (*Pyrola elliptica*), common wood sorrel (*Rumex acetosella*), lady's slipper (*Cypripedium* spp.), daisy fleabane (*Erigeron* spp.), cow wheat (*Melampyrum lineare*), wild or prickly gooseberry (*Ribes cynosbatti*), starflower (*Trientalis borealis*), *Achillea millefolium*, carrot (*Daucus carota*), Mushroom, shin leaf (*Pyrola rotundifolia*), *Lonicera*, and wild rose (*Rosa* spp) were very scarce or absent in unburned controls but found in all or at least in one or more types of burns. Common dandelion (*Taraxacum officinale*), *Solidago* spps, *Aster sagittifolius*, and *Chenopodium vulgare* were among the other species found in very small numbers.

Species that were present only in the four times (repeatedly) burned plots were staghorn sumac (*Rhus typhina*), *Solidago* spps., blueberry (*Vaccinium* spps), bunch berry (*Cornus canadensis*), pin or fire cherry (*Prunus pensylvanica*) and clammy cudweed (*Gnaphalium macounii* Greene). If disturbance frequency or intensity is high, communities may have greater numbers of fire adapted species. Without disturbances

Table 2.7: Analysis of the number of two ground vegetation species per treatment plot (m^2), $n=12$.

Species	Overall treatment effect p>Chi-sq	F-test p-value	Control		One Burn		Two Burns		Four Burns	
			Mean count	CL Lower Upper	Mean count	CL Lower Upper	Mean count	CL Lower Upper	Mean count	CL Lower Upper
Red raspberry	0.012	0.0831	1.1 a	0.66538 1.9327	1.3 ab	0.8568 2.488	1.4 abc	0.94 2.729	2.3 c	1.819 5.284
Red pine	0.0113	0.0813	1.4 a	1.36793 0.794	1.3 a	0.7754 2.301	1.8 b	1.529 3.097	1.4 a	0.811 2.408
Contrasts										
Red raspberry			Red pine							
Control vs All Burns			ns		ns					
C & 1B vs 2B & 4B			s		s					
1B vs 2B & 4B			ns		s					
CL= Confidence Limits										
The values are the Least Square Means (LSM) and the Confidence limits are the log-back transformed values.										
LSM were not significantly different at $p \leq 0.1$										
s and ns signifies significance and non-significance, respectively, at $p \leq 0.1$.										
Control: 1B, One Burn; 2B, Two Burns; 4B, Four Burns										

these species decline. For example, in northern hardwoods, large scale disturbance dependent species like pin cherry may be locally extirpated except for seeds in soil (Marks 1974).

Partridge berry (*Mitchelia repens*) was scarce and found only in unburned control and absent in other burn treatments. Moss, false Solomon seal (*Smilacina* spp.), wild fern (*Dryopteris carthusiana*) and lycopodium generally decreased with burning. Both moss and lichen were found to decrease in burned plots in their average and relative percent cover and a similar decrease for these species was reported by Henning and Dickmann (1996).

2.3.3 Understory trees (>1.4 m height and < 10 cm dbh)

The understory trees were mainly composed of red pine, red maple, beech, black cherry, white ash, juneberry and sugar maple (relative frequencies 47, 16, 9, 9, 4, 3 and 3 percent). Remaining species – choke cherry, eastern hophornbeam (*Ostrya virginiana*, white pines, and others were – each were less than three percent of total. The binomial comparison of proportions carried out between two groups, i.e., each of the understory woody species versus the remaining species grouped together, did not show any significant treatment effects.

2.3.3.1 Understory density

The density of understory woody species of all size classes combined together ranged from 2738 to 6377 trees ha⁻¹ and the lowest was in unburned and the highest in

two-burn plots (Table 2.8). There was no significant treatment effect on the overall stem density of understory woody vegetation; however, there were some remarkable increases in densities across different burns. For example, the overall density for two, one and four-burn plots increased over control by about 133, 124 and 61%, respectively. The increase in the overall density of understory woody vegetation in all of the burn plots was due to post-fire regeneration and establishment, and the magnitude of this effect varied with the number of burns. The lack of fire for a long period (10 to 18 years) allowed seeds to germinate and root suckers and stump sprouts to grow. The changes brought about in the understory woody species composition by burning are visually prominent among the treatments (Figure 2.4). Similarly, understory trees also increased by 52% after burning in loblolly pine in the Piedmont, North Carolina (Oosting 1944).

Understory tree density was negatively correlated with parameters such as overstory tree density ($n = 93$; $r = -0.2314$; $p = 0.0256$); basal area ($n = 93$; $r = -0.3614$; $p = 0.0004$) and volume and MAI ($n = 93$; $r = -0.28605$; $p = 0.0053$). A high overstory tree density certainly will cause a decrease in understory woody density, but fire, especially if repeated, has a much more profound negative effect on the woody understory.

2.3.3.2 Diameter and age

Treatments had a significant effect on the average diameter at breast height (dbh) of understory woody trees ($>1.4\text{m}$ height and $< 10\text{cm}$ dbh) (Table 2.9). Average dbh ranged from 0.9 to 3.0 cm, with the lowest in four-burn plots and the highest in the unburned plots. All of the burned plots had significantly lower average diameter than

Table 2.8: Woody understory stem density (trees ha⁻¹) and relative density in descending order under different size classes

Treatment	Sps Code	0-4 cm	% of total	Sps Code	4.1-6 cm	% of total	Sps Code	6.1-10 cm	% of total	Sps Code	Total	% of total
Control	RP	687	33	RM	158	49	RM	200	60	RM	746	27
	RM	388	19	SM	47	14	SM	47	14	RP	704	26
	SM	267	13	AB	42	13	WA	30	9	SM	358	13
	BC	168	8	WA	35	10	HH	20	6	AB	208	8
	AB	151	7	WP	25	8	AB	17	5	WA	179	7
	WA	116	6	RP	12	4	WP	8	3	BC	167	6
	AM	104	5	HH	4	1	RP	4	1	AM	104	4
	CC	72	3	Oaks	4	1	Others	4	1	CC	71	3
	Others	44	2	BC	0	0	Oaks	4	1	WP	71	3
	WP	37	2	AM	0	0	BC	0	0	HH	58	2
	HH	35	2	CC	0	0	AM	0	0	Others	50	2
	Oaks	12	1	Others	0	0	CC	0	0	Oaks	21	1
Total		2080	(±577.7)		325	(±38.8)		334	(±37.1)		2738	
One Burn	RP	2868	48	RP	48	30	BC	19	50	RP	2915	48
	RM	795	13	AB	38	24	WA	10	25	RM	838	14
	AB	714	12	RM	38	24	RM	5	13	AB	753	12
	BC	477	8	BC	14	9	SM	5	13	BC	510	8
	WA	324	5	Oaks	10	6	AB	0	0	WA	338	6
	AM	296	5	CC	5	3	AM	0	0	AM	295	5
	CC	200	3	WA	5	3	CC	0	0	CC	205	3
	Others	114	2	AM	0	0	HH	0	0	Others	114	2
	SM	86	1	HH	0	0	Oaks	0	0	SM	91	1
	Oaks	47	1	Others	0	0	Others	0	0	Oaks	57	1
	HH	20	0	SM	0	0	RP	0	0	HH	19	0
	WP	0	0	WP	0	0	WP	0	0	WP	0	0
Total		5940	(±632.8)		157	(±38.8)		38	(±38.8)		6135	
Two Burns	RP	3418	54	Oaks	21	45	HH	8	40	RP	3430	54
	RM	884	14	Others	8	18	Oaks	4	20	RM	884	14
	AB	604	10	RP	8	18	RP	4	20	AB	604	9
	BC	588	9	HH	4	9	WA	4	20	BC	588	9
	AM	154	2	WA	4	9	AB	0	0	Oaks	171	3
	WA	150	2	AB	0	0	AM	0	0	WA	158	2
	Oaks	146	2	AM	0	0	BC	0	0	AM	154	2
	SM	104	2	BC	0	0	CC	0	0	Others	154	2
	Others	88	1	CC	0	0	Others	0	0	SM	104	2
	CC	46	1	RM	0	0	RM	0	0	HH	58	1
	HH	46	1	SM	0	0	SM	0	0	CC	46	1
	WP	25	0	WP	0	0	WP	0	0	WP	25	0
Total		6310	(±577.7)		46	(±38.8)		20	(±37.3)		6377	
Four Burns	RP	2305	53	Oaks	21	50	HH	4	50	RP	2322	53
	RM	709	16	RP	17	40	WA	4	50	RM	709	16
	BC	471	11	HH	4	10	AB	0	0	BC	471	11
	AB	217	5	AB	0	0	AM	0	0	AB	217	5
	HH	113	3	AM	0	0	BC	0	0	HH	121	3
	Others	158	4	BC	0	0	CC	0	0	Others	158	4
	AM	96	2	CC	0	0	Oaks	0	0	WA	100	2
	WA	96	2	Others	0	0	Others	0	0	AM	96	2
	CC	75	2	RM	0	0	RM	0	0	Oaks	83	2
	Oaks	63	1	SM	0	0	RP	0	0	CC	75	2
	SM	33	1	WA	0	0	SM	0	0	SM	33	1
	WP	17	0	WP	0	0	WP	0	0	WP	17	0
Total		4352	(±632.8)		42	(±38.8)		7	(±37.3)		4402	

Standard errors of mean are given in parenthesis (±).

Note: The common and the Latin names of the species codes are explained in Appendix-2.1

Figure 2.4: Pronounced variation in the understory in unburned and one-, two- and four-burned treatments in a 70-year-old red pine plantation, summer 2001 (photos by D.I. Dickmann).

a. Unburned control



b. One burn, 1985

(no burn for the past 16 years)



c. Two burns, 1985-1990

(no burn for the past 11 years)



d. Four burns, 1985-1991

(no burn for the past 10 years)



the control; however, there were no significant differences among different burns in their average diameters. Also, when contrasted unburned control versus burned plots, control and one-burn versus repeatedly burned plots, and one-burn versus repeatedly burned plots were all significantly different. The overall analysis revealed that multiple burning lowered the average diameter of understory woody stems significantly. The mean understory woody diameter was positively correlated with the overstory tree density ($n = 93$; $r = 0.4295$; $p = 0.0001$) because the advanced large-sized understory woody regeneration (seedlings and saplings) in the unburned plots were killed by the fires in the burned plots. However, the average understory woody diameter was negatively correlated with other parameters of the overstory trees: heights ($n = 93$; $r = -0.2568$; $p = 0.013$), mean diameter ($n = 93$; $r = -0.21825$; $p = 0.0356$), and basal area ($n = 93$; $r = -0.23027$; $p = 0.0264$). Also the new post-fire regeneration was very young and small in average diameter.

Treatment effects were significant only on the average diameter of beech and red maple (Table 2.9); the more frequent the fires, the smaller the diameter of those two species. These two species, which comprise most of the large-size class understory trees, were reduced the most in the repeatedly (two and four) burned plots. DBH of both red maple and American beech in one-burn plots also were significantly different from four-burned plots. In beech DBH was significantly higher in one-burn than in two-burn plots. In case of red maple, DBH in one-burn treatments was significantly lower than in unburned control. Contrast of unburned control versus burn plots, one-burn and unburned

Table 2.9: Mean Diameter at breast height (dbh) of understory woody vegetation in experimental red pine plantation, 2003. (n=93; All species df=6, Beech df=5.81, Red maple df=8.01).

	All species	Beech	Red Maple	Red pine
	dbh	dbh	dbh	dbh
	cm	cm	cm	cm
F-test, p-value	0.0142	0.0257	0.0069	ns
Chi-square value	0.0002	0.0002	0.0001	ns
Treatments				
Control	3.0 a (0.6)	4.1 a (0.4)	5.3 a (0.6)	0.33 (0.13)
One Burn	1.2 b (0.2)	4.3 a (0.4)	3.8 b (0.4)	0.15 (0.1)
Two Burns	1.7 b (0.3)	3.5 b (0.3)	3.0 bc (0.3)	0.26 (0.1)
Four Burns	0.9 b (0.2)	3.0 b (0.3)	2.8 c (0.3)	0.21 (0.1)
Contrast				
Control vs All Burns	s	s	s	...
4B & 2B vs 1B & Control	s	s	s	...
1B vs 2B & 4B	s	s	s	...
dbh is back transformed values of Natural log, for which the Least Square Means (LSM) are given above, except for red pine.				
Values with the same letter/s not significantly different from one another at $p \leq 0.1$.				
s and ns indicate significance and non-significance, respectively, at $p \leq 0.1$.				
Standard errors of means ($\pm$) are in parenthesis.				
1B, 2B & 4B are one-, two- & four-burn treatments				
Differences among treatments for average diameter of other species were non-significant				

plots versus the two- and four-burn plots together, and one- with two- and four-burn treatments together showed significant differences for both species. This also indicates that two- and four-burn lower DBH more than one-burn. There were differences seen in other species across the treatments also, but they were not significantly different.

The average age of understory woody vegetation, determined by counting rings of red pine, red maple, black cherry, white ash and beech cross-sections was 13.0 years (S.E. $\pm$ 2.69) in the burned plots and 15.0 years (S.E. $\pm$ 5.3) in the unburned plots, which

shows that the new regeneration in the burned plots was established right after the fire i.e., within the past 10 to 18 years and had smaller average diameter than in control (Table 2.10). Average diameter and age of all the species were correlated ($n = 218$; $r = 0.6767$; $p = 0.0001$). Only beech was >18 years in unburned controls and most variable in age among others. All of the species were older and of larger-diameter in unburned controls than in burned treatments. Of the total of 218 cross sections studied, 192 were of 0-4 cm and the remaining 25 of 4.1 to 6.0 cm and only one of 6.1-10 cm dbh.

2.3.3.3 Density by size class

Understory trees of different diameter classes showed different responses to the prescribed burns (Table 2.8, Figures 2.5a and b). The frequency of the 0-4, 4.1-6.0 and 6.1-10 cm diameter classes were 95, 3 and 2%, respectively. Seedlings up to 4 cm dbh were extremely dense in all of the plots compared to the other two larger diameter classes (Figure 2.5), with unburned plots having the lowest and two-burn plots having the highest density. In contrast, understory tree density of 4.1 to 6.0 cm and 6.1 to 10 cm diameter saplings decreased sharply as the frequency of burns increased (Table 2.8; Figure 2.5b).

The largest (6.1 to 10 cm) diameter understory trees had the lowest density and the highest decrease over control in the four-burn plots. As the response of different diameter seedlings to fire was different, for convenience, I created several new groups of diameter classes and analyzed binomial proportions. The understory woody stems were divided into two groups: large diameter (6.1-10 cm) and remaining others (0-6.0 cm); the second grouping is 2.1 to 10 cm and 0-2.0 cm. The frequency analysis showed that the

Table 2.10: Age and diameter of understory woody seedlings in experimental red pine plantation, 2004

Species	Treatments	Number of cross- sections	Mean ($\pm$ Standard Error)				Correlation	
			DBH	$\pm$ SE	Age years	$\pm$ SE	Age by DBH p-value < r	Correlation Coefficient r
Beech	Control	12	1.28	0.7	18.6	7	0.0004	0.85
	All burns	41	0.85	0.5	14.2	2.9	0.0010	0.71
Black cherry	Control	9	0.53	0.3	13.55	4.8	0.0260	0.54
	All burns	25	0.52	0.3	11.7	1.8	0.0060	0.53
Red maple	Control	16	0.97	0.6	13.93	2.2	0.0010	0.85
	All burns	36	0.74	0.5	13.8	3	0.0001	0.88
Red pine	Control	14	0.91	0.7	14.8	4.2	0.0009	0.78
	All burns	47	1	0.6	12.13	2.2	0.0001	0.61
ALL Total	Control	58	0.92	0.7	15.1	5.3	0.0001	0.78
	All burns	160	0.79	0.5	13	2.7	0.0001	0.62

Note: Species (ALL Total) also includes white ash which had a total of only 18 cross-sections.

large-sized (6.1-10 cm) understory trees had a relative density of 2% whereas the smaller seedlings (0-6.0 cm) were 98% of the total. Binomial comparisons for the proportions of both of the above size classes were tested using General Linear Mixed Model (Proc GLIMMIX). There was a significant treatment effect ($n = 4530$; $df = 6$; $p = 0.0157$) on the proportions of the large (6.1 to 10 cm) and others. Also, the control was significantly different from all of the burns; however, there were no proportional differences among any of the three different burns. Another similar binomial test between the small (0-2.0 cm) and others (2.1-10.0 cm) also showed that there was a significant treatment effect of burning on the proportions of the diameter classes ($n = 4530$; $df = 6$; $p = 0.0383$); however, no significant differences were detected among any of the four treatments. Further analyses also showed that the differences between unburned control and four-burn plots for both large and small understory trees were greater than one- and both

Figure 2.5a : Density of understory woody vegetation in the 0-4 cm size class under different burn treatments with standard error bars (n=93)

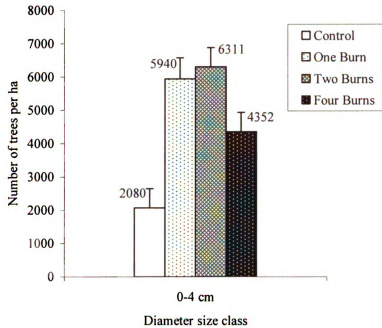
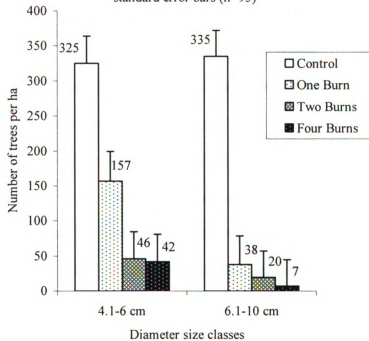


Figure 2.5b: Density of understory woody vegetation in two size classes under different burn treatments with standard error bars (n=93)



frequently burned plots and two and four-burn plots. Thus, both binomial tests suggest that the burning in the red pine stand substantially altered the structure of the woody understory that was evident even 10 to 18 years after the prescribed fires.

Since the above proportions were significant, further analysis was done. The chi-square tests showed significant effects of burning on small (0-2 cm), medium (2.1-6.0 cm) and large (6.1-10 cm) size classes of understory trees (Table 2.11). However, Mixed Linear Model (F-tests) for plot level means showed significant treatment effects only on the density of small (0-0.2 cm) and large diameter (6.1-10 cm) but not the medium understory trees. Small diameter understory trees were significantly lower in unburned controls and four-burn than in one- and two-burn treatments. Further, the contrast comparing the control against all of the burns was significantly different for density of small-sized understory trees. Unlike small-sized understory trees, large-sized understory trees in unburned controls were significantly higher than in burned treatments; however, one-burn and two-burns and also two-burns and four-burns were not significantly different from each other. Further, the contrasts comparing the unburned control against all of the burns, one-burn and unburned controls against two- and four-burn treatments as well as one-burn plots against two- and four-burn plots were significantly different. These analyses clearly show that unburned controls had the highest density of large-diameter understory trees than the burned treatments, the size goes on decreasing as the number of burns increases and such effects remain in the forest one to two decades after low-intensity prescribed burns.

Table 2.11: Woody understorey species density (trees ha⁻¹) of different diameter size classes under different burning treatments, 2003 (n=12).

Diameter Classes cm	Treatment effect p>F-value Chi-sq	Control						One Burn						Two Burns						Four Burns					
		CL			CL			CL			CL			CL			CL			CL			CL		
		Density trees ha ⁻¹	Lower	Upper	Density trees ha ⁻¹	Lower	Upper	Density trees ha ⁻¹	Lower	Upper	Density trees ha ⁻¹	Lower	Upper	Density trees ha ⁻¹	Lower	Upper	Density trees ha ⁻¹	Lower	Upper	Density trees ha ⁻¹	Lower	Upper	Density trees ha ⁻¹	Lower	Upper
Small (0-2.0)	0.0406 0.0020	1286 a	318	5201	4573 b	1131	18498	4665 b	1159	18970	1825 a	451	7382												
Medium (2.1-6.0)	0.4768 0.4189	746 a	234	1545	759 a	242	1565	466 a	92	1128	265 a	18	799												
Large (6.1-10.0)	0.0134 0.0001	259 a	63	1073	39 b	10	163	10 bc	2	42	6 c	2	26												
Contrasts		Small		Medium		Large																			
All burns vs Control	s	ns		s		s																			
1B & Control vs 2B & 4B	ns	ns		ns		s																			
1B vs 2B & 4B	ns	ns		ns		s																			

CL=Confidence limits, lower and upper are given after the means for each treatment.

The density are the Least Square Means (LSM). Density and the Confidence limits are the back transformed values of natural log, except for Medium diameter class which are the backtransformed values of square root.

The values across rows followed by same letter are not significantly different from one another at $p \leq 0.1$.

An, s denotes significant and ns denotes non-significant at $p \leq 0.1$.

1B, One Burn; 2B, Two Burns; 4B, Four Burns

Killing of stems smaller than 10 cm diameter by low intensity burns has also been reported by Niering et al. (1970) and Hodgkins (1958). A decrease in density of large understory trees (6 to 10 cm) was reported by Henning and Dickmann (1996), who surveyed in the growing season immediately after the prescribed burns. However, recruitment of small-diameter seedlings was enhanced in all the burned plots. In a study of a red and white pine forest in Michigan, 0 to 6 cm diameter seedlings and saplings decreased due to burning (Neumann and Dickmann, 2001), but the sampling was done right after the fire.

One of the obvious reasons for a low density of seedlings in the absence of fire is that the seedbed was not suitable for the germination and establishment of new seedlings since the understory low herb and shrub canopy, and thick duff and litter layer in the forest floor prevented seeds from reaching the mineral soil (Figure 2.6a and b). The reduction in depth of organic matter by fire increases establishment directly because the seedlings are near to a more constant water supply and more decomposed organic layers and mineral soil (Thomas and Wein 1985). In my study, two-burn plots had the highest frequency and density of seedlings; thus the preparation of seedbed must have been much better than in unburned control and one-burn plots (Figure 2.6a and b). In the four-burn plots newly recruited seedlings were killed again and again, suppressing their establishment and development until after the last burn. However, repeated burns must have consumed more duff and litter, allowing more seeds to reach the soil and delayed the growth of understory shrubs. The exposed mineral soil (Figure 2.6a) favored red pine more than its associates (Table 2.8, Figure 2.4a to d), because it is more adapted to

Figure 2.6a: A plot just after its second burning (two-year interval), with an unburned plot in the background. Most of the soil organic layer has been consumed, leaving a layer of ash over mineral soil, and all understory vegetation has been killed back to ground level (photo by D.I. Dickmann).



Figure 2.6b: A plot after the first fire in 1985, which was relatively "cool." A patchy mosaic of unburned forest floor and ash-covered mineral soil was created. This plot was burned again with a hotter fire five years later (photo by D.I. Dickmann).



post-fire establishment. Average age (13 years) of 0 to 6 cm seedlings of red pine and other important species from the burned plots (Table 10) also suggest that the new regeneration was from seeds that germinated and established right after the fires. In a long-term study in a boreal forest in Yukon, British Columbia and in interior Alaska, recruitment of dominant tree species were highest in the first five years (Johnstone et al. 2004).

The introduction of fire has brought changes in the overall structure and composition of the forest I studied. Burned plots have basically two layers; one of overstory canopy red pine trees and the other an understory of small-diameter woody vegetation. Additionally, there is a low ground vegetation layer at the forest floor. The burned stands in due course of time would develop a different composition and structure than the unburned plots (see Chapter 3). The extent of changes that occur in the forest structure and composition depends on the number of burns carried out, the burn intervals, and the time period lapsed after the last burns. Since large hardwoods such as red maple, sugar maple and basswood were eliminated by fire, the repeatedly burned forest will develop into two layers: an overstory of red pine trees without any hardwood species and a lower, red pine - dominated understory layer with other hardwood species mixed in. Once-burned plots also will have red pine - dominated understory; however, it will have some sub-canopy overstory trees of red maple, sugar maple, beech, and white ash. The species densities measured a few years after fire and two to three decades later show that future stand structure can be predicted from observations made early in succession and

that early post-fire colonizers usually will dominate the canopy of mature stands (Johnstone et al. 2004).

2.3.3.4 Species diversity and abundance

The species area curves (SPA) shows that the number of species in all of the blocks tended to stabilize after sampling about five 100 sq m plots out of a total of 8 (Figure 2.7). Statistical analysis of the species richness and diversity indices revealed that there was no significant overall treatment effect on species richness and diversity indices of the understory trees (Table 2.12). However, once and twice-burned plots tended towards highest species richness than four-burn and unburned plots. A similar significant decrease of species richness in four-burn and an increased species richness in two-burn plots were reported earlier by Henning and Dickmann (1996). Simpson's Index was the highest in four-burn plots and lowest in control and one-burn, which indicated that the four-burn plots showed dominance of fewer species, in this case red pine. This finding is very important if the goal of management is the establishment and growth of red pine trees. The Simpson's Reciprocal ($1/D$), Shannon and Evenness indices indicate that the diversity of species tended to be highest in control and once burned plots and the lowest in the four-burn plots.

The frequency for all size classes of woody understory species increased due to burning and was the highest (34 %) in two-burn plots and the lowest (14%) in control. Among the different size classes, the 0-4 cm size class was most frequent, with the red

Figure 2.7: Species area curves by block for understory woody vegetation in a mature red pine plantation under burning treatments.

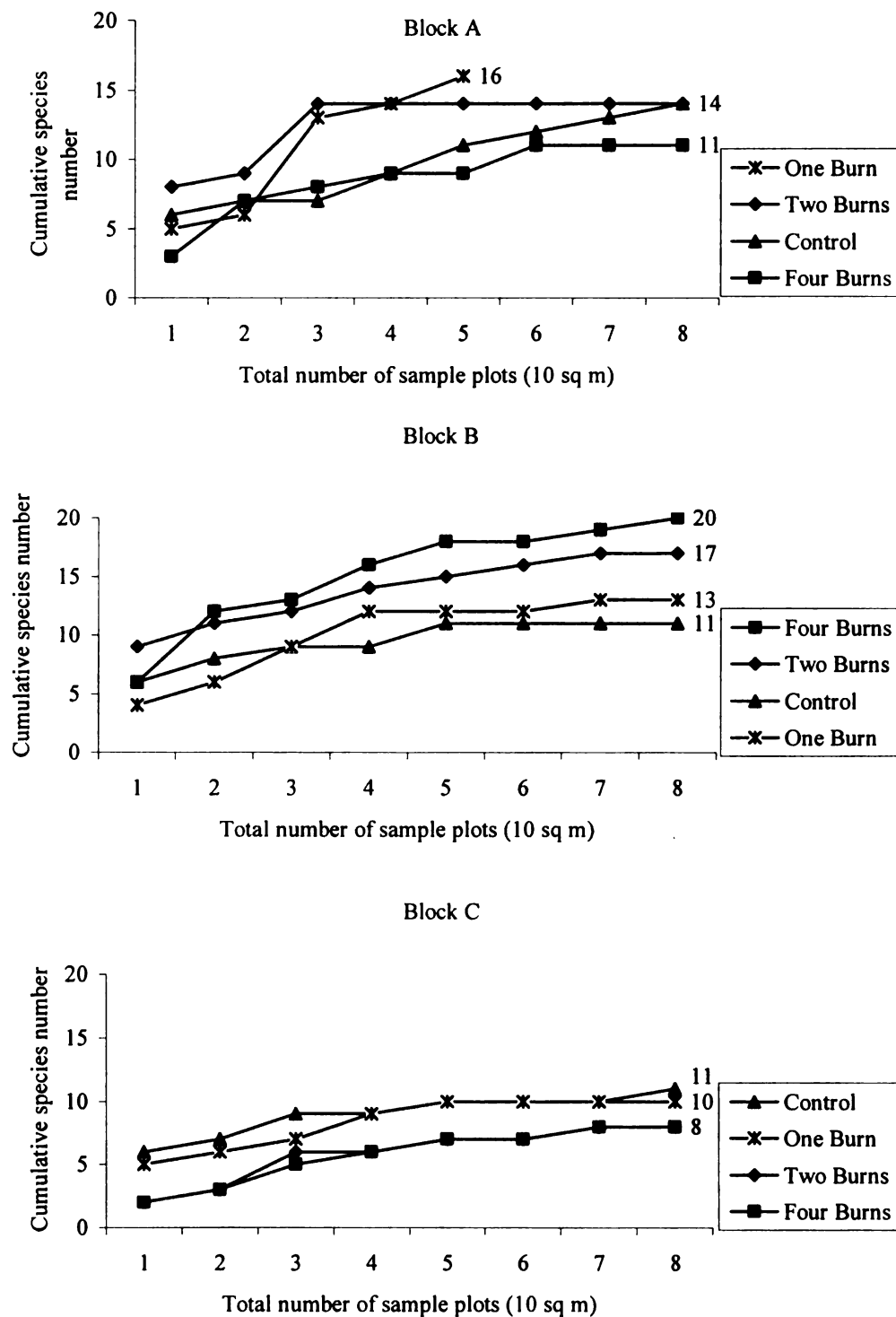


Table 2.12: Indices of species diversity of understory woody vegetation in experimental red pine plantation, 2003. (n=12)

	Species richness S	Simpson D	Simpsons' Reciprocal 1/D	Shanon H'	Evenness J
Treatments	ns	ns	ns	ns	...
Control	5.4 a (1.2)	0.4 a (0.07)	3.2 a (0.5)	1.2 a (0.17)	0.7 (0.08)
OneBurn	6.1 a (1.2)	0.4 a (0.07)	3.1 a (0.5)	1.2 a (0.18)	0.7 (0.09)
TwoBurn	6.0 a (1.2)	0.5 a (0.07)	2.8 a (0.5)	1.1 a (0.17)	0.6 (0.08)
FourBurn	4.4 a (1.2)	0.6 a (0.07)	2.0 a (0.5)	0.8 a (0.17)	0.6 (0.08)
Species diversity under Simpson column are backtransformed natural log vlaues. For others, the Least Square Means (LSM) are given and the values with the same letters are not significantly different from one another at $p \leq 0.1$. ns signifies non-significance, respectively, at $p \leq 0.1$. Standard errors of means ($\pm$) are in parenthesis. Evenness index was not analyzed as it was not normal even after transformations					

pine (49%) the most frequent species followed by red maple, beech and black cherry. However, red maple was the highest occurring species for both the 4.1-6 cm and 6.1-10 cm classes with 35% and 52% relative frequency, respectively. For each of the above diameter classes beech, choke cherry, black cherry, non-commercial trees, and oaks were below 5% of total. There was no significant treatment effect (F-test) on any of the major species density. Also binomial comparison of proportions among each of the important species and the remaining species were not different across the treatments and, therefore, only important species will be discussed.

There was a remarkable overall increase of understory red pine density in one-, two- and four-burn plots—314, 387 and 230 %, respectively, over unburned controls,

mainly in the 0-4 cm class (Table 2.8). The importance value (IV) of red pine was the highest in two-burn plots and the lowest in unburned controls (Table 2.13). Red pine obviously will be dominant in the canopy of future stands, especially after burning, but few conifers—with the exception of an occasional white pine—will accompany it.

Red maple was second to red pine in density and relative density in burned plots (Tables 2.8) but its IV was highest in unburned control (Table 2.13). Relative density of red maple was remarkably similar in all of the burned plots. Vigorous sprouting and enhanced seed germination on the exposed mineral soil after burning allowed red maple to successfully recruit into the 0-4 cm class following fire (Table 2.8). The canopy of future stands also will be occupied by red maple. Other, hardwood tree species with significant densities and IV in burned plots were beech, black cherry and white ash. Sugar maple, on the other hand, was much reduced following burning. Very few hardwoods survived burning to recruit into the sapling and small pole classes (4.1 – 10 cm dbh), especially if the burning was repeated (Table 2.8).

Table 2.13: Importance Value (IV) of the understory woody species.

Treatments	Species*											
	AB	AM	BC	CC	HH	Oaks	Others	RM	RP	SM	WA	WP
Control	33	14	14	11	17	6	14	79	44	31	31	12
One Burn	54	17	41	22	3	7	17	52	52	12	29	0
Two Burns	44	12	42	12	8	23	13	29	92	6	14	4
Four Burns	27	12	58	15	21	16	10	20	68	11	31	1
IV=Importance Value (sum of relative frequencies, density and basal area).												
*AB=American beech, AM=Amalanchier, BC=black cherry, CC=choke cherry, HH=Hophornbeam, RM=red maple, Others=non-commercial species, RP=red pine, SM=sugar maple, WA=white ash, WP=white pine.												

2.4 Conclusion

The effects of prescribed fires conducted during 1985 to 1991 were still evident in 2003, even after such a long gap. Fires affected differently the overstory, mid- and sub-canopy trees, understory woody seedlings and saplings, and herbaceous ground vegetation. Such differential effects on size classes and species as well as dense recruitment after fire create distinctive stand structures (Peet and Christensen 1987). Henning and Dickmann (1996) and Neumann and Dickmann (2001) reported that there was no adverse effect on mature red pine overstory trees when measured immediately after fire. In my study, overstory tree density was affected, where as there was no effect on other features of overstory red pine trees. Also, the structure and composition beneath the red pines, from the sub-canopy to the ground layer, was altered by fire, and the alteration was substantial after repeated burning. In the southern Appalachians, Philips and Shure (1990) also found a considerable shifting in tree composition following fire. The effects of fire as a disturbance agent vary at different levels because of the hierarchical organization and patchy nature of ecosystems (Pickett and White 1985, Rykiel 1985, Holling 1992, Wu and Levin 1994). Whereas the response to burning shown by different species and their size classes varied in my study and depended on the number of low-intensity burns applied, the burn intervals, and the number of growing seasons passed since the last fire, recovery was nonetheless rapid. In fact, forests or biological communities are always recovering from the last disturbances (Spurr 1956, Reice 1994).

Prescribed low-intensity burns, particularly if repeated, reduced the sub-canopy tree density sharply and wiped out most sub-canopy conifer and hardwood trees.

However, post-fire recruitment of most species—especially red pine, red maple, beech and black cherry—did occur via seedlings or sprouts. Consequently, these burnings altered the intra-specific competition among the mid-canopy and dominant overstory red pine trees. The fires eventually must have also changed the availability of nutrients and other resources reaching the remaining mid-canopy and large-sized overstory trees. Lunt (1950 in Dickmann 1993) found red pine to increase in height and volume after 20 years of annual burning in Connecticut, and such increase was thought to be due to release of phosphorous and exchangeable calcium and increased pH due to burning. Disturbances release nutrients tied in pre-disturbed vegetation and also those utilized by vegetation before disturbance (Bormann and Likens 1979). Usually, phosphorous, calcium and potassium are released after fire and utilized quickly after their release by existing or new vegetation (Alban 1977, Boerner 1988). Vitousek (1985) suggested that such nutrient availability declines after the canopy closes.

Size of openings created by fire also affects micro-environment, species composition and increases productivity (Philips and Sure 1990), and if the openings become larger, productivity increases further. Three to four times increases in net primary productivity of above ground biomass in larger gaps were shown by Philips and Shure (1990). Ahlgren (1960) reported the increase of early plant invaders or pioneers in burned areas for several years, which declines as the time from burning increases. The nutrients leached from the system after burning gets trapped by larger mature trees. Resources in disturbed gaps are under-utilized as the gaps partially or completely lack vegetation (Marks 1974). These resources will be available to dominant overstory trees

and also to fast growing pioneers that occupy the open space first after disturbances and nutrients are tied up in the biomass of those early invaders (Boring et al. 1981). In spite of the losses due to volatilization and leaching during the rainy season, nitrogen and phosphorus availability increases immediately after fire due to increased soil temperature and moisture, nitrogen fixation, mineralization and release (Christensen 1985, Vitousek 1985, Raison 1979). In my study, enhanced growth in the dominant overstory trees in all of the burned plots and particularly in four-burn plots, confirms such effects of fire.

Additionally, the highest IV of the overstory red pine trees in the burned treatments and the gradual increase of IV for overstory red pine trees from control to one- to two- to four-burn treatments indicates that red pine becomes more dominant with more frequent burning. Prediction of canopy dominance of trees in future stands based on higher IV of younger age/size classes has been suggested (Flaccus and Ohmann 1964). The greater IV of red pine of different ages and size classes in burned treatments indicates that red pine will be important in the canopy of future stands (see Chapter 3).

One- to almost two-decade-old prescribed burns have enhanced overall vegetation diversity and cover in the understory and favored the reproduction of red pine. Enhanced immediate post-fire red pine recruitment was reported by Henning and Dickmann (1996), and this cohort has developed over time. These effects probably will be carried over, but as the overstory trees, understory woody seedlings and saplings and the herbaceous ground vegetation grow in time and space, diversity will decline. Species richness and diversity increase quickly after fire (disturbance) and reach a peak but

decrease later as the succession progresses (Loucks 1970; Denslow 1985). In boreal forests in British Columbia and interior Alaska, early recruitment was highest in the first five years and then some of the species declined after 10 years in mixed stands (Johnstone et al. 2004). In my study, the higher relative densities and IV but lower overall densities of red pine reproduction in the four-burn plots than in once- and twice-burned plots show clearly how repeated burning can shift composition toward a highly fire-adapted species (Van Wagner 1970, Dickmann 1993). Absence of fire caused highly fire adapted longleaf pines to convert to loblolly and slash pines along Southeast coastal areas (Walker 1980) and increased fire sensitive species (Arthur et al. 1998). Even infrequent disturbances can have long lasting effects in forest structure and composition (Henry and Swan 1974).

The most remarkable changes in structure in the red pine forests in my study was the shift from a bimodal diameter distribution in unburned plots to a unimodal distribution in two- and four-burn plots. A single burn created a structure roughly in between bi- and unimodal because it eliminated only a few large-sized sub-canopy trees. Frequent burning virtually eliminated the sub-canopy stratum. These overall changes in the species composition and structure of these stands can reflect future stand development.

Burning decreased the height of shrubs and sub-canopy trees (Little and Moore 1949; Ahlgren 1960; Dickmann 1993). Early stages of red pine plantations were considered as unsuitable for white tailed deer, snowshoe hare, and ruffed grouse (Gysel

1966). However, after burning in mature red pine plantations, herbs and shrubs increase and the heights of the sub-canopy stratum is reduced (Little and Moore 1949; Dickmann 1993). The increase in herb and shrub richness and the sprouting back of hardwood species provide a good source of browse for animals; thus, thinning and burning could be very useful for wildlife management (Dickmann 1993). Bender et al. (1997) found small and large mammals such as elk and deer increased after overstory thinning, again due to increased quantity and quality of forage. Although thinning and prescribed burning are different, they have some common benefits because they both create openings, enhance sprouting and seedling recruitment, and decrease heights of hardwoods, all of which enhance wildlife habitat in red pine stands.

2.5 Recommendations

Prescribed burning should be considered a tool for the long-term management of red pine forests. The number of burns carried out, the burn intervals, and the period of gap to be left after prescribed burning should be chosen judiciously and will depend entirely on the management goals and objectives.

A single fire with a long growing period (one to two decades) without fire results in a forest with an overstory of red pine and a few small-sized sub-canopy overstory trees of other species below them. Red pine seedlings and saplings will be mixed with hardwoods in the understory woody layer. If the focus of management is the enhancement of growth and yield of the red pine only, one-burn alone may not be sufficient since the effects of single low-intensity fire declines with time. The

determination of the length of the growing period after last fire or other silvicultural practices to be adopted in combination with burning have to be chosen judiciously so that forest growth is revitalized and stimulated. Burning such forests every 15 to 20 years favors red pine growth as well as some browse in a sustained basis for wildlife management.

A red pine forest with a history of two-burns at a five-year interval and left to grow for a long gap of about 11 years will lead to a unimodal distribution of overstory trees. Such repeated burnings increase the importance of red pine in both the overstory and understory tree layers, increase overall density and diversity of understory woody seedlings, enhance sprouting of red maple and other hardwood species, increase tree density in the herbaceous ground vegetation layer, increase openness in the forest, and kill back small hardwood stems, many of which resprout. This is a better option for management of red pine as well as wild animals, compared to a single or no burning.

Multiple fires at two- to five- year intervals, and then a period of fire exclusion seems to be the best option to obtain vigorous red pine reproduction. This fire regime will clear everything from the sub-canopy and understory leading to a unimodal overstory tree distribution with the highest annual growth in the overstory trees. It also creates an ideal seedbed for red pine. Red maple, black cherry, beech, oaks, hophornbeam, white ash and other species also get favored due to repeated burnings, although their relative density will be low. Thus, with multiple burns we get a dominance of red pine in all the three strata: the overstory, the woody understory, and the ground

vegetation. So this regime is the best option if the objective is the long-term management of red pine. Multiple prescribed burns combined with some other silvicultural practices, such as thinning, would also give increased growth and yield of red pine. The low understory vegetation created by this regime would be very favorable to browsing wildlife and low-nesting birds, although the lack of mid- and sub-canopy strata would not provide habitat for other mammals and birds. Understory vegetation, which has low commercial value, should be given due importance as it has a very important ecological role in occupying disturbed sites and yielding to other late successional.

Additionally, extremely dense red pine regeneration established after one to two decades of repeated prescribed burning in mature red pine stands on nutrient rich sites might need release from suppression by pre-commercial thinning so as to maximize growth and yield (Benzie 1977). On nutrient poor sites repeated burning should be applied to the extent that it may suppress hardwood species sprouting and enhance red pine establishment and growth; however, burning should not retard or interfere with red pine regeneration and establishment. On these less fertile and often droughty sites red pine recruitment following fire may not be as vigorous or predictable as occurred on my site, so early pre-commercial thinning may not be necessary.

Chapter 3: Using the Forest Vegetation Simulator (FVS) to Project the Long-Term Effect of Prescribed Fires in a Red Pine Plantation.

3.1 Forest Simulation

The Forest Vegetation Simulator (FVS) is the USDA Forest Service's nationally supported framework for forest growth and yield modeling (Dixon 2002). The Growth and Yield Unit of the Forest Management Service Center (FMSC) in Fort Collins, Colorado develops, maintains, supports and transfers FVS and related technology. FVS developed from Prognosis, a modular structure developed by Stage (1973 in Dixon 2002) and is an individual-tree, distance-independent growth and yield model. It can simulate a wide range of silvicultural treatments for most major forest tree species, forest types, and stand conditions, ranging from even-aged to uneven-aged. There are different variants developed for different geographic regions. For example, the Lake States (LS) Variant used in this study is an adaptation of the LS-TWIGS model and applied to the Lake State Regions (MI, WI, and MN). However, since it is a distance-independent model, it does not do well with thinning by group selection. FVS treats a stand as the population unit, using forest inventories or stand examination data. FVS works through the Suppose interface (platform), which is a graphical user-interface that accesses FVS software through Windows 95 operating system 9. Simulations are reproducible and deterministic by default; however, they can also be run stochastically. While simulating, post-processors (other programs) are used for further reporting and analysis of FVS output (discussed further under Materials and Method section of this chapter).

Canavan and Ramm (2000) compared the actual measured growth, BA and mortality for seven upland hardwood species in northern Lower Michigan with TWIGS and FVS_LS five and 10-year projections. They found that FVS-LS produced more accurate results for diameter and BA growth than LS_TWIGS, whereas neither of the two simulators produced as accurate results in case of ten-year mortality (tree density). The diameter prediction was within ± 3.2 cm across all projections, species and size classes.

Similarly, Smith-Mateja (2003) used RPAL (REDPINE) to project stand level attributes and FVS-LS to project tree and stand level attributes of large trees of red pine (*Pinus resinosa*) at Kellogg Forest in Lower Michigan. Overall FVS was more robust than RPAL. FVS was found to be a good predictor of diameter growth and was even better when diameter growth data from increment cores was used to calibrate it. She suggested that validation should be carried out in small-sized red pines and minor species and different site conditions as well.

The red pine plantations that were the basis for my simulations were mature (established in 1931) and partially harvested in 1970, leaving an understocked condition with a variable residual basal area (BA) averaging $10 \text{ m}^2 \text{ ha}^{-1}$. The stands were burned using low-intensity single and multiple prescribed fires during 1985 to 1991 and were left to grow without further intervention (Henning and Dickmann 1996). The re-measurement of the stands was done in 2001 and 2003 (Chapter 2). The data in Chapter 2 revealed that the average diameter of the burned and unburned stands was about 43.2 cm and the overstory trees were mature, occupying between 17.9 to $23.3 \text{ m}^2 \text{ ha}^{-1}$ in

differently burned plots (Table 2.1). Moreover, there was a very dense advance post-fire regeneration of red pine and hardwoods established after different prescribed burnings were carried out, but the stands needed some kind of silvicultural operation or management to enhance growth and productivity. Re-burning was not an option as the burned plots already had a well-established one- to two-decade-old advance regeneration which needed protection; young red pine recruitments cannot withstand even a low-intensity fire (Van Wagner 1970). So, several obvious questions emerged. First, how will current stand structure and composition change during 100 years of growth and development? Second, which management system could be applied for maximum and sustained yield from the burned and unburned forests and when could such silvicultural management be started? Third, how much volume of wood or BA could be removed during thinning to maximize saw log production of such stands?

The uniqueness of this study is that since the plots were affected differently by prescribed fires, the data from burned and unburned plots could be projected 100 years into the future using FVS with both no-management as well as thinning to examine the long-term effects. The results could be useful for managers and planners as they formulate desired future conditions for red pine dominated ecosystems.

My hypotheses are as follows: Burned plots, if allowed to grow for a long period of time (longer than one to two decades), will be different from unburned plots in their species composition and structures, and the changes or the differences will depend on the frequency of burns. The successional trajectory of the red pine stands will be different

among differently burned and unburned plots and also the management applied (no-management and thinning). The net volume yield of thinned stands will be higher than those of unthinned stands whether they are burned or unburned.

The objectives of this study are:

- To examine compositional and structural changes in previously burned and unburned plots of mature red pine stands simulated 100 years into the future with and without thinning.
- To summarize growth and yield in previously burned and unburned mature red pine stands managed differently.

3.2 Materials and Method

The Forest Vegetation Simulator (FVS) was used for forest growth and yield modeling. The data input, interpretation of output, simulating management scenarios and regeneration were carried out as suggested in the “Essential FVS: A User’s Guide to the Forest Vegetation Simulator” (Dixon 2002) and the use of keywords from the “Keyword Reference Guide for the Forest Vegetation Simulator” (Van Dyck 2003). Data on mature overstory trees (>10cm in dbh) and understory trees (>1.4m in height and 0-10 cm dbh) (Chapter 2) were entered in FVS tree data files. All the understory trees >30 cm to 1.4 m in height were counted from all of the respective burned and unburned treatments and were entered with an assigned diameter of 0.254 cm (Dixon 2002). This manipulation was required by FVS, otherwise it would not grow anything <1.4 m during simulations.

FVS works through three sets of file systems that work in coordination through the Suppose interface: the location file (*.loc), the stand list file (*.slf) and the tree data file (*.fvs). As a first step, all the tree data (from 2001 and 2003 measurements) in Microsoft Excel were changed to comma delimited files and then reformatted into FVS input format (*.fvs) which had settings id, design purpose code and measurement numbers. Later, stand-level information such as variant description, group codes and tree data files were entered to the stand list file (*.slf). Finally, specific information about each setting, such as sample design, was entered in the Suppose locations file (*.loc), which also contained the tree list file name and a grouping code. Suppose version 1.18 and FVS Version 6.21 of Lake States Twigs (Revised 03.07.06) were used to project the data into different management simulations which were manipulated through keywords. Simulations were used deterministically by default (although they can also be run stochastically) and were reproducible. While simulating, the post-processors (other programs in FVS) were used for further reporting and analysis of FVS output, which was later brought back to Excel for further study and analysis.

To test the study hypotheses and address study objectives these steps were followed. First, the stands were projected without any silvicultural management. A Mean Annual Increment (MAI) was obtained which showed that the stand was still growing up to the year 2044. It was suspected that this observed MAI could have been due to the actively growing advance post-fire recruitments. Rapid growth of MAI in red pine occurs at 15 to 45 years of age and later the growth slows down before it culminates (Lundgren 1983). Therefore, to see if the mature trees were still growing or not, the seedlings or

saplings below 10 cm were all removed by using “thinning from below with dbh removal from 0-4 inch” option from the FVS model and then the stands were projected again. Once the fast-growing small seedling/saplings (0-10 cm dbh) were removed, growth started declining much earlier than observed previously, after about the year 2004 in some of the stands. This demonstrated that the growth observed in previous run was mainly due to the growth of understory trees and the large overstory trees were mostly growing at a very slow rate. Thus, some silvicultural intervention could be performed immediately or within a few years in both the burned and unburned stands. The simulation was started in 2003, the year when the inventory of trees and the understory vegetation for this study was completed. Since the MAI started decreasing after 2004 (at least in some of the stands), the silvicultural operations were always scheduled in the year 2004.

The following two options of management were chosen to be simulated for 100 or more years into the future in all of the burned and unburned plots using FVS. The no-management projection provides a longer-term perspective of different fire regimes and their effects without any external disturbance, whereas thinning, as an additional disturbance, provides an opportunity to study the effects of multiple silvicultural disturbances. The stands were 78-year-old when simulations began and 178-year-old at the end, when they exhibited some of the characteristics of old growth forests.

Thinning (partial cutting) is one of the best silvicultural operations for the management of even-aged red pine (Benzie 1977) and is recommended to be done every

10 years or more (Lundgren 1983). I chose thinning at different residual BA targets for different cuttings through the FVS simulator. Although there are some limitations, fixed target BA seemed to suit this site, as it had lower understory trees waiting to be released. Thinning from below does not seem to be appropriate as the advance post-fire regeneration needs protection and release, and the slow-growing tolerant smaller woody understory species would all be removed from the stands. Rather, healthy and vigorous intermediate and co-dominant trees need to be released from competition by dominant trees for better growth in diameter. In other words, the removal of mature dominant trees can rejuvenate the vigor of residual trees as well as the stand as a whole.

As per the stocking guide for red pine (Benzie 1977), stands having an average diameter of 43 cm dbh (my study) need to retain a residual BA following thinning between 24.1 and 27.5 m² ha⁻¹. However, Lundgren (1965) advised for high investment returns to go as low as 20.6 m² ha⁻¹ thinned every 10 years, regardless of the density and stocking of the stands. My stands were highly variable in their BA, with some carrying a BA smaller than 22.9 m² ha⁻¹. To determine the residual BA of subsequent thinnings, the number of thinnings to be carried out and the interval periods between them, several runs were made with various target residual BA. First, the residual BA of two different sets, 25.2, 27.5 and 34.4 m² ha⁻¹ and 25.2, 29.8 and 34.4 m² ha⁻¹, both at intervals of 20 as well as 30 years were run for one-, two- and three-times thinning over the next 100 years. For both the sets of residual BA used, the final growth in BA did not reach as high as 57.3 m² ha⁻¹. Later, as I kept lowering the target BA, the first thinning lowered to 22.9 m² ha⁻¹ basal area, resulting in a final BA as high as 57.3 m² ha⁻¹ after 100 years. Thus 22.9 m²

ha⁻¹ BA was decided to be retained for the first thinning for all of the regimes. After analyzing several runs I tested the following three thinning regimes that provided the highest final basal area and yield:

- Single Thinning: retaining BA at 22.9 m² ha⁻¹ after a single cut in year 2004.
- Two Thinnings: retaining BA at 22.9 m² ha⁻¹ in 2004 and 27.5 m² ha⁻¹ after the second thinning in 2034.
- Three Thinnings: retaining BA at 22.9 m² ha⁻¹ in 2004, 27.5 m² ha⁻¹ in 2034 and 34.4 m² ha⁻¹ after the last thinning in 2064.

As I needed to retain and release the advance post-fire red pine and hardwood establishment as well as competing co-dominants, I chose the 'THINDBH' key word which considers thinning of all diameter class trees; however, a calculated proportion of trees is removed until target basal area is met. This algorithm begins thinning the largest diameter trees first, so the target BA may be reached before any smaller trees are removed.

The tree density after the 'single' thinning was almost the same as under no-management but much lower than that under the 'two' and 'three' thinning because adequate or sufficient number of trees were not removed from the understory. Further, the high BA (22.9 m² ha⁻¹) chosen to be retained during the first cut in 2004 was not even available in some of the stands, particularly the one-burn ones. Thus, only the three times thinning was used for this study as it retained highest density, species richness and

cumulative volume at the end of simulation compared to one and two times thinnings. It will be referred to as thinnings or thinning, hereafter.

Because of the unusually high density of post-fire recruitment, the FVS model was not performing well in the beginning; this problem was fixed with the help of Dr. Don Dixon, biometrician with the USDA Forest Service, Fort Collins, Colorado. Normally, regeneration is assumed to be around 988 seedlings per ha, whereas my stands had a greater post-fire understory seedling density. There was virtually no space for new seedlings to emerge as the ground was either covered with seedlings (in case of burned plots), litter, or in open areas with thickets of *Rubus* and grasses. In unburned controls there was a dense understory and sub-canopy of mainly the hardwoods and the duff was so thick that very little regeneration was occurring. After discussing the matter with Dr. Dixon and Prof. Don Dickmann, I decided to keep the new regeneration to only 2% of total seedlings in each of the burned and unburned controls. For example, in unburned controls the seedlings/saplings to be regenerated were controlled by creating regeneration files (*.kcp) and regeneration was limited to 208 trees ha⁻¹. Similarly, regeneration files (*.kcp) were created for other treatments: one-, two- and four-burn plots with 388, 395 and 319 trees ha⁻¹, respectively. Thus four sets of regeneration files were created by averaging among the replicates of each treatment for use in the FVS simulations. Those files helped to control the erratic behavior of FVS and the model ran perfectly fine after the adjustments. I observed that the low rate of regeneration chosen to run the simulation did not matter much as there was very little new regeneration taking place under the dense advance regeneration thickets in the study sites anyway.

The FVS model averaged all the data in the output and the results were obtained on a per stand basis, so I averaged the output for the three replicates of each treatment (n=3) and then summarized and discussed. As the model result was based on so many assumptions, I did not use statistical analysis. Consultants at the MSU Statistical Consulting services recommended that such analyses are inappropriate because of the multiple assumptions that are inherent in simulation models, including FVS.

I summarized tree density, BA, MAI and total cubic merchantable and sawlog volumes. For detailed study, the trees in two strata or horizontal layers were categorized by breast height diameter class (dcl) into the understory (0-11 cm dcl) and the overstory (>11 cm dcl) trees. The understory trees were further categorized into small (0-6 cm dcl) and large (6-11 cm dcl) trees. Similarly, the overstory trees (>11 cm dcl) were categorized into sub-canopy (>11-32 cm dcl), mid-canopy (32-42 cm dcl) and dominant (>42cm dcl) overstory trees.

The cumulative total cubic and saw log volumes were calculated from the output data. Relative densities and relative BAs for different treatment plots as well as species also were calculated. Relative density is the number of individuals of one species as a percentage of the total number of individuals of all species. Similarly, relative BA is the BA of species as a percent of the total BA of all species. Relative value index or importance value (IV) then was calculated from the relative densities and relative BA. Percent increase over unburned treatments was calculated for each period to look at the

long-term effects of fire. Also, the percent change over no-management was calculated for each period to assess the effects of post-fire silvicultural management.

MAI was taken directly from the output of the model, which by default added all the previous removals of cubic volume (through thinning, if any) to the total cubic volume before thinning at any age and divided the sum by the age of the stand. To calculate the cumulative cubic volume for the year in which the cutting occurs, the removals of the same year were not added. The previously removed total cubic volume by thinning was added to the volume before thinning to compare the yield between thinned versus unthinned stands but not for total growth (Spurr et al. 1957). Thus, yield has been used as the additions of all the net annual increments as in Buckman (1962).

3.3 Results

3.3.1 Tree density

Tree density at the beginning of the simulation ranged from 10,067 to 19,934 trees ha⁻¹ with the highest density in two-burn and the lowest in the unburned treatments (Table 3.1). The trees were categorized into two groups; the woody understory (0-11 cm dcl) and the overstory (>11 cm dcl) trees. Understory trees constituted 98% (unburned plots) to 99% (burned plots) of the total trees. Overall tree density dropped sharply in all of the treatment plots by the end of both of the no-management and thinning simulations.

3.3.1.1 Understory tree density

At the end of no-management, the relative density of understory trees had declined sharply, especially in the burned treatments. At the end of thinning, relative density declined less and was still quite high in the frequently burned treatments (Table 3.1). After no-management, the unburned controls retained the highest understory tree density, despite their lowest density in the beginning. However, at the end of thinning, the densities of understory trees retained in the one-burn and unburned controls were 6 to 7 times lower than that in the two- and four-burn plots. When compared with no-management, understory tree density after thinning was more than double in unburned controls and one-burn treatments and more than 20 fold in two-burn treatments and 90 fold in the four-burn treatments.

Small understory tree (0-6 cm dcl) density in the unburned controls was almost one-half that in the burned plots in the beginning (Figure 3.1a, Appendix 3.1). At the end of the no-management, the density of small understory trees retained was the highest in the unburned controls, whereas in all of the burned treatments, small trees were nearly absent (Figure 3.1b). After thinning, the densities of small understory trees retained were much higher in the two- and four-burn treatments than the other treatments (Figure 3.1c)—two, six, 45 and 90 times more in control, one-, two- and four-burn plots, respectively, than after no-management. At the end of no-management, the relative density of the small understory trees declined to 7% and 2% of total trees in unburned controls and all burned treatments, respectively, whereas the relative percentage was much higher after thinning, particularly in the burned treatments.

In the beginning, large understory trees (6-11 cm dcl) were absent or <0.5 % of total trees in all of the burned treatments, whereas they were >6 fold higher in unburned controls (Figure 3.1a). Unlike the small trees, the large understory trees increased in density and relative density in all of the burned plots during early periods of both the no-managements and thinning simulations and then declined gradually (Figures 3.1b and 3.1c, Appendix 3.1). At the end of no-management, few large understory trees remained, with an especially large drop in density in the control (Figure 3.1b). However, at the end of thinning, trees in this size class also were lost in unburned treatments but big gains were shown in frequently burned treatments. At the end of thinning, the increase in density of large understory trees was more than three times in unburned controls and more than five times in all of the burned treatments than in no-management.

3.3.1.2 Overstory tree density

Initially, overstory tree (>11 cm dcl) density was greatest in the control plot followed by that in the four, two and one-burn plots (Table 3.1). As the no-management and thinning simulations progressed, overstory tree densities in all burning treatments increased and reached their highest value in the year 2044, then declined slightly; however, densities were still much higher (about 3 to 5 times) at the end of the run than in the beginning. At the end of both no-management and thinning, the burned stands had a higher density of overstory trees than the unburned controls, which had the highest density in the beginning (Table 3.1). Relative densities after thinning were one-half those after no-management in two and four-burn treatments; however, they were only slightly less in one-burn and control plots.

Table 3.1: Average and relative live understory (0-11 cms dcl) and overstory (>11 cm dcl) tree density* under 100 years of simulation** in mature red pine stands.

Year	Understory-density trees ha ⁻¹				Overstory-density trees ha ⁻¹			
	Burn treatments							
	C	1B	2B	4B	C	1B	2B	4B
Beginning								
2003	9869	18797	19793	16725	198	115	141	154
%	98	99	99	99	2	1	1	1
No-management								
2014	8418	16143	15902	13977	385	129	164	159
%	96	99	99	99	4	1	1	1
2044	778	3413	2192	3059	741	1063	911	704
%	51	76	71	81	49	24	29	19
2074	126	133	91	71	549	767	641	509
%	19	15	12	12	81	85	88	88
2104	45	18	30	8	437	593	513	445
%	9	3	6	2	91	97	94	98
Thinnings								
2014	8226	16143	15600	13325	370	129	150	139
%	96	99	99	99	4	1	1	1
2044	1783	3260	3042	3109	557	824	639	491
%	76	80	83	86	24	20	17	14
2074	349	624	1017	1720	469	568	475	330
%	43	52	68	84	57	48	32	16
2104	106	101	610	711	378	483	427	417
%	22	17	59	63	78	83	41	37

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

Burn treatments in columns are: C, Unburned Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns

% (in rows) is the percent of total tree density.

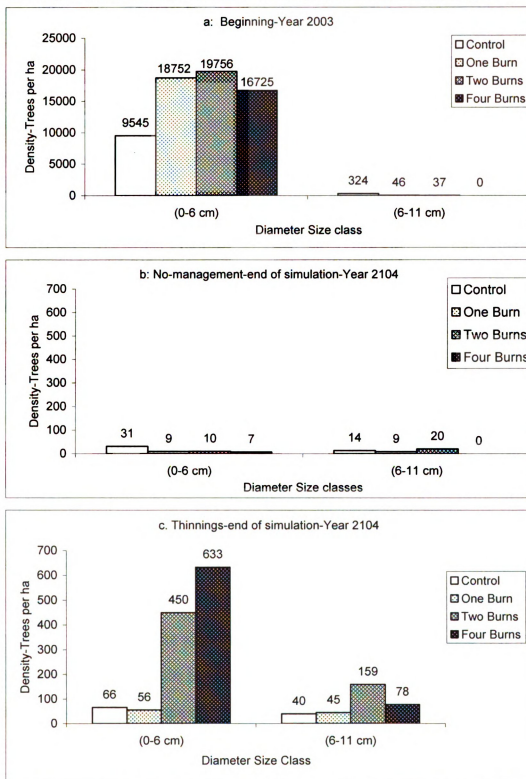
dcl=diameter size class.

*Stand density does not include removals in thinnings.

**Simulation started on year-2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Figure 3.1: Understory (0-11 cm dcl) tree density in differently burned plots under no-management and thinnings* simulations for 100 years in mature red pine stand.



*First, second and third thinning were done in years-2004, 2034 and 2064, respectively.

3.3.2 Stand structure

Trees were distributed in two distinct age or size-class strata at the beginning of the simulation (Figures 3.1a and 3.2a; Appendix 3.3a). The understory was formed of extremely dense post-fire regeneration as well as sub-canopy trees, the latter especially in unburned treatments. The upper stratum contained mature mid-canopy and dominant overstory trees and formed a uniform bell shape, with most trees in the 37 to 52 cm dcl. The overstory tree distributions were similar in the beginning and during early simulations in both the no-management and the thinning; however, they became different towards the end of the simulations. As both the simulations progressed, a shift of trees from smaller to larger dcl occurred, which led to the formation of different vertical strata in the stands at the end of the simulations than at the beginning (Figures 3.2a to c; 3.3a to d). In general, the burned plots had higher average densities in the entire range of diameter classes than in the unburned controls.

3.3.2.1 Bimodal tree distribution

After no-management, the trees formed a bimodal distribution of which the lower stratum formed a normal bell shape, with understory trees and overstory trees to 47 cm, whereas the upper stratum formed a J-shape with large trees from 47 to >62 cm (Figures 3.1b, 3.2b; 3.3a to d). There was a shift from 'inverse-J' shape in the understory and the sub-canopy tree layers in the beginning to a more uniform and normally distributed (bell) shape at the end. Second, the bell shaped distribution in overstory trees at the start shifted to a J-shape at the end of the simulation (Figure 3.2b). The bell shaped distributions

showed distinct peaks for unburned, one-burn, and two-burn treatments but was much flatter for four-burn treatments.

3.3.2.2 Tri-modal tree distribution

After thinning, the trees formed a tri-modal distribution, which was most pronounced in the burned treatments, with an inverse-J shape in the understory layer, a uniform bell shape in middle layer (sub-canopy and mid-canopy overstory trees) and a J-shape in the dominant overstory layer (Figures 3.1c and 3.2c; 3.3 a to d). The bell shaped distributions again showed distinct peaks for unburned controls and both one- and two-burn treatments, but was essentially flat for four-burn treatments.

Total tree density was always higher in the thinned than in the unthinned plots (Appendix 3.3). More trees were found in the 32 to 47 dcl as the management changed from no-management to thinning, in both unburned and burned treatments. Thinning thus enhanced more diameter growth in sub-dominant trees, resulting in the shifting of smaller to larger size classes, than no-management. Because the thinning was from above, the density of dominant overstory trees (> 57 cm) was lower in the thinned stands than in the unthinned ones in all of the treatment plots (Figure 3.3a to d). The highest density of large trees was in four-burn treatment followed by the two, one and unburned controls in both managements.

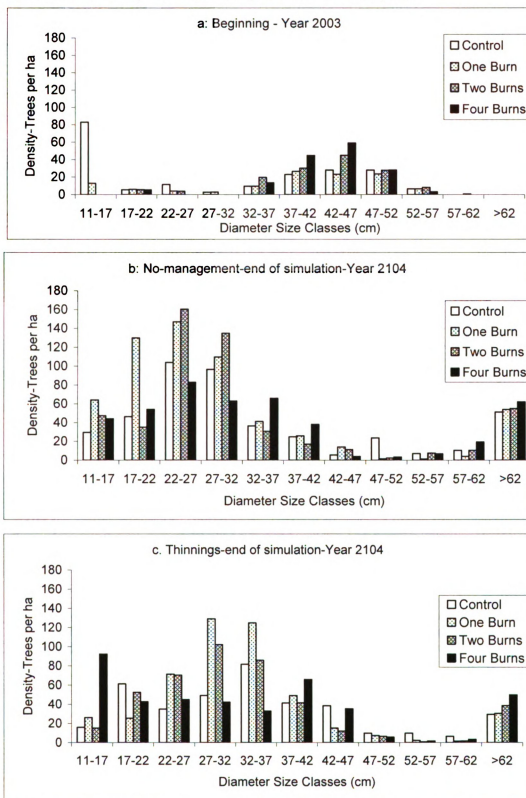
3.3.3 Species density

In the beginning, red pine, red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), choke cherry (*Prunus virginiana*) and black cherry (*Prunus serotina*) had high densities and relative densities, followed by the least represented species white ash (*Fraxinus americana*), beech (*Fagus grandifolia*), and others (Table 3.2). Red pine density was higher than any other species, with highest density in two-burn and lowest in unburned controls, which also were lowest for all other species except sugar maple. Red maple was next to the red pine in its density and relative density.

The density and relative density of red pine was highest in all of the treatments throughout the simulations (Table 3.2). They were higher in the burned than in the unburned controls at the end of no-management, whereas, they were much lower in the burned treatments (except in the once burned) than in unburned controls at the end of thinnings. After thinning, most species except red maple and beech had their highest densities in the four-burn plots.

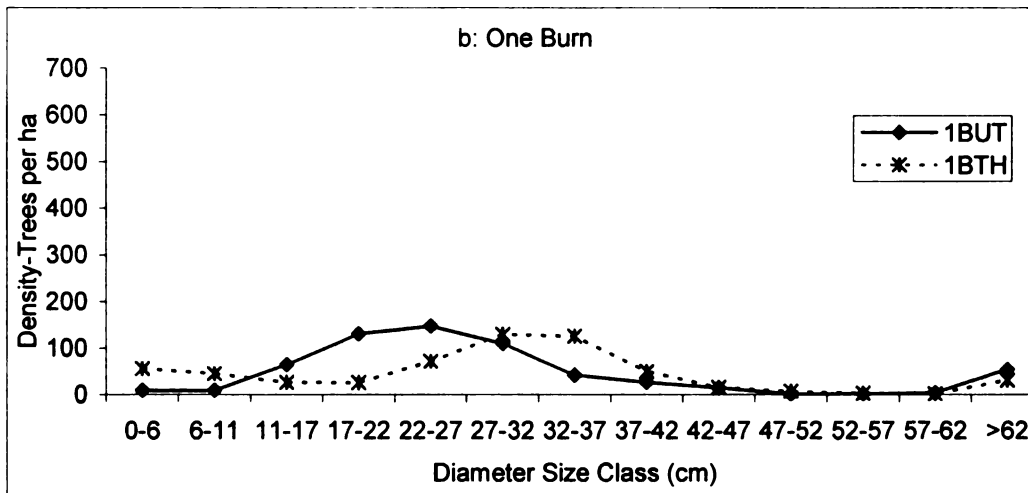
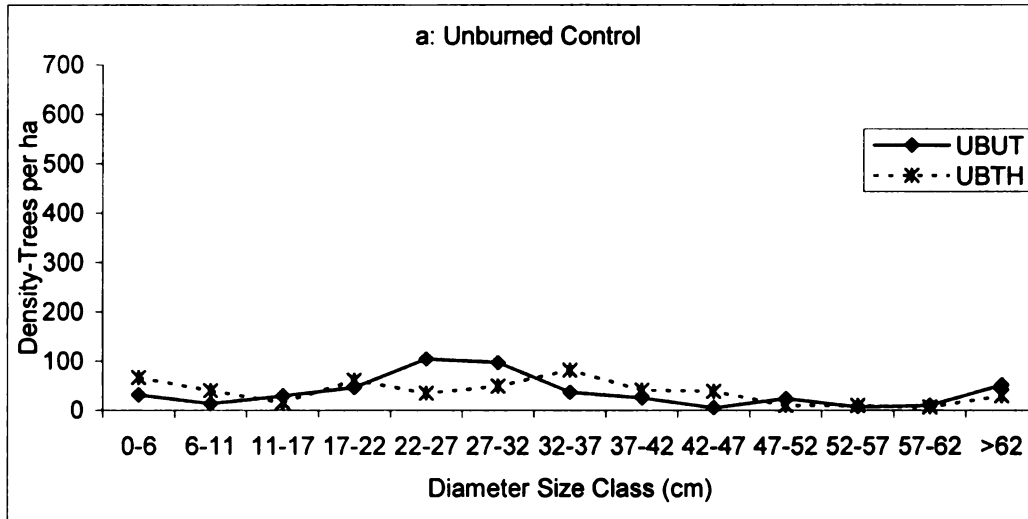
Despite an overall decline, red maple was next to red pine in species dominance until the end for both of the managements, and it was the lowest in four-burn treatments among different burn treatments (Table 3.2). Red maples were higher in all of the thinned treatments than the corresponding no-management treatments. The density of red maple was the lowest in unburned controls than in other treatments until the year 2044; however, later it increased and became the highest in control at the end of no-management, while it remained higher in one and four-burn treatments after thinning.

Figure 3.2: Tree distribution by diameter size classes in differently burned red pine stands under no-management and thinning* simulations for 100 years.



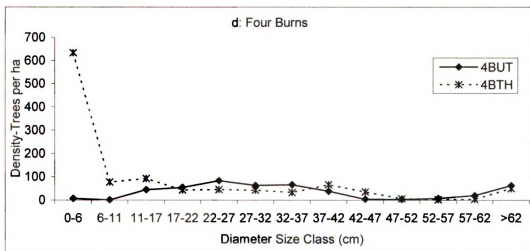
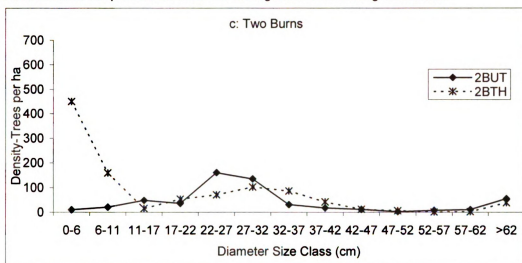
*First, second and third thinnings were done in years - 2004, 2034 and 2064, respectively.

Figure 3.3: Tree distribution by diameter class in year 2014 in differently burned mature red pine stands under no-management and thinning simulations.



Thinned and unthinned (TH and UT respectively); Unburned Control (UB), One Burn (1B), Two Burns (2B), Four Burns (4B).

Figure 3.3 (continued) : Tree distribution by diameter class in year 2014 in differently burned mature red pine stands under no-management and thinning simulations.



Thinned and unthinned (TH and UT respectively): Unburned Control (UB), One Burn (1B), Two Burns (2B), Four Burns (4B).

Sugar maple density was highest in unburned than in other treatments throughout the simulations and it persisted until the end of no-management, at least in the unburned treatments. Its density was highest in the four-burn treatments at the end of thinning. Black and choke cherry, white ash, beech and other trees disappeared or almost disappeared after the year 2044 under no-management (Table 3.2), but they persisted at relatively low densities after thinning.

3.3.3.1 Understory woody and overstory species

In the beginning of the simulation, the density of understory red pine was lower than other understory species (Figure 3.4a) but all species had much higher densities in burned plots than in unburned controls. Understory red pine density declined to almost nothing—except in the unburned controls—at the end of no-management (Figure 3.4b) due to ingrowth to higher dcl and mortality. A similar sharp decline occurred in all other species over the course of the simulation.

The higher dominance of other understory species over red pine was apparent in the frequently burned treatments compared to the unburned controls at the end of the thinning simulation, despite their overall decline after 2044. At the end of thinning, the four-burn plots had the highest density of woody understory red pines, but the decline from initial conditions again was abrupt (Figure 3.4c). Understory red pine densities in two and four-burn plots were much higher than that in similar plots under no-management.

There was not much influence on mid-canopy and dominant overstory species density during both management regimes. Ingrowth into the sub-canopy by red pine trees occurred in all of the treatments during both management simulations (Figure 3.5a & 3.5b). Sub-canopy red pine density was highest in unburned controls in the beginning; however, at the end of no-management it was highest in the burned plots. Growth into the sub-canopy by red pine in the four-burn treatments was remarkable as there were no trees of this size class at the beginning of the simulation. Other species were highest in unburned treatments throughout. Sub-canopy hardwood species increased somewhat in all of the burned plots but their relative density actually decreased.

3.3.4 Basal area (BA)

The standing total BA at the outset ranged from 17.1 to 24.1 m² ha⁻¹ with the lowest in one-burn and the highest in four-burn treatments (Appendix 3.3b). During no-management, the overall BA increased rapidly until about the year 2044, and thereafter grew slowly and formed a plateau until the end (Figure 3.6; Appendix 3.3b). However, BA formed the classical zigzag, saw-tooth shape during successive thinnings and was always lower than no-management.

3.3.4.1 Understory basal area

Although their density was high (Table 3.1) understory trees formed only 19, 12, 6 and 3 % of the total understory BA in unburned, one-, two- and four-burn treatments, respectively, and the remaining portion constituted the overstory trees (Table 3.3).

Table 3. 2: Average tree density* (trees ha⁻¹) and relative density (%) of all species under different management simulations** for 100 years in mature red pine stand.

Treatments	Year	AB	%	BC	%	CC	%	Others	%	RM	%	RP	%	SM	%	WA	%	Total
Beginning																		
Control	2003	292	3	583	6	896	9	1735	17	1290	13	3930	39	940	9	400	4	10067
One Burn		788	4	1013	5	2381	13	2598	14	4007	21	5948	31	827	4	1351	7	18913
Two Burns		701	4	1551	8	2673	13	2235	11	2886	14	9163	46	430	2	296	1	19934
Four Burns		321	2	2097	12	2247	13	2721	16	2143	13	5726	34	896	5	727	4	16879
No-Management																		
Control	2014	268	3	401	5	708	8	1396	16	1058	12	3794	43	864	10	314	4	8803
One Burn		695	4	771	5	1962	12	2026	12	3269	20	5611	34	767	5	1173	7	16273
Two Burns		599	4	526	3	2023	13	1649	10	2087	13	8630	54	377	2	176	1	16067
Four Burns		267	2	1475	10	1774	13	2148	15	1531	11	5526	39	794	6	621	4	14136
Control	2044	66	4	0	0	23	2	62	4	184	12	880	58	292	19	12	1	1519
One Burn		306	7	157	4	901	20	631	14	624	14	1286	29	385	9	185	4	4476
Two Burns		220	7	48	2	138	4	410	13	357	12	1711	55	183	6	35	1	3103
Four Burns		54	1	273	7	634	17	580	15	196	5	1488	40	415	11	123	3	3763
Control	2074	19	3	0	0	0	0	5	1	77	11	487	72	87	13	0	0	675
One Burn		41	5	8	1	0	0	6	1	64	7	774	86	5	1	2	0	899
Two Burns		28	4	0	0	0	0	13	2	6	1	677	93	7	1	0	0	731
Four Burns		0	0	0	0	0	0	4	1	0	0	573	99	0	0	1	0	579
Control	2104	11	2	0	0	0	0	3	1	40	8	380	79	49	10	0	0	483
One Burn		13	2	2	0	0	0	4	1	17	3	575	94	1	0	0	0	612
Two Burns		18	3	0	0	0	0	11	2	4	1	508	93	4	1	0	0	544
Four Burns		0	0	0	0	0	0	3	1	0	0	449	99	0	0	0	0	453
Thinnings																		
Control	2014	251	3	397	5	700	8	1345	16	1037	12	3778	44	791	9	298	3	8596
One Burn		695	4	771	5	1962	12	2026	12	3269	20	5611	34	767	5	1173	7	16273
Two Burns		549	3	514	3	2000	13	1569	10	2002	13	8611	55	337	2	167	1	15750
Four Burns		251	2	1321	10	1700	13	1982	15	1504	11	5429	40	676	5	600	4	13463
Control	2044	84	4	6	0	76	3	168	7	195	8	1482	63	291	12	37	2	2340
One Burn		247	6	190	5	779	19	620	15	765	19	915	22	319	8	250	6	4084
Two Burns		210	6	85	2	507	14	514	14	594	16	1546	42	167	5	58	2	3681
Four Burns		48	1	500	14	539	15	637	18	277	8	1047	29	378	10	174	5	3600
Control	2074	41	5	2	0	28	3	63	8	129	16	356	44	182	22	17	2	819
One Burn		113	9	36	3	171	14	114	10	155	13	462	39	110	9	30	3	1192
Two Burns		133	9	46	3	79	5	257	17	334	22	500	33	111	7	33	2	1492
Four Burns		33	2	293	14	284	14	371	18	112	5	634	31	252	12	72	4	2051
Control	2104	23	5	0	0	0	0	5	1	84	17	262	54	109	22	2	0	484
One Burn		65	11	12	2	0	0	9	1	61	11	390	67	42	7	4	1	583
Two Burns		114	11	25	2	40	4	144	14	187	18	418	40	91	9	18	2	1037
Four Burns		22	2	148	13	67	6	172	15	20	2	515	46	167	15	16	1	1128

Note: % Tot (in columns) are the percent of total density.

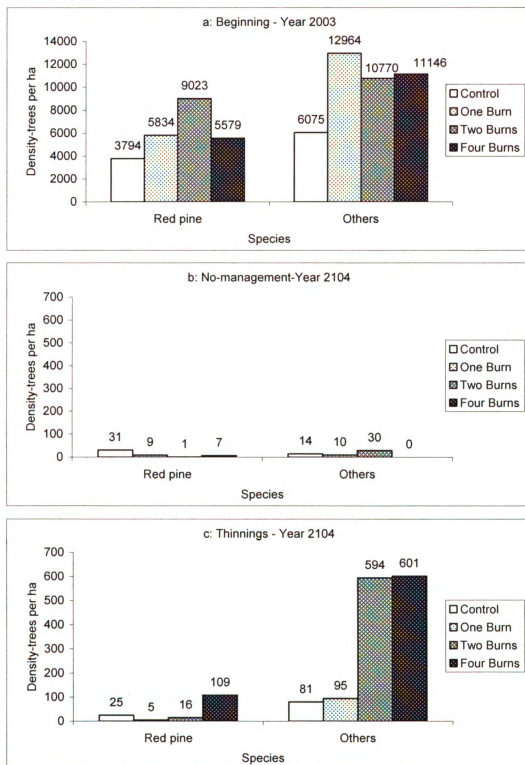
Some of the 'zeros' in % Tot, column have values below 0.5% and have been rounded to zero.

*Stand density does not include removals in thinnings.

**Simulation started on year-2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Figure 3.4: Woody understory (0-11 cm dcl) red pine and other species combined density in different burn treatments and management simulations* for 100 years in a mature red pine stand.



*First, second and third thinnings were done in years - 2004, 2034 and 2064, respectively.

Initially all burned treatments had about one-half or less understory BA than in unburned controls; however, later understory BA decreased almost to nothing in all of the treatments at the end of both management regimes.

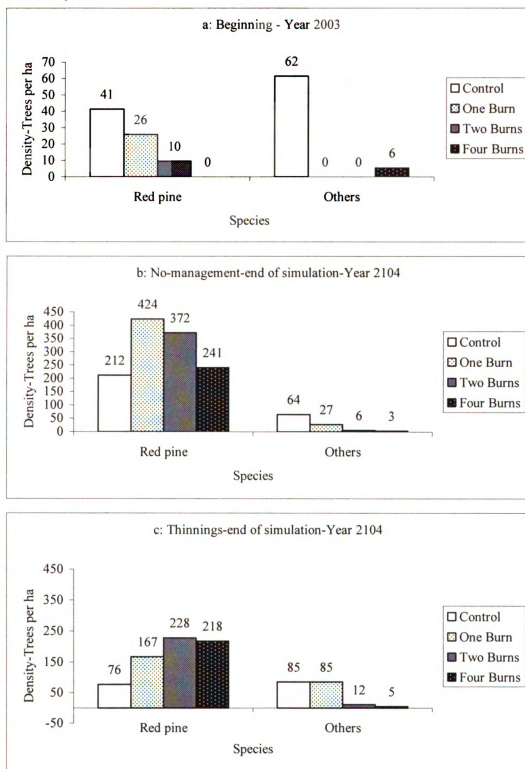
3.3.4.2 Overstory basal area

Unlike the understory, the overstory BA doubled or tripled at the end of both management regimes (Table 3.3). Burned plots were higher in their average BA than the unburned treatments after both managements. Relative basal area (RBA) of the overstory reached 100 % in all of the treatments after no-management, whereas it was only slightly lower after thinning.

Among the sub-canopy, mid-canopy and dominant overstory trees the latter constituted the highest BA and relative BA of total overstory throughout the simulations (Table 3.4). Although considerable growth in the BA of the dominants occurred, their relative BA changed little or declined. The dynamics of the sub- and mid-canopy were different than the dominants. Under no-management major BA ingrowth and growth occurred in the sub-canopy, with less in the mid-canopy. When thinning was applied major growth and ingrowth occurred in both the sub- and mid-canopy. Burning treatments had little effect on BA.

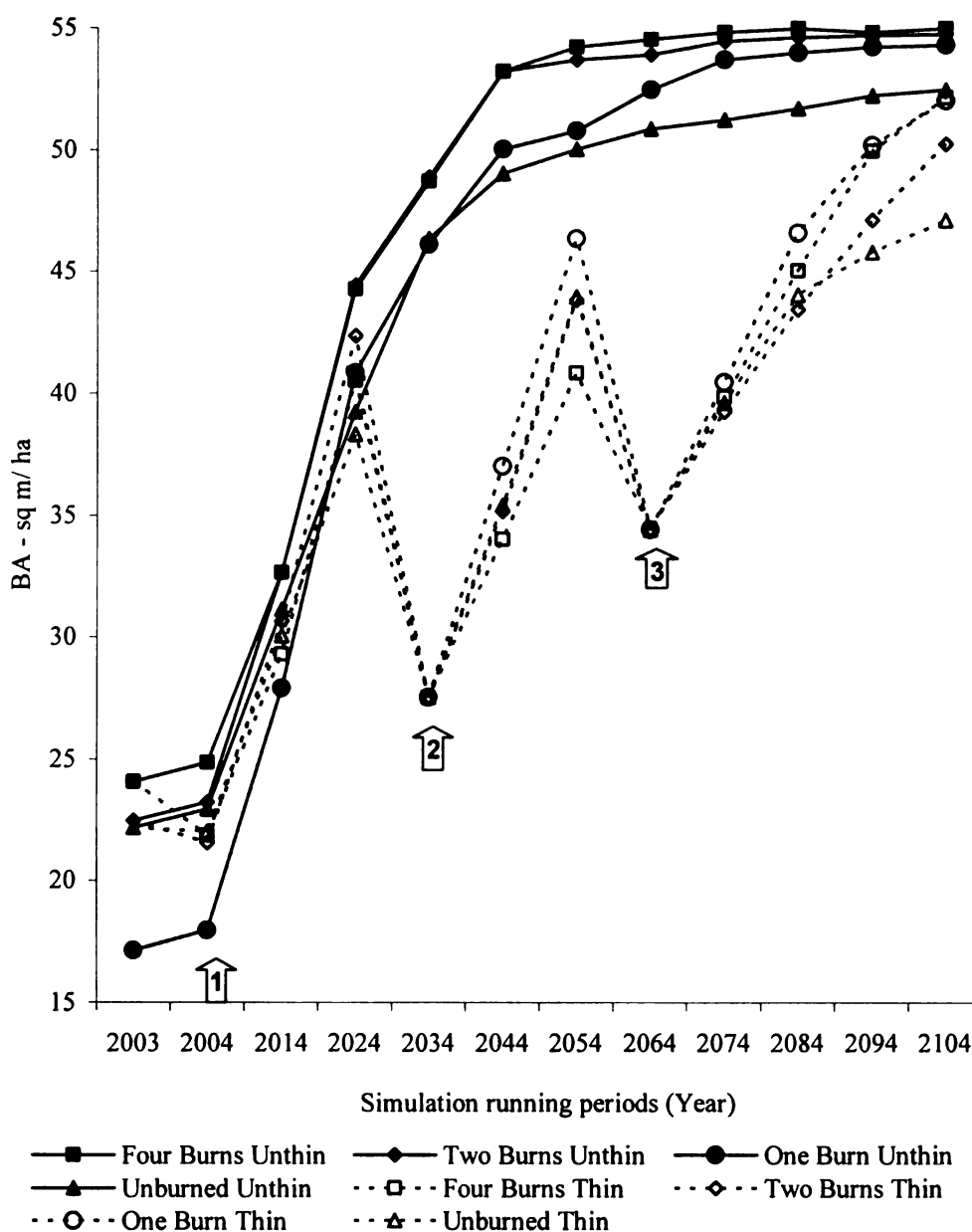
Red pine had a very high dominance over other species. Its relative BA ranged from 76% in unburned treatments to 90 to 97% in burn treatments, with the highest value

Figure 3.5: Average sub-canopy (>11-32 cm dcl) red pine and other species combined density in different burn treatments and management simulations for 100 years in mature red pine stands.



*First, second and third thinnings were done in years - 2004, 2034 and 2064, respectively.

Figure 3.6: Basal area in different treatments under no-management and thinnings with residual basal area set at 22.9, 27.5 & 34.4 $\text{m}^2 \text{ha}^{-1}$ at 30 years cycle for 100 of years of simulation in mature red pine stand.



Note: 1, 2 and 3 arrows indicate first, second and third thinnings, respectively, scheduled on years-2004, 2034 and 2064. Note that the "one burn thin" treatment was below the target basal area for the first thinning ($22.9 \text{ m}^2 \text{ha}^{-1}$), so it could not be thinned.

Table 3.3: Average and relative live understory (0-11 cms dcl) and overstory (>11 cm dcl) basal area under 100 years of simulation* in mature red pine stands.

Year	Understory-BA				Overstory-BA			
	m ² ha ⁻¹				m ² ha ⁻¹			
	Burn treatments							
	C	1B	2B	4B	C	1B	2B	4B
Beginning								
2003	4.2	2.0	1.2	0.8	18.0	15.1	21.2	23.3
%	19	12	6	3	81	88	94	97
No-management								
2014	5.4	8.5	5.5	4.5	25.8	19.4	27.1	28.2
%	17	31	17	14	83	69	83	86
2044	2.6	5.3	3.3	2.2	46.3	44.7	50.0	51.0
%	5	11	6	4	95	89	94	96
2074	0.5	0.8	0.5	0.4	50.8	52.8	54.0	54.3
%	1	1	1	1	99	99	99	99
2104	0.1	0.1	0.2	0.0	52.3	54.3	54.6	54.9
%	0	0	0	0	100	100	100	100
Thinnings								
2014	5.3	8.5	5.5	4.5	24.8	19.4	25.1	24.8
%	18	31	18	15	82	69	82	85
2044	2.7	4.0	3.0	1.7	32.7	33.1	32.3	32.3
%	8	11	8	5	92	89	92	95
2074	0.7	1.1	1.7	2.7	38.9	39.3	37.4	37.2
%	2	3	4	7	98	97	96	93
2104	0.4	0.4	2.0	1.8	46.7	51.7	48.2	50.3
%	1	1	4	4	99	99	96	96

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

Burn treatments in columns are: C, Unburned Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns

% (in rows) is the percent of total basal area.

dcl=diameter size class.

*Stand basal area does not include removals in thinnings.

**Simulation started on year-2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

in four-burn treatments (Table 3.5). Other species contribution to BA was low and relative BA was highest in unburned treatments and consisted mainly of red maple (13% RBA) and sugar maple (8%). Red pine BA more than doubled in all of the treatments after both managements (Table 3.5). Red pine BA always was higher after burning, and increased with the frequency of burning.

Table 3.4: Average and relative sub-canopy (>11-32 cm dcl), mid-canopy (32 & 42 cm dcl) and dominant overstory (>42 cm dcl) basal area* under 100 years of simulations** in mature red pine stands.

Year	Sub-canopy m ² ha ⁻¹				Mid-canopy m ² ha ⁻¹				Dominant overstory m ² ha ⁻¹			
	Burn treatments											
	C	1B	2B	4B	C	1B	2B	4B	C	1B	2B	4B
Beginning												
2003	2.3	0.8	0.4	0.2	4.0	4.4	5.9	7.3	11.7	9.9	14.9	15.9
%	10	4	2	1	18	26	26	30	53	58	66	66
No-management												
2014	6.7	1.3	0.7	0.3	1.9	2.0	2.9	2.1	17.2	16.1	23.4	25.8
%	21	5	2	1	6	7	9	6	55	58	72	79
2044	18.0	20.6	15.9	14.3	2.9	0.1	0.7	0.9	25.4	24.0	33.4	35.8
%	37	41	30	27	6	0	1	2	52	48	63	67
2074	16.9	23.1	19.9	16.7	4.0	4.4	2.2	2.1	29.8	25.3	31.9	35.5
%	33	43	37	31	8	8	4	4	58	47	59	65
2104	14.1	20.5	20.1	11.3	6.6	7.5	5.2	11.2	31.6	26.3	29.3	32.5
%	27	38	37	21	13	14	9	20	60	48	54	59
Thinnings												
2014	6.4	1.3	0.7	0.3	1.8	2.0	2.5	1.7	16.6	16.1	22.0	22.8
%	21	5	2	1	6	7	8	6	55	58	72	78
2044	14.9	17.2	12.1	10.3	1.9	0.1	0.4	0.5	15.9	15.8	19.8	21.4
%	42	46	34	30	5	0	1	1	45	43	56	63
2074	16.3	22.1	16.9	11.0	6.4	3.5	2.9	4.7	16.2	13.8	17.7	21.5
%	41	55	43	28	16	9	7	12	41	34	45	54
2104	7.8	14.6	13.0	8.4	13.2	18.5	13.8	11.7	25.8	18.6	21.4	30.1
%	16	28	26	16	28	36	28	22	55	36	43	58

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded up to zero.

Burn Treatments columns are: C, Unburned Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns.

% (in rows) is the percent of total basal area.

dcl=diameter size class.

*Stand basal area does not include removals in thinnings.

**Simulation started on year-2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Table 3.5: Average and relative basal area of red pine and other species* combined under different management simulations** for 100 years in mature red pine stand.

Treatments	Year	Red pine m ² ha ⁻¹	% Tot	Others* m ² ha ⁻¹	% Tot	Total m ² ha ⁻¹
Beginning						
Control	2003	16.9	76	5	24	22.2
One Burn		15.3	90	2	10	17.1
Two Burns		21.5	96	1	4	22.5
Four Burns		23.4	97	1	3	24.1
No-management						
Control	2014	22.2	71	9	29	31.2
One Burn		24.2	87	4	13	27.9
Two Burns		31.1	95	1	5	32.6
Four Burns		31.6	97	1	3	32.7
Control	2044	38.4	79	10	21	48.9
One Burn		43.2	86	7	14	50.1
Two Burns		51.3	96	2	4	53.3
Four Burns		51.4	97	2	3	53.2
Control	2074	43.7	85	8	15	51.3
One Burn		50.8	95	3	5	53.6
Two Burns		53.9	99	1	1	54.5
Four Burns		54.5	100	0	0	54.7
Control	2104	46.7	89	6	11	52.4
One Burn		53.2	98	1	2	54.3
Two Burns		54.3	99	1	1	54.8
Four Burns		54.8	100	0	0	54.9
Thinnings						
Control	2014	21.4	71	9	29	30.1
One Burn		24.2	87	4	13	27.9
Two Burns		29.2	95	1	5	30.6
Four Burns		28.3	97	1	3	29.3
Control	2044	25.5	72	10	28	35.4
One Burn		31.1	84	6	16	37.1
Two Burns		33.1	94	2	6	35.3
Four Burns		32.4	95	2	5	34.0
Control	2074	27.7	70	12	30	39.6
One Burn		34.3	85	6	15	40.4
Two Burns		36.1	92	3	8	39.2
Four Burns		37.3	94	3	6	39.8
Control	2104	34.2	73	13	27	47.2
One Burn		46.8	90	5	10	52.1
Two Burns		46.0	92	4	8	50.2
Four Burns		49.2	94	3	6	52.1

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

*Consists of red maple, sugar maple, American beech, black cherry, choke cherry, white ash, non-commercial species, and other minor species.

**Stand basal area does not include removals after thinnings.

% Tot (in columns) is the percent of total basal area.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Importance values (IV) also reflect the dominance of red pine in my stand, both at the beginning and end of the simulations (Table 3.6). The importance of hardwoods declined under no-management but changed little after thinning. Burning increased IV of red pine, especially under no-management.

Table 3.6: Importance (*IV) of all species under no-mangement and thinning simulations** run for 100 years in differently burned mature red pine.

Treatments	Year	Species***						
		AB	BC	CC	RM	RP	SM	WA
Beginning								
Control	2003	2	3	4	13	58	9	3
One Burn		3	3	6	13	61	3	4
Two Burn		2	4	7	8	71	1	1
Four Burn		1	6	7	6	65	3	3
No-management								
Control	2104	1	0	0	7	84	7	0
One Burn		1	0	0	2	96	0	0
Two Burn		2	0	0	1	96	0	0
Four Burn		0	0	0	0	99	0	0
Thinnings								
Control	2104	3	0	0	17	63	16	0
One Burn		6	2	0	8	78	4	1
Two Burn		6	1	2	11	66	5	2
Four Burn		1	7	3	1	70	8	2

*IV is the average of relative density and relative basal area of all trees but does not include removals in thinnings.

**Simulations were started on year 2004.

Non-commercial and other minor species which form a total of <10% are not shown in the column.

Note: Some of the 'zeros' in columns are values $\leq 0.5\%$ and have been rounded to zero.

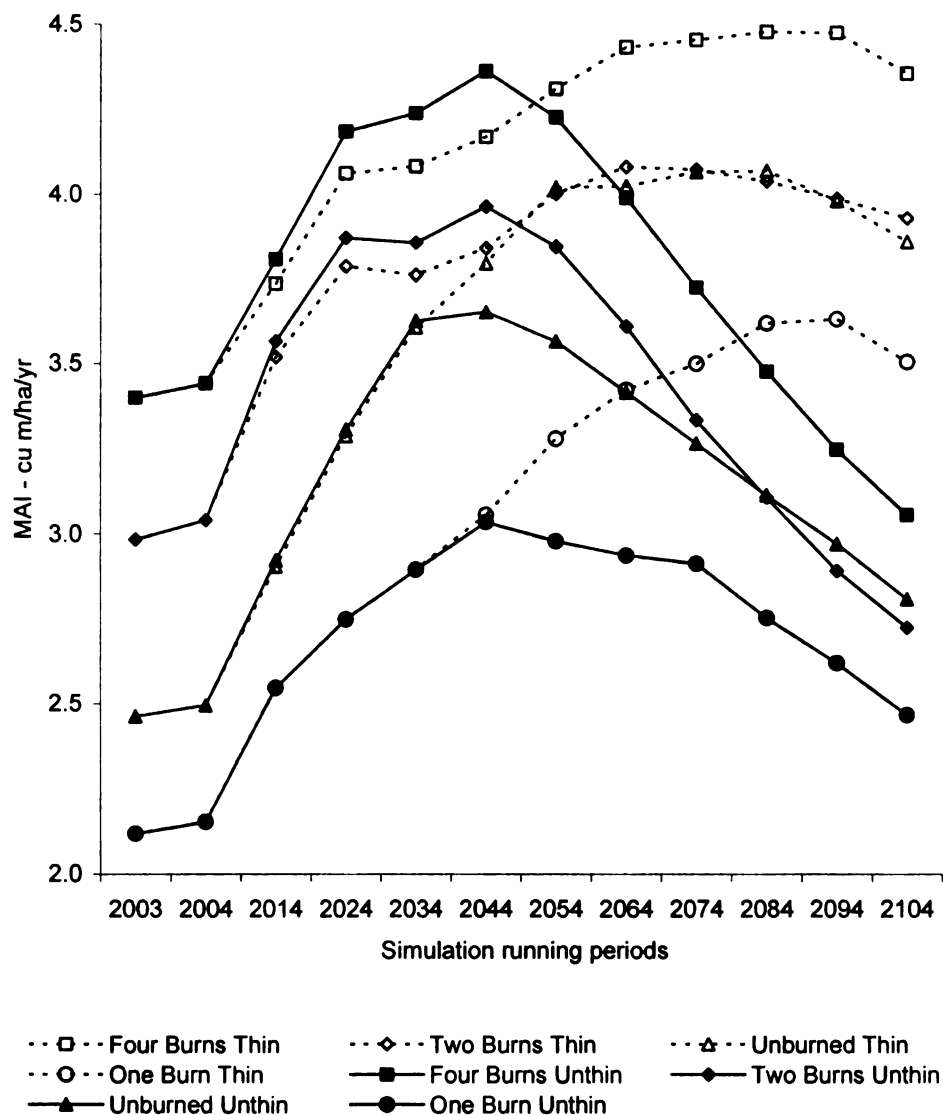
***AB=American beech, BC=black cherry, CC=choke cherry, RM=red maple, RP=red pine, SM=sugar maple, WA=white ash.

3.3.5 Mean annual increment (MAI)

In the beginning of the simulation, mean annual increment (MAI) was highest in four-burn followed by two-burn, unburned controls and one-burn treatments (Figure 3.7). Without any management, MAI increased slowly until 2044 and then declined.

Differences in MAI among treatments were less at the end of the simulation than at the beginning. At the end of thinning, MAI was higher than under no-management and peaked between 2084 and 2094, much later than the unthinned regime (Figure 3.7). As under no-management, MAI was highest in the four-burn treatments than all others throughout the simulation period.

Figure 3.7: Mean annual increment (MAI) in different burn treatments under no-management and thinnings* for 100 years of simulation in mature red pine stand



* First, second and third thinnings were scheduled on years - 2004, 2034 and 2064, respectively.

3.3.6 Sawlog volume

The total standing sawlog volume at the beginning of the simulation was highest in the four-burn plots followed by the two-burn, unburned, and one-burn treatments in decreasing order (Figure 3.8; Appendix 3.3c). In the beginning, most of the sawlog volume was contributed by dominant overstory trees, with less in the mid-canopy and virtually nothing in the sub-canopy (Table 3.7).

Table 3.7: Average and relative standing* sawlog volume of sub-canopy (>11-32 cm dcl), mid-canopy (32-42 cm dcl) and dominant overstory (>42 cm dcl) trees under 100 years of no-management and thinning simulation** in mature red pine stands.

Year	Sub-canopy m ³ ha ⁻¹				Mid-canopy m ³ ha ⁻¹				Dominant overstory m ³ ha ⁻¹			
	Burn treatments											
	C	1B	2B	4B	C	1B	2B	4B	C	1B	2B	4B
Beginning												
2003	1	2	1	0	38	39	51	66	114	95	140	154
%	1	1	0	0	25	29	26	30	75	70	73	70
No-management												
2014	3	5	1	0	17	19	26	19	181	169	243	267
%	2	3	0	0	8	10	10	7	90	88	90	93
2044	8	10	5	9	22	1	4	8	299	281	392	418
%	3	3	1	2	7	0	1	2	91	96	98	96
2074	22	17	20	36	21	27	14	11	352	310	385	428
%	5	5	5	8	5	8	3	2	89	88	92	90
2104	29	22	38	20	33	41	28	58	362	313	350	396
%	7	6	9	4	8	11	7	12	85	83	84	84
Thinnings												
2014	3	5	1	0	16	19	23	15	175	169	228	237
%	2	3	0	0	8	10	9	6	90	88	91	94
2044	12	9	3	8	14	1	3	4	188	186	233	251
%	6	5	1	3	7	0	1	2	88	95	97	95
2074	30	28	29	26	34	22	17	27	189	170	218	265
%	12	13	11	8	13	10	7	9	75	77	82	83
2104	12	29	26	14	66	81	72	66	266	216	257	348
%	4	9	7	3	19	25	20	15	77	66	73	81

Burn Treatments columns are: C, Unburned Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns

% (in rows) is the percent of total sawlog volume.

*Standing volume does not include removals in thinning.

**Simulation started on year-2004.

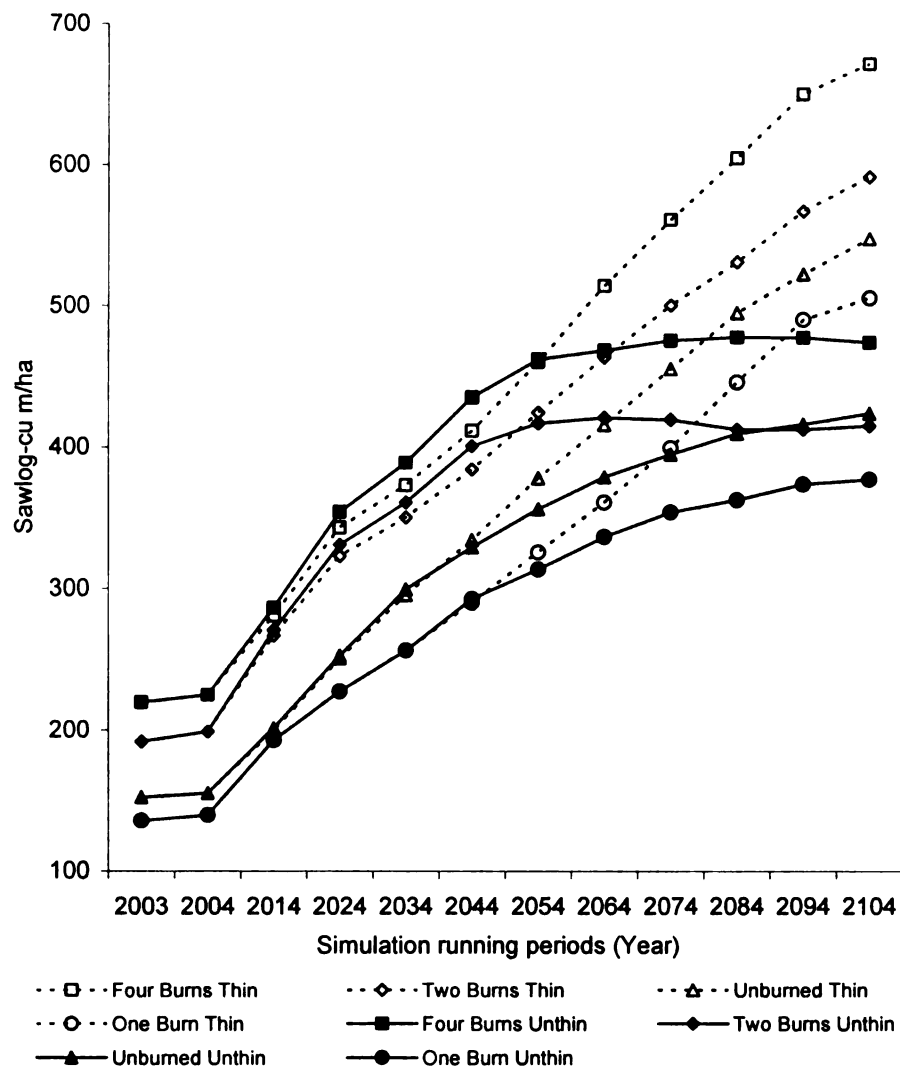
The first, second and third thinnings occurred in 2004, 2034, and 2064.

During no-management and thinning, standing sawlog volume increased gradually towards the end; however, with a flattening curve in all treatments after year 2054. Total standing sawlog volume was slightly lower after thinning by 45 to 80 m³ ha⁻¹ in all of the treatments compared to no-management (Table 3.7; Appendix 3.3c). However, total cumulative volume (including thinning removals) was much higher in the thinned than unthinned regimes at the end of the simulation, with no decline in production (Figures 3.8 and 3.9). Among the burn treatments, the four-burn plots continually produced the highest cumulative sawlog volume, whereas the once-burned treatment produced the least (Figure 3.10). The relative effects of burns on sawlog production declined as simulation progressed for both managements. Differences among different burns in cumulative sawlog production were higher after thinning than no-management, especially in four-burn treatments.

At the end of both managements, the proportional change in relative volume was substantial in sub-canopy trees but they never constituted more than 13% of the standing volume. Even the four-burn treatments, which did not have any live sawlog in sub-canopy stratum in the beginning increased to 3 to 4% of total sawlog by the end of both managements. The proportion of total volume in mid-canopy overstory trees dropped somewhat during the simulation, especially under no-management where 84% of the volume was in the dominant overstory. Almost no change occurred in the relative standing volume of the dominant overstory in the thinning regimes but it increased under no-management.

Red pine was the major contributor to sawlog volume (96% to 100%) both in the beginning and at the end of simulation in most of the burning management regimes. However, at the end of thinning, the volume in red pine in the unburned controls had declined to 84% (Appendix 3.4), with the remaining volume made up by red and sugar maple.

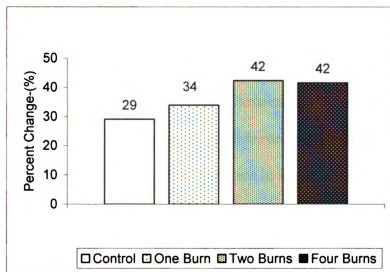
Figure 3.8: Average cumulative* sawlog volume in different treatments under no-management and thinning** for 100 years of simulation in mature red pine stand.



*Includes the volume removed in thinning.

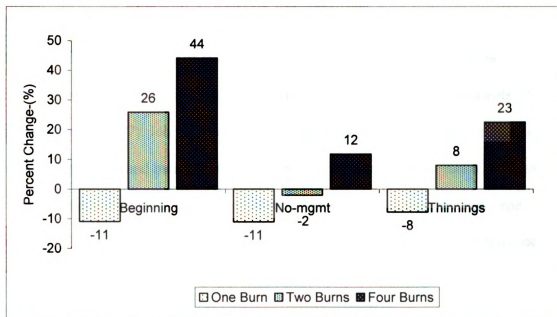
** First, second and third thinning were scheduled on years - 2004, 2034 and 2064, respectively.

Figure 3.9: Percent change of cumulative* sawlog production after thinnings over no-management in different burn treatments for 100 years of simulation in mature red pine.



*Includes volume removed in thinnings.

Figure 3.10: Percent change of cumulative* sawlog production under different burn treatments and management over unburned controls run for 100 years in mature red pine stands.



*Includes volume removed in thinnings.

3.4 Discussion

The inequality in size classes in the beginning of the simulation due to dense recruitment is reflected in the stratified distribution of trees in all of the burned and unburned treatments and is typical of mature and productive forests that are regenerating and growing aggressively (Peet and Christensen 1987, Leak et al. 1995). The extremely high tree density observed in all of the burned plots was due to newly established post-fire regeneration, which caused variation in size classes and a highly left-skewed distribution.

At the start of and during no-management simulations, self-thinning and mortality, occurring mainly in the smaller understory layer, resulted in the decline in size class inequality (Peet and Christensen 1987). These processes in my stands match with the stand initiation and stem exclusion phases of stand development (Bormann and Liken 1979, Peet and Christensen 1987). Mortality occurs after crown closure, as the suppressed trees cannot compete for light, water, growing space or soil nutrients (Peet and Christensen 1987). Johnstone et al. (2004), found aspen and lodgepole pine to decline due to self-thinning and mortality a decade after burning in a boreal system in Yukon British Columbia, Canada. The canopy closure timing matches with my study site, inventoried 10 to 18 years after prescribed burns were carried out; thus self-thinning and mortality were already occurring.

Mortality caused a sharp decline in small-sized understory trees in all treatments under no-management. At the end of no-management, slower understory growth and

reduced ingrowth to sub-canopy trees resulted in the lowest overstory tree density in unburned controls. One- or two- burn treatments are sufficient to kill unwanted vegetation and decrease competition, resulting in faster growth as well as higher ingrowth (shifting) of large understory to sub-canopy trees compared to unburned and four-burn treatments, both of which had lower initial sub-canopy densities. Four-burn treatments completely lacked large-sized understory trees. Single and multiple fires reduced 60 to 80% of 2 to 10 cm size class (i.e., large-sized understory) fire sensitive species in oak forests of the Cumberland Plateau (Arthur et al. 1998). Species richness of large woody understory species in pine understories was reduced immediately by even a single burn (Henning and Dickmann 1996, Neumann and Dickmann 2001). At the end of no-management, destruction of the sub-canopy trees during repeated burnings lowered the sub-canopy density and BA the most in the four-burn treatments. Low-intensity fires instantly kill red and white pines below 15 cm diameter class or 6 m height (McConkey and Gedney 1951, Van Wagner 1970). Whereas the pines <18 m tall are susceptible to fires (Henning and Dickmann 1996). Red pine trees with up to 75% of the crown scorched survive fires (Van Wagner 1970), although some with >75% crown scorching may die later. Mature red pines with >95% crown scorching had up to 50% mortality (Van Wagner 1970). In my four-burn treatments, repeated burnings every two years may have increased exposure of already scorched mature but small stature (low height) trees, leading to death of some of them. In the Pigeon River area (other than the study plots), some mature red pine trees with >90% crown scorch even if not killed instantly, were killed later by bark beetles.

As no-management simulations progressed, diameter distribution became more normal with a shift to older age classes forming a more positively skewed distribution than in the beginnings (Mohler et al. 1978, Peet and Christensen 1987). All of the treatments formed a bi-modal stand structure with higher densities in dominant overstory classes than in the beginning, because burning, at the cost of smaller understory trees, stimulated faster growth in larger size classes. This effect was more pronounced in progressively burned treatments.

All treatments lost a remarkably high proportion of understory trees by the end of no-management and according to Cullen and Leak (1988 in Leak et al. 1995) such decline to <10% relative understory tree density would not sustain productivity. In contrast, frequent burning plus thinning produced a relatively dense understory, which could sustain productivity and could be the basis for a succeeding stand if the overstory was removed. The gaps created during thinnings reduced understory mortality and stimulated faster growth of dominant trees while burning created a favorable seed bed for seedling recruitment. In 63-year-old unthinned pine stands mortality was ten times higher than in similar but thinned stands (Burgess and Robinson 1998). Thinning increases diameter growth which is greater in progressively heavier thinned plots (Buckman 1962, Day and Rudolph 1972). Increased light level enhanced seedling survival and also their height, diameter and volume growth after thinning young red and white pine plantations and hardwood stands (Volk and Fahey 1994, Stiell et al. 1994, Burgess and Robinson 1998, Parker et al. 2001). They also suggested that such gaps enhance succession in young red pine plantations.

The repeatedly burned treatments (two- and four-burn) responded quickly to thinnings and they produced a higher density of large-sized understory trees than in other treatments. Large-sized understory trees must have developed from post-fire recruitments in repeatedly burned plots, since they lacked them in the beginning. Larger understory trees are stronger and more vigorous (Smith 1986, Nyland 1996) and they will enhance future productivity of forests (Leak et al. 1995) and create a more complex long-term stand structure.

The occurrence of dense and aggressively growing understory seedlings and saplings and their shifting to larger diameter classes, particularly in the two- and four-burn treatments, created a tri-modal stand structure in which the overstory (>11 cm dcl) shifted to the right in progressively higher size classes after thinnings. Increase in understory trees after thinning, however, produced less sub-canopy but more mid-canopy trees as compared to no-management. Among different burn treatments after thinning, four-burn treatments had little size or age class differentiation in 17-47 cm dcl as compared to two- and one-burn treatments. This shows that four-times burning, in the long run, created more uniformity in overstory size classes or reduced the variation among the overstory size classes as compared to two- and one-burn treatments. One-burn treatments had the highest sub-canopy tree density and variation in overstory tree size classes.

Burning and thinning interactions did not produce much difference in BA among different treatments, although four-burn plots always maintained the highest overall BA

for both simulations. BAs in my study plots, in the beginning, were one-half to one-third of what has been predicted for a red pine plantation of the same age and site index by Benzie (1977). Such a low residual BA after thinning increases the future diameter growth of retained trees (Haberland and Wilde 1961; Lundgren 1981) but reduces the overall BA, MAI and the ultimate volume production of red pine stand as there is vacant space that is not utilized by the overstory (Gilmore 2005). At the end of no-management, the overall BA produced was similar to that suggested by Burgess and Robinson (1998), who found the BA in their 101-year-old unthinned white and red pine stands to be $51 \text{ m}^2 \text{ ha}^{-1}$. Similarly, in another study the BA in unthinned stands was about $52.7 \text{ m}^2 \text{ ha}^{-1}$, varying, however, with mortality (Spurr et al. 1957). Yet, my study plots were much older (173-year-old) at the end than the stands in these examples. The FVS predicted BAs were low because a low residual BA ($\sim 10 \text{ m}^2 \text{ ha}^{-1}$) was retained during earlier thinnings carried out in the year 1970 (Henning and Dickmann 1996), i.e., long before the current prescribed burn study started. At a given age and SI, BA growth will be about the same (Buckman 1962), whereas at mature age growth is affected by SI, tree age and density (Lundgren 1981).

Partial or complete killing of understory vegetation and sub-canopy trees due to repeated burnings reduced competition and enhanced diameter growth of mature overstory trees, which increased MAI and sawlog volume. However, the effects were not great. During no management, the differences both in MAI and sawlog volume between treatments started narrowing after the decline of overall tree productivity at age 113 years, which matches closely to the growth culmination age predicted by Lundgren

(1981). He showed that production levels off when plantations exceeded 3954 tpha. If stands are not thinned for a long period both the net and gross volume production decline due to self-thinning and mortality (Coffmann 1976).

MAI after thinning in four-burned treatments started picking up and increased up to year 2094 (age 163) before it declined after thinning. Four-burn treatments always had highest growth; however, they started higher also. Despite starting higher, there was still somewhat higher growth in four-burn treatments as compared to other treatments, especially after the second thinning. In addition to the effects of burning, the gaps created by removal of large overstory trees and the cutting cycle during thinning provided additional space and resources (light, moisture, nutrients, and space) to the residual trees increasing their growth and vigor. The result is consistent with one of the major objectives of thinning, which shortens the rotation age (Lundgren 1983); i.e., intended volume can be obtained earlier than in unthinned stands. In my study, the continued growth of red pine stands up to 163 years was because of the actively growing young post-fire recruitments that were released after thinning. Thus, the effects of multiple (frequent) burnings lasted long for MAI and sawlog production after thinning. These results have important implications for the management of red pine forests.

At the end of my study, percent change of cumulative sawlog volume over unburned control declined as simulation progressed during both managements in repeatedly burned plots; however, this effect was not pronounced if thinning occurred. A 13% higher percent change of cumulative volume over no-management in four- and two-

burn treatments than in unburned controls after thinning show that there was a remarkable increase in cumulative sawlog volume in repeatedly burned treatments, even though they had higher values to start with. The multiple burned plots acquired higher growth vigor from earlier burnings carried out one to almost two decades before the measurements were taken for this study. Removal of dominant overstory trees increases radial increment of the retained overstory trees, resulting in the increase of net volume and yield (Assman 1970, Nyland 1996). Removal also lowered the total standing overstory sawlog volume compared to no-management; however, when the volume removed during thinnings was included there was a net increase in cumulative sawlog volume (cf. Coffmann 1976). The slight decrease in relative volume of red pine in burned plots after thinning as compared to no-management, as well as the higher decrease in unburned controls when thinned were due to an increase of hardwood volume, especially red and sugar maple.

Red pine dominance increased in burned treatments as the shade intolerant species—black cherry, choke cherry, white ash and other minor hardwood species—declined gradually and disappeared during no-management simulations. These findings are backed up by the increase in IV of red pine in all treatments, especially the burned ones. Bormann and Likens (1979) also suggested such a shift in relative importance (IV) among species due to mortality of those suppressed ones during self-thinning. Thus, if unmanaged for a long time, mature red pine stands lose hardwood species, especially shade intolerants, and become low in species richness. There was virtually no new regeneration in the no-management treatments, as post-fire recruitment depends on time

elapsed after fire. For example, it occurred in first five years after fire in boreal forests in British Columbia, Canada (Johnstone et al. 2004). Mineral soil gradually becomes covered with re-growth and litter deposits that prevent seeds from germinating and establishing (Metheven and Murray 1974). Red and white pines and hardwood species (except birches and black cherry) failed to establish under different managements, including clearcutting (McRae 1994, Smith and Ashton 1993). However, burning and thinning reduced depth of organic matter, exposed mineral soil and increased pine seedling establishment (Little and Moore 1949, Buel and Cantlon 1953, Thomas and Wein 1985, Mallik and Roberts 1994, Duvall and Grigall 1999).

Despite lack of new recruitments in most treatments, new red pine and hardwood recruits established in the understory in four-burn plots after thinning. Other hardwood species recruits were also very high compared to the red pine in two-burn plots. Relatively more shade tolerant red and sugar maple recruit in smaller gaps (Abrams 1982, Arthur et al. 1998). Smaller gaps are covered within two to three years of their formation, whereas larger gaps increase species richness and biodiversity (Parker et al. 2001) and such gaps were created during successive thinnings of burned treatments in this study. The new recruits reveal that the forest floor in two- and four-times burned treatments remained relatively more suitable for germination and establishment for a longer period than other treatments. Single and multiple burns have been suggested for successful eradication or control of unwanted understory vegetation such as balsam fir and hazel-nut in red pine plantations as well as pine seedling germination and establishment (Van Wagner 1970, Alban 1977). Further, reduction in mortality after thinning reduces the

coarse woody debris in the young stands and might facilitate seeds of some species to reach soil (Duvall and Grigall 1999). Three times thinning of red and white pine stands increased recruitment of understory shrubs and other species (Bender et al. 1997, Burgess and Robinson 1998). Besides increase in IV of red maple and sugar maple, beech and cherries also persisted in my study. Volk and Fahey (1994) also found that black cherry (a short lived shade intolerant species) had higher mortality in the unthinned than in the thinned Alleghany hardwood forest.

Dense understory seedlings and their mortality resulted in higher red pine sub-canopy density, relative density and faster growth of residual trees, especially in one- and two-burn treatments after no-management compared to thinning. However, removal of trees after thinning reduced competition and enabled residual large-sized trees of other sub-canopy species to grow by more than two-fold in burned plots, compared to no-management. Increase in IV of other hardwood species after thinning compared to no-management has important ecological and management implications. Increase in hardwood species provides better habitat, cover, mast and browse for wild animals, as well as hunting and recreational scope (Little and Moore 1949, Rouse 1988, Dickmann 1993, Bender et al. 1997), in addition to biodiversity benefits.

Comparison between the total merchantable volume production by FVS in this study and that predicted by Benzie (1977) for similar age and SI shows that FVS predicted volume was slightly lower than that of Benzie in the beginning of the simulation (Appendix 5.5). At age 143 the standing merchantable volume change

obtained for no-management was within a range of -12 to +12% compared to Benzie's values in all treatments, with the highest in four-burn and lowest in one-burn treatments. However, the cumulative volume predicted was much higher than Benzie for similar age and SI after thinning, with the highest in four-burn and the lowest in one-burn treatments. These predictions would actually be even higher if trees removed during thinning in 1970 (Hennings and Dickmann 1987) had been included in the FVS projections. In this study, the high variation in volume predicted by FVS could also be because the FVS model was developed for young red pine plantations or natural stands without disturbance, whereas I used it to simulate differently burned plots. However, considering such a very long projection period of FVS simulation (100 years), the result could still be considered useful in red pine management.

3.5 Summary

Mature red pine stands re-measured one to two decades after prescribed burnings (one-, two- and four-times burned) and projected through FVS for 100 years with and without a series of thinnings showed unique differences in vegetative and growth responses. The long-term effects depended on number of burnings and thinnings and their combinations and also the past history of disturbances. Stand structure, species composition, density, BA and volume changed differently among burned and unburned treatments as simulations progressed.

1. Extremely dense post-fire regeneration and inequality in size-classes at the outset showed increased productivity of the burned stands, but the regeneration experienced high mortality compared to unburned controls.
2. Decline in density started at the time of re-measurement of the stands, i.e., 10-18 years after burning, and was due to self-thinning mortality; however, a sharp decline occurred five to six decades after burnings.
3. Lower mortality, slower growth and reduced ingrowth occurred in unburned controls. However, unburned plots retained the highest small understory and lowest overstory density.
4. High red pine sub-canopy density produced by one- and two-times burnings at the end of no-management indicate that fires were sufficient to kill competing low vegetation, including some of the sub-canopy red pines in the beginning, and stimulated growth of small diameter red pines for a long period.

5. Low sub-canopy density due to fire-caused mortality and increase in mid-canopy trees due to ingrowth in four-burn treatments indicate that fire effects were long-term and still apparent after a century.
6. Thinnings slowed down mortality and enhanced recruitment of understory trees in burned plots, resulting in an increase in an inequality in size classes, in contrast to decrease in inequality during no-management.
7. Two- and four-burn treatments produced dense, aggressively growing understory seedling and saplings after thinning, and such repeated burns were more productive.
8. A tri-modal stand structure developed in progressively burned plots due to growth of larger trees as compared to the bimodal stand structure after no-management.
9. Four-times burning created a more uniform structure across size classes in sub- and mid-canopy layers (17-47 cm dcl) as compared to two- and one-burn treatments.
10. MAI in repeatedly burned treatments, particularly the four-burn, was greater and faster for both managements, indicating stimulated growth both in the understory and overstory. MAI declined at age 113 in unthinned simulations but not until age 163 in thinned simulations. In both cases, the growth culmination age was much greater than normal for red pine and was due to both fast-growing, dense post-fire understory after burning and their release after thinning.
11. Four-burn treatments, particularly after the second thinning, produced highest cumulative volume although they started higher in the beginning. Also, higher

- percent change of volume production in burned treatments over no burning after thinning reveals that the effects of burning can be extended for a long period.
12. Red pine dominance was highest in burned plots throughout both simulations, followed by red and sugar maple. The latter two species were better represented in unburned controls compared to burned treatments at the end of no-management.
 13. Disappearance of most hardwood species (except red maple, sugar maple and American beech) and occurrence of few new recruits regardless of burnings by the end of no-management indicates that species diversity declined as succession progressed. In contrast, repeated burnings followed by multiple thinnings increased the establishment, growth and sustenance of red pine as well as other hardwood species for period as long as a century; consequently, species diversity increased as succession progressed.
 14. The highest ingrowth of red pine density into the sub-canopy in burned plots, as well as new red pine and hardwood recruits in the understory show increased sustainability of red pine, along with other species, when thinned.

3.6 Conclusion

Frequent burning in mid-rotation, especially if combined with subsequent thinning, could be the basis of long-term sustainability, high productivity, and increases in biodiversity of red pine stands.

APPENDICES

Appendix 2.1: Species codes

The following species codes have been used in the tables and text

Latin names	Species codes	Common names
<i>Acer rubrum</i>	RM	Red maple
<i>Acer saccharum</i>	SM	Sugar maple
<i>Amelanchier</i> spps	AM	Juneberry
<i>Fagus grandifolia</i>	AB	Beech
<i>Fraxinus americana</i>	WA	White ash
<i>Ostrya virginiana</i>	HH	Eastern hophornbeam
<i>Pinus resinosa</i>	RP	Red pine
<i>Pinus strobus</i>	WP	White pine
<i>Prunus serotina</i>	BC	Black cherry
<i>Prunus virginiana</i>	CC	Choke cherry

Following species are grouped under the different species codes and each of the species constitutes less than 1% of total density in my study.

NC (Non commercial trees) and others:

	<i>Acer pensylvanicum</i>	ST	Stripped Maple
	<i>Betula alleghaniensis</i>	YB	Yellow birch
	<i>Hamamelis virginiana</i>	WH	Witch hazel
	<i>Malus baccata</i>	SC	Siberian crab apple
	<i>Populus balsamifera</i>	BP	Balsam poplar
	<i>Populus grandidentata</i>	BT	Bigtooth aspen
	<i>Populus tremuloides</i>	QA	Quaking aspen
	<i>Prunus pensylvanicum</i>	PR	Pin cherry
	<i>Salix</i> spps	WI	Willow
	<i>Tilia americana</i>	BW	Bass wood
	<i>Tsuga canadensis</i>	EH	Hemlock
	<i>Ulmus americana</i>	AE	American elm
	<i>Viburnum acerifolium</i>	MV	Maple-leaf Viburnum
Oaks:	<i>Quercus rubra</i>	RO	Red oak
	<i>Quercus alba</i>	WO	White oak
	<i>Quercus velutina</i>	BO	Black oak

Appendix 2.2: Density, Basal Area, Volume, MAI and Importance Value (IV) of Overstory trees under different burns.

Density (trees ha ⁻¹)	Percent of total										Percent of total		Total			
	Treatments	BW	JP	Percent of total	RM	Percent of total	RP	Percent of total	SM	Percent of total	WA	Percent of total		WP		
Control One Burn Two Burns Four Burns	Control	0	0	27	8	105	32	116	35	73	22	0	0	10	3	332
	One Burn	0	0	24	17	0	0	118	82	2	1	0	0	0	0	144
	Two Burns	0	0	1	1	16	10	139	89	0	0	0	0	0	0	156
	Four Burns	2	1	0	0	0	0	148	95	0	0	6	4	0	0	156
Basal Area																
Control One Burn Two Burns Four Burns	Control	0	0	1	3	1	7	16	82	1	7	0	0	0	1	19.3
	One Burn	0	0	0	2	0	0	18	97	0	2	0	0	0	0	18.6
	Two Burns	0	0	0	1	0	2	21	97	0	0	0	0	0	0	21.4
	Four Burns	0	1	0	0	0	0	23	98	0	0	0	1	0	0	23.3
Volume																
Control One Burn Two Burns Four Burns	Control	0	0	3	1	7	4	182	89	11	5	0	0	1	0	203.9
	One Burn	0	0	1	1	0	0	191	98	3	2	0	0	0	0	195.1
	Two Burns	0	0	1	0	3	1	223	98	0	0	0	0	0	0	227.0
	Four Burns	2	1	0	0	0	0	258	99	0	0	2	1	0	0	261.8
MAI																
Control One Burn Two Burns Four Burns	Control	0	0	0	1	0	4	3	94	0	0	0	0	0	0	2.7
	One Burn	0	0	0	1	0	0	3	99	0	0	0	0	0	0	2.8
	Two Burns	0	0	0	0	1	3	98	0	0	0	0	0	0	0	3.2
	Four Burns	0	1	0	0	0	0	4	98	0	1	0	1	0	0	3.7
IV (%)																
Control One Burn Two Burns Four Burns	Control	0	17	50	186	43	0	0	4							
	One Burn	0	24	0	267	9	0	0	0							
	Two Burns	0	6	16	278	0	0	0	0							
	Four Burns	6	0	0	285	4	5	0	0							

Note: IV is the sum of relative density, frequency and basal area of trees.

Appendix 2.3: Basal Area, Volume & MAI of Overstory trees under different Diameter size classes

Diameter Classes in cm and the corresponding percent of totals (%)																																				
Treatments	10	11	%	12	17	%	17	22	%	22	27	%	27	32	%	32	37	%	37	42	%	42	47	%	47	52	%	52	57	%	57	62	%	62	Total	
Basal Area																																				
(m ² ha ⁻¹)																																				
Control	0.7	3	1.6	9	0.4	2	0.6	3	0.2	1	0.6	3	3.1	16	4.0	21	5.4	28	2.7	14	0.0	0	19.1													
One Burn	0.0	0	0.3	2	0.2	1	0.2	1	0.3	2	1.4	8	3.8	21	3.7	21	6.3	35	1.9	11	0.0	0	18.1													
Two Burns	0.0	0	0.3	1	0.2	1	0.2	1	0.0	0	1.9	9	3.2	15	7.5	34	5.9	27	2.9	13	0.2	1	22.3													
Four Burns	0.0	0	0.0	0	0.2	1	0.0	0	0.0	0	1.0	4	5.0	22	9.9	43	5.5	24	1.7	7	0.0	0	23.3													
Volume																																				
(m ³ ha ⁻¹)																																				
Control	4	2	9	5	2	1	4	2	2	1	5	3	39	19	46	23	63	31	29	14	0	0	203.9													
One Burn	0	0	1	1	1	1	1	1	2	1	17	9	42	22	39	20	69	36	21	11	0	0	195.1													
Two Burns	0	0	1	1	1	1	0	1	1	0	0	20	9	27	12	78	34	65	29	31	14	2	1	227.0												
Four Burns	0	0	0	0	2	1	0	0	0	0	11	4	57	22	110	42	63	24	19	7	0	0	261.8													
MAI																																				
(m ³ ha ⁻¹ yr ⁻¹)																																				
Control	0.1	2.0	0.1	4.6	0.0	0.9	0.1	2.1	0.0	1.0	0.1	2.6	0.5	18.7	0.6	22.3	0.9	30.6	0.4	14.2	0.0	0.0	2.9													
One Burn	0.0	0.0	0.0	0.7	0.0	1.9	0.0	0.7	0.0	0.0	0.2	9.1	0.6	22.0	0.5	20.3	1.0	36.2	0.3	10.9	0.0	0.0	2.7													
Two Burns	0.0	0.0	0.0	0.6	0.0	0.5	0.0	0.5	0.0	0.0	0.3	8.8	0.4	11.9	1.1	34.2	0.9	28.8	0.4	13.6	0.0	1.0	3.2													
Four Burns	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.2	4.3	0.8	21.5	1.5	41.7	0.9	24.1	0.3	7.3	0.0	0.0	3.7													

Appendix 3.1: Average relative understory (0-11 cms dcl) tree density* under 100 years of no-management and thinning simulations** in mature red pine stands.

Year	Small understory (0-6 cm)				Large understory (6-11 cm)			
	trees ha ⁻¹				trees ha ⁻¹			
	Burn tr Burn treatments							
	C	1B	2B	4B	C	1B	2B	4B
Beginning								
2003	9545	18752	19756	16725	324	46	37	0
%	95	99	99	99	3	0	0	0
No-management								
2014	8007	15719	15755	13735	411	424	147	242
%	91	97	98	97	5	3	1	2
2044	477	3000	1949	2941	300	412	243	118
%	31	67	63	78	20	9	8	3
2074	72	58	48	20	54	75	43	51
%	11	6	7	3	8	8	6	9
2104	31	9	10	7	14	9	20	0
%	7	2	2	2	3	1	4	0
Thinnings								
2014	7824	15719	15455	13086	402	424	145	239
%	91	97	98	97	5	3	1	2
2044	1527	2970	2897	3052	256	290	145	57
%	65	73	79	85	11	7	4	2
2074	297	573	960	1591	53	51	57	129
%	36	48	64	78	6	4	4	6
2104	66	56	450	633	40	45	159	78
%	14	10	43	56	8	8	15	7

Note: Some of the 'zeros' in % column of BA have values below 0.5% and have been rounded to zero.

Burn Treatments columns are: C, Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns

% (in rows) is the percent of total woody understory tree density.

dcl=diameter size class.

*Stand density does not include removals in thinnings.

**Simulation started on year-2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.2: Average and relative sub-canopy (>11-32 cm dcl), mid-canopy (32 & 42 cm dcl) and dominant overstory (>42 cm dcl) tree density* under 100 years of simulations** in mature red pine stands.

Year	Sub-canopy trees ha ⁻¹				Mid-canopy trees ha ⁻¹				Dominant overstory trees ha ⁻¹			
					Burn treatments							
	C	1B	2B	4B	C	1B	2B	4B	C	1B	2B	4B
Beginning												
2003	103	26	10	6	33	36	50	58	63	53	82	90
%	1	0	0	0	0	0	0	0	1	0	0	1
No-management												
2014	287	37	30	10	16	16	24	17	82	76	111	132
%	3	0	0	0	0	0	0	0	1	0	1	1
2044	624	980	790	564	28	1	7	8	90	82	114	133
%	41	22	25	15	2	0	0	0	6	2	4	4
2074	414	653	526	372	37	42	20	23	98	71	95	114
%	61	73	72	64	6	5	3	4	14	8	13	20
2104	277	451	378	245	62	67	48	104	99	75	87	96
%	57	74	70	54	13	11	9	23	20	12	16	21
Thinnings												
2014	276	37	26	9	15	16	21	14	79	76	103	116
%	3	0	0	0	0	0	0	0	1	0	1	1
2044	483	770	569	410	17	0	4	4	56	54	66	77
%	21	19	15	11	1	0	0	0	2	1	2	2
2074	359	497	398	222	59	34	28	46	52	37	49	62
%	44	42	27	11	7	3	2	2	6	3	3	3
2104	161	252	240	223	123	174	127	99	94	57	59	96
%	33	43	23	20	25	30	12	9	19	10	6	8

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded up to zero.

Burn Treatments columns are: C, Unburned Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns.

% (in rows) is the percent of total tree density.

dcl=diameter size class.

*Stand density does not include removals in thinnings.

**Simulation started on year-2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.3a: Average tree density* (trees ha⁻¹) and their relative values (%) by diameter classes under different management simulations for 100 years.

Treatments	Year	0-6	%	6-11	%	11-17	%	17-22	%	22-27	%	27-32	%	32-37	%	37-42	%	42-47	%	47-52	%	52-57	%	57-62	%	>62	%	Total	%	
Beginning	Control	2003	9545	95	324	3	83	1	6	0	12	0	3	0	10	0	23	0	28	0	28	0	7	0	0	0	0	0	10067	15
	One Burn		18752	99	46	0	13	0	6	0	4	0	3	0	10	0	27	0	23	0	23	0	7	0	0	0	0	0	18913	29
	Two Burns		19756	99	37	0	0	0	6	0	4	0	0	0	20	0	30	0	45	0	28	0	8	0	1	0	0	0	19934	30
	Four Burns		16725	99	0	0	0	0	6	0	0	0	0	0	14	0	45	0	59	0	28	0	3	0	0	0	0	0	16879	26
	No-management																													
2014	Control		8007	91	411	5	184	2	83	1	11	0	9	0	3	0	13	0	27	0	23	0	28	0	4	0	0	0	8803	16
	One Burn		15719	97	424	3	24	0	3	0	0	0	10	0	4	0	12	0	21	0	25	0	22	0	7	0	1	0	16273	29
	Two Burns		15755	98	147	1	21	0	2	0	6	0	0	0	4	0	20	0	32	0	40	0	26	0	10	0	2	0	16067	29
	Four Burns		13735	97	242	2	5	0	0	0	5	0	0	0	7	0	10	0	50	0	54	0	24	0	3	0	0	0	14136	26
	2044																													
2044	Control		477	31	300	20	302	20	222	15	74	5	26	2	23	2	5	0	2	0	15	1	19	1	26	2	28	2	1519	12
	One Burn		3000	67	412	9	776	17	126	3	68	2	10	0	0	0	1	0	3	0	10	0	22	0	19	0	28	1	4476	35
	Two Burns		1949	63	243	8	669	22	75	2	40	1	5	0	7	0	0	0	5	0	15	0	23	1	30	1	41	1	3103	24
	Four Burns		2941	78	118	3	329	9	147	4	87	2	1	0	2	0	5	0	5	0	19	0	41	1	43	1	26	1	3763	29
	2074																													
2074	Control		72	11	54	8	75	11	144	21	352	21	52	8	23	3	14	2	19	3	3	0	12	2	13	2	51	8	675	23
	One Burn		58	6	75	8	129	14	355	39	126	14	43	5	32	4	10	1	0	0	2	0	5	1	13	1	51	6	899	31
	Two Burns		48	7	43	6	69	9	246	34	182	25	29	4	12	2	8	1	2	0	4	1	11	2	18	2	59	8	731	25
	Four Burns		20	3	51	9	47	8	139	24	97	17	89	15	22	4	0	0	5	1	5	1	12	2	35	6	57	10	579	20
	2104																													
2104	Control		31	7	14	3	30	6	46	10	104	22	97	20	37	8	25	5	6	1	24	5	7	1	11	2	51	11	483	23
	One Burn		9	2	9	1	64	10	130	21	147	24	110	18	41	7	26	4	14	2	1	0	1	0	4	1	54	9	612	29
	Two Burns		10	2	20	4	48	9	35	6	160	30	135	25	31	6	17	3	11	2	2	0	8	1	11	2	55	10	544	26
	Four Burns		7	2	0	0	44	10	54	12	83	18	63	14	66	15	38	8	4	1	3	1	7	2	20	4	62	14	453	22

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.
 % in columns are the percent of total density. *Stand density does not include removals in thinnings. **Simulation started on year- 2004.
 The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.3a (continued): Average tree density* (trees ha⁻¹) and their relative values (%) by diameter classes under different management simulations for 100 years.

Treatments Year	0-6	% 6-11	% 11-17	% 17-22	% 22-27	% 27-32	% 32-37	% 37-42	% 42-47	% 47-52	% 52-57	% 57-62	% >62	% Total														
Thinnings																												
Control 2014	7824	91	402	5	177	6	81	1	10	0	8	0	3	0	12	0	26	0	22	0	27	0	4	0	0	8596	16	
One Burn	15719	97	424	3	24	0	3	0	0	10	0	4	0	12	0	21	0	25	0	22	0	7	0	1	0	16273	30	
Two Burns	15455	98	145	1	19	0	2	0	5	0	0	4	0	17	0	29	0	38	0	25	0	10	0	2	0	15750	29	
Four Burns	13086	97	239	2	5	0	0	4	0	0	4	0	9	0	42	0	50	0	21	0	3	0	0	0	13463	25		
Control 2044	1527	65	256	11	220	28	165	7	55	2	44	2	13	1	4	0	2	0	9	0	12	0	14	1	20	1	2340	17
One Burn	2970	73	290	7	596	44	114	3	52	1	8	0	0	0	0	2	0	6	0	14	0	13	0	19	0	4084	30	
Two Burns	2897	79	145	4	461	38	72	2	32	1	3	0	4	0	0	2	0	9	0	13	0	17	0	26	1	3681	27	
Four Burns	3052	85	57	2	256	21	90	2	61	2	2	0	1	0	3	0	2	0	8	0	22	1	28	1	17	0	3600	26
Control 2074	297	36	53	6	77	28	81	10	107	13	94	11	36	4	23	3	8	1	8	1	4	0	3	0	29	4	819	15
One Burn	573	48	51	4	57	14	143	12	225	19	71	6	22	2	11	1	2	0	1	0	2	0	3	0	30	2	1192	21
Two Burns	960	64	57	4	68	14	123	8	137	9	70	5	23	2	5	0	4	0	0	0	3	0	5	0	37	2	1492	27
Four Burns	1591	78	129	6	12	2	71	3	72	3	67	3	37	2	9	0	4	0	3	0	3	0	6	0	46	2	2051	37
Control 2104	66	14	40	8	16	10	61	13	35	7	49	10	82	17	41	9	39	8	10	2	10	2	7	1	29	6	484	15
One Burn	56	10	45	8	26	13	26	4	71	12	129	22	125	21	49	8	15	3	7	1	2	0	2	0	30	5	583	18
Two Burns	450	43	159	15	15	4	52	5	70	7	102	10	86	8	41	4	12	1	6	1	1	0	2	0	39	4	1037	32
Four Burns	633	56	78	7	92	25	43	4	45	4	42	4	33	3	66	6	35	3	6	1	2	0	3	0	50	4	1128	35

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

% in columns are the percent of total density. *Stand density does not include removals in thinnings. **Simulation started on year- 2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.3b: Average basal area* ($m^2 ha^{-1}$) and their relative values (%) by diameter classes under different management simulations** for 100 years.

Treatments	Year	0-6	%	6-11	%	11-17	%	17-22	%	22-27	%	27-32	%	32-37	%	37-42	%	42-47	%	47-52	%	52-57	%	57-62	%	Total	%		
Beginning Control	2003	1.7	8	2.5	11	1.3	6	0.2	1	0.6	3	0.2	1	1.0	4	3.1	14	4.6	21	5.5	25	1.5	7	0.0	0	0.0	0	22.2	26
	One Burn	1.7	10	0.2	1	0.2	1	0.2	1	0.2	1	0.2	1	0.6	3	4.0	20	3.8	22	4.6	27	1.5	9	0.0	0	0.0	0	17.1	20
	Two Burns	0.9	4	0.3	1	0.0	0	0.2	1	0.2	1	0.0	0	1.9	9	4.0	18	7.3	32	5.5	25	1.9	9	0.2	1	0.0	0	22.5	26
	Three Burns	0.8	3	0.0	0	0.0	0	0.2	1	0.0	0	0.0	0	1.3	6	5.9	25	9.6	40	5.5	23	0.8	3	0.0	0	0.0	0	24.1	28
	Four Burns	0.8	3	0.0	0	0.0	0	0.2	1	0.0	0	0.0	0	1.3	6	5.9	25	9.6	40	5.5	23	0.8	3	0.0	0	0.0	0	24.1	28
No-management Control	2014	2.3	7	3.1	10	3.0	10	2.5	8	0.6	2	0.6	2	0.3	1	1.6	5	4.5	15	4.6	15	6.7	22	1.3	4	0.0	0	31.2	25
	One Burn	5.4	20	3.1	11	0.4	2	0.1	0	0.0	0	0.8	3	0.4	2	1.5	6	3.5	13	5.0	18	5.4	19	1.8	6	0.5	2	27.9	22
	Two Burns	4.5	14	1.0	3	0.4	1	0.1	0	0.3	1	0.0	0	0.4	1	2.5	8	5.4	16	8.2	25	6.4	20	2.8	8	0.7	2	32.6	26
	Three Burns	2.9	9	1.7	5	0.1	0	0.0	0	0.3	1	0.0	0	0.7	2	1.3	4	8.3	25	10.9	33	5.6	17	0.9	3	0.0	0	32.7	26
	Four Burns	2.9	9	1.7	5	0.1	0	0.0	0	0.3	1	0.0	0	0.7	2	1.3	4	8.3	25	10.9	33	5.6	17	0.9	3	0.0	0	32.7	26
2044 Control	2044	0.5	1	2.1	4	5.7	12	6.7	14	3.9	8	1.7	4	2.4	5	0.6	1	0.4	1	3.0	6	4.6	9	7.5	15	9.9	20	48.9	24
	One Burn	1.7	3	3.6	7	12.8	26	3.8	8	3.3	7	0.7	1	0.0	0	0.1	0	0.5	1	2.0	4	5.4	11	5.6	11	10.5	21	50.1	24
	Two Burns	1.4	3	2.0	4	11.3	21	2.4	4	1.8	3	0.4	1	0.7	1	0.0	0	0.9	2	3.1	6	5.7	11	8.8	17	14.8	28	53.3	26
	Three Burns	1.0	2	1.2	2	5.6	11	4.5	9	4.1	8	0.1	0	0.2	0	0.7	1	0.8	2	3.9	7	10.0	19	12.3	23	8.8	17	53.2	26
	Four Burns	1.0	2	1.2	2	5.6	11	4.5	9	4.1	8	0.1	0	0.2	0	0.7	1	0.8	2	3.9	7	10.0	19	12.3	23	8.8	17	53.2	26
2074 Control	2074	0.0	0	0.5	1	1.4	3	4.9	9	6.8	13	3.9	8	2.3	4	1.8	3	3.0	6	0.6	1	3.0	6	3.8	7	19.4	38	51.3	24
	One Burn	0.1	0	0.7	1	2.4	5	11.7	22	5.8	11	3.1	6	3.1	6	1.2	2	0.0	0	0.4	1	1.2	2	3.9	7	19.8	37	53.6	25
	Two Burns	0.1	0	0.4	1	1.2	2	8.1	15	8.5	16	2.1	4	1.2	2	1.0	2	0.3	1	0.9	2	2.7	5	5.3	10	22.7	42	54.5	25
	Three Burns	0.0	0	0.4	1	1.0	2	4.6	8	4.8	9	6.4	12	2.1	4	0.0	0	0.8	1	1.0	2	3.0	5	10.2	19	20.5	38	54.7	26
	Four Burns	0.0	0	0.4	1	1.0	2	4.6	8	4.8	9	6.4	12	2.1	4	0.0	0	0.8	1	1.0	2	3.0	5	10.2	19	20.5	38	54.7	26
2104 Control	2104	0.0	0	0.1	0	0.6	1	1.5	3	5.4	10	6.7	13	3.5	7	3.1	6	0.9	2	4.8	9	1.6	3	3.1	6	21.2	40	52.4	24
	One Burn	0.0	0	0.1	0	1.2	2	4.3	8	7.4	14	7.6	14	4.1	8	3.4	6	2.2	4	0.3	1	0.3	1	1.2	2	22.2	41	54.3	25
	Two Burns	0.0	0	0.1	0	0.9	2	1.1	2	8.5	15	9.7	18	2.9	5	2.2	4	1.8	3	0.5	1	1.9	3	3.1	6	22.1	40	54.8	25
	Three Burns	0.0	0	0.0	0	0.8	1	1.9	3	4.2	8	4.4	8	6.5	12	4.7	9	0.7	1	0.7	1	1.7	3	5.9	11	23.5	43	54.9	25
	Four Burns	0.0	0	0.0	0	0.8	1	1.9	3	4.2	8	4.4	8	6.5	12	4.7	9	0.7	1	0.7	1	1.7	3	5.9	11	23.5	43	54.9	25

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

% in columns are the percent of basal area. *Stand basal area does not include removals in thinnings. **Simulation started on year- 2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.3b (continued): Average basal area* ($\text{m}^2 \text{ha}^{-1}$) and their relative values (%) by diameter classes under different management simulations** for 100 years.

Treatments	Year	0-6	%	6-11	%	11-17	%	17-22	%	22-27	%	27-32	%	32-37	%	37-42	%	42-47	%	47-52	%	52-57	%	57-62	%	>62	%	Total	%
Thinnings																													
Control	2014	2.2	7	3.1	10	2.9	10	2.5	8	0.5	2	0.6	2	0.3	1	1.6	5	4.3	14	4.5	15	6.5	22	1.2	4	0.0	0	30.1	26
One Burn		5.4	20	3.1	11	0.4	2	0.1	0	0.0	0	0.8	3	0.4	2	1.5	6	3.5	13	5.0	18	5.4	19	1.8	6	0.5	2	27.9	24
Two Burns		4.5	15	1.0	3	0.4	1	0.1	0	0.2	1	0.0	0	0.4	1	2.1	7	4.8	16	7.7	25	6.1	20	2.7	9	0.7	2	30.6	26
Four Burns		2.8	10	1.7	6	0.1	0	0.0	0	0.2	1	0.0	0	0.4	1	1.2	4	7.0	24	10.0	34	5.0	17	0.9	3	0.0	0	29.3	25
Control	2044	0.7	2	2.0	6	4.3	12	5.0	14	2.6	7	3.0	9	1.4	4	0.5	1	0.4	1	1.7	5	2.8	8	3.9	11	7.0	20	35.4	25
One Burn		1.5	4	2.5	7	10.6	29	3.4	9	2.6	7	0.6	2	0.0	0	0.1	0	0.3	1	1.3	3	3.4	9	3.7	10	7.2	19	37.1	26
Two Burns		1.7	5	1.3	4	8.2	23	2.1	6	1.6	4	0.2	1	0.4	1	0.0	0	0.3	1	1.8	5	3.1	9	5.0	14	9.5	27	35.3	25
Four Burns		1.2	4	0.5	2	4.4	13	2.8	8	3.0	9	0.2	0	0.1	0	0.4	1	0.4	1	1.8	5	5.3	16	8.1	24	5.9	17	34.0	24
Control	2074	0.3	1	0.4	1	1.6	4	2.5	6	5.4	14	6.7	17	3.6	9	2.8	7	1.3	3	1.6	4	1.0	2	1.0	3	11.3	28	39.6	25
One Burn		0.6	2	0.4	1	1.0	3	4.8	12	11.4	28	4.9	12	2.1	5	1.4	3	0.3	1	0.2	0	0.5	1	0.9	2	11.9	29	40.4	25
Two Burns		1.3	3	0.4	1	1.3	3	4.1	10	6.7	17	4.8	12	2.2	6	0.6	2	0.7	2	0.0	0	0.8	2	1.3	3	14.9	38	39.2	25
Four Burns		1.6	4	1.0	3	0.2	1	2.3	6	3.5	9	4.9	12	3.6	9	1.1	3	0.6	1	0.6	2	0.8	2	1.8	4	17.7	44	39.8	25
Control	2104	0.1	0	0.3	1	0.3	1	2.1	5	1.8	4	3.6	8	8.0	17	5.2	11	6.3	13	1.9	4	2.5	5	1.9	4	13.1	28	47.2	23
One Burn		0.1	0	0.3	1	0.5	1	0.8	1	3.9	7	9.4	18	12.1	23	6.4	12	2.5	5	1.4	3	0.5	1	0.5	1	13.7	26	52.1	26
Two Burns		0.9	2	1.0	2	0.3	1	1.7	3	3.7	7	7.3	14	8.5	17	5.4	11	1.9	4	1.3	3	0.2	0	0.5	1	17.6	35	50.2	25
Four Burns		1.3	2	0.5	1	1.7	3	1.2	2	2.4	5	3.1	6	3.2	6	8.5	16	5.6	11	1.2	2	0.4	1	1.0	2	21.9	42	52.1	26

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

% in columns are the percent of basal area. *Stand basal area does not include removals in thinnings. **Simulation started on year- 2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.3c: Average sawlog volume* ($\text{m}^3 \text{ ha}^{-1}$) and their relative values (%) by diameter classes under different management simulations** for 100 years.

Treatments	Year	0-6	% 6-11	% 11-17	% 17-22	% 22-27	% 27-32	% 32-37	% 37-42	% 42-47	% 47-52	% 52-57	% 57-62	% >62	Total	%										
Control	2003	0	0	0	0	0	0	1	1	8	5	29	19	45	30	54	35	15	10	0	0	0	0	152	22	
One Burn		0	0	0	0	0	1	1	1	9	7	30	22	35	26	45	33	15	11	0	0	0	0	136	19	
Two Burns		0	0	0	0	0	1	0	0	16	8	35	18	66	35	53	27	19	10	2	1	0	0	192	27	
Four Burns		0	0	0	0	0	0	0	0	11	5	55	25	90	41	55	25	8	4	0	0	0	0	220	31	
No-management																										
Control	2014	0	0	0	0	0	2	1	2	1	15	8	47	24	49	24	71	36	13	7	0	0	0	201	21	
One Burn		0	0	0	0	0	0	5	3	4	2	15	8	36	19	51	26	58	30	20	10	4	2	193	20	
Two Burns		0	0	0	0	0	1	0	0	3	1	24	9	53	20	85	31	67	25	30	11	9	3	271	28	
Four Burns		0	0	0	0	0	0	0	0	7	2	12	4	85	30	114	40	60	21	9	3	0	0	287	30	
Control	2044	0	0	0	0	0	2	1	6	2	18	5	4	1	5	2	33	10	54	17	89	27	117	35	329	23
One Burn		0	0	0	0	0	7	2	3	1	0	0	1	0	6	2	22	7	62	21	66	23	126	43	293	20
Two Burns		0	0	0	0	0	3	1	2	0	4	1	0	0	10	2	35	9	67	17	103	26	178	44	401	27
Four Burns		0	0	0	0	0	9	2	0	0	2	0	7	2	8	2	43	10	117	27	145	33	104	24	435	30
Control	2074	0	0	0	0	0	8	2	13	3	12	3	9	2	29	7	6	2	36	9	46	12	236	60	395	24
One Burn		0	0	0	0	0	5	2	12	3	18	5	8	2	0	0	5	1	14	4	48	13	244	69	354	22
Two Burns		0	0	0	0	0	11	3	9	2	7	2	8	2	2	1	10	2	32	8	64	15	276	66	419	26
Four Burns		0	0	0	0	0	9	2	27	6	11	2	0	0	9	2	12	2	35	7	123	26	250	53	475	29
Control	2104	0	0	0	0	0	8	2	21	5	16	4	17	4	6	1	41	10	18	4	37	9	260	61	424	25
One Burn		0	0	0	0	0	3	1	20	5	19	5	23	6	16	4	2	1	4	1	15	4	276	73	377	22
Two Burns		0	0	0	0	0	11	3	27	6	13	3	14	3	14	3	5	1	21	5	38	9	272	65	415	25
Four Burns		0	0	0	0	0	6	1	14	3	31	6	28	6	8	2	8	2	19	4	72	15	288	61	474	28

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

% in columns are the percent of total sawlog volume. *Stand sawlog does not include removals in thinnings. **Simulation started on year- 2004
The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.3c (continued): Average sawlog volume* ($m^3 ha^{-1}$) and their relative values (%) by diameter classes under different management simulations** for 100 years.

Treatments Year	0-6	% 6-11	% 11-17	% 17-22	% 22-27	% 27-32	% 32-37	% 37-42	% 42-47	% 47-52	% 52-57	% 57-62	% >62	% Total											
Thinnings																									
Control 2014	0	0	0	0	0	1	2	1	1	15	7	45	23	47	24	70	36	13	7	0	0	194.2	22		
One Burn	0	0	0	0	0	0	5	3	4	2	15	8	36	19	51	26	58	30	20	10	4	2	192.8	22	
Two Burns	0	0	0	0	0	1	0	0	3	1	20	8	47	19	79	31	65	26	29	11	9	3	252.1	28	
Four Burns	0	0	0	0	0	0	0	0	5	2	11	4	71	28	104	41	53	21	9	4	0	0	252.4	28	
Control 2044	0	0	0	0	0	3	1	9	4	10	5	4	2	3	2	20	9	34	16	48	22	83	39	213.4	23
One Burn	0	0	0	0	0	6	3	3	1	0	1	0	3	2	14	7	39	20	43	22	87	44	196	22	
Two Burns	0	0	0	0	0	2	1	1	0	3	1	0	0	2	1	21	9	37	16	59	24	115	48	239.5	26
Four Burns	0	0	0	0	0	7	3	1	0	1	0	4	1	4	1	19	7	63	24	96	37	69	26	262.8	29
Control 2074	0	0	0	0	0	5	2	25	10	17	7	16	6	9	4	17	7	12	5	12	5	139	55	252.2	24
One Burn	0	0	0	0	0	14	6	14	7	12	6	9	4	2	1	2	1	7	3	11	5	148	67	220.2	21
Two Burns	0	0	0	0	0	11	4	18	7	13	5	4	2	6	2	0	0	9	3	16	6	186	71	264.1	25
Four Burns	0	0	0	0	0	6	2	20	6	20	6	8	2	5	2	7	2	10	3	22	7	221	69	318.5	30
Control 2104	0	0	0	0	0	1	0	11	3	37	11	29	9	41	12	15	4	27	8	19	5	165	48	344.5	24
One Burn	0	0	0	0	0	5	1	24	8	45	14	35	11	19	6	12	4	5	2	6	2	174	53	326	22
Two Burns	0	0	0	0	0	4	1	21	6	38	11	33	9	14	4	11	3	2	1	6	2	224	63	355	24
Four Burns	0	0	0	0	0	5	1	10	2	207	3	52	12	41	10	11	3	5	1	11	3	280	65	428.5	29

Note: Some of the 'zeros' in % column have values below 0.5% and have been rounded to zero.

% in columns are the percent of total sawlog volume. *Stand sawlog does not include removals in thinnings. **Simulation started on year- 2004

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.4: Average and relative standing* sawlog volume of major species under 100 years of no-management and thinning simulations in differently burned and unburned mature red pine stands.**

Year	Red maple m ³ ha ⁻¹				Red pine m ³ ha ⁻¹				Sugar maple m ³ ha ⁻¹				Others m ³ ha ⁻¹				Total m ³ ha ⁻¹			
	C	1B	2B	4B	C	1B	2B	4B	C	1B	2B	4B	C	1B	2B	4B	C	1B	2B	4B
Beginning																				
2003	0	0	1	0	150	134	190	219	2	1	0	0	0	0	0	1	152	136	192	220
%	0	0	1	0	98	99	99	100	2	1	0	0	0	0	0	0				
No-management																				
2014	0	0	2	0	197	191	269	285	4	2	0	0	0	0	0	1	201	193	271	287
%	0	0	1	0	98	99	99	100	2	1	0	0	0	0	0	0				
2044	2	0	2	0	320	290	398	429	8	2	0	0	0	0	0	7	329	293	401	435
%	1	0	1	0	97	99	99	98	2	1	0	0	0	0	0	2				
2074	9	0	1	0	378	352	418	474	8	2	0	0	0	0	0	2	395	354	419	475
%	2	0	0	0	96	99	100	100	2	1	0	0	0	0	0	0				
2104	9	0	2	0	407	376	414	474	8	1	0	0	0	0	0	0	424	377	415	474
%	2	0	0	0	96	100	100	100	2	0	0	0	0	0	0	0				
Thinnings																				
2014	0	0	2	0	190	191	250	251	4	2	0	0	0	0	0	1	194	193	252	252
%	0	0	1	0	98	99	99	100	2	1	0	0	0	0	0	0				
2044	6	0	2	0	202	194	238	258	6	2	0	0	0	0	0	4	213	196	239	263
%	3	0	1	0	95	99	99	98	3	1	0	0	0	0	0	2				
2074	20	1	6	0	222	214	257	311	9	1	0	0	1	3	1	8	252	220	264	318
%	8	1	2	0	88	97	97	98	4	1	0	0	0	2	1	2				
2104	34	6	9	0	291	315	341	415	19	1	0	0	1	4	5	13	344	326	355	429
%	10	2	3	0	84	97	96	97	5	0	0	0	0	1	1	3				

* consists of American beech, black cherry, choke cherry, non-commercial species, others and white ash.

Burn Treatments columns are: C, Unburned Control; 1B, One Burn; 2B, Two Burns; 4B, Four Burns

% (in rows) is the percent of total species sawlog volume.

*Stand volume does not include removals in thinning.

**Simulation started on year-2004.

The first, second and third thinnings occurred in 2004, 2034, and 2064.

Appendix 3.5: Comparison of Forest Vegetation Simulator (FVS) projection with that given in Benzie (1977) for *standing merchantable cubic volume ($\text{m}^3 \text{ha}^{-1}$) and the predicted values in differently burned mature red pine stands at site index 19.8m in the beginning and at the end of no-mangement and thinning.

A. Stand age 72** years in the beginning of the simulation (year 2003***)

	Standing volume							
	FVS predicted volume				Benzie predicted volume			
	C	1B	2B	4B	C	1B	2B	4B
Basal Area ($\text{m}^3 \text{ha}^{-1}$)	22.2	17.1	22.5	24.1	22.2	17.1	22.5	24.1
Volume ($\text{m}^3 \text{ha}^{-1}$)	180	155	218	248	227	172.3	227	245
% change over Benzie	-21	-10	-4	1.2				

B. Stand age 143** and BA set to 34.4 sq m/ha in year 2074

	FVS predicted (No-management) Standing volume				FVS predicted (Thinnings) Cumulative volume				Benzie Predicted Volume
Volume ($\text{m}^3 \text{ha}^{-1}$)	470	420	480	536	586	504	586	641	480
% change over Benzie	-2	-12	0	12	22	5	22	34	

*Standing volume does not include removals in thinning.

**Predicted volumes were chosen for the closest stand ages 70 and 140 years in Benzie's Table.

The average values in Benzie (1977) for corresponding age, site index and basal area (BA) were converted to metric.

*** The average standing volume from the beginning (year 2003) was used instead of the year 2004 when the first cutting was done as they were in the same age range in Benzie's table (1977).

Treatments in the columns were C, Unburned Control, 1B, One Burn; 2B, Two Burns and 4B, Four Burns.

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