

**EFFECTS OF FOREST MANAGEMENT AND CLIMATE ON
RED PINE (*PINUS RESINOSA*) PRODUCTIVITY IN MICHIGAN**

By

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ABSTRACT

EFFECTS OF FOREST MANAGEMENT AND CLIMATE ON RED PINE (*PINUS RESINOSA*) PRODUCTIVITY IN MICHIGAN

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Changes in climate are predicted to significantly affect the productivity of trees in the Great Lakes region over the next century. Forest management techniques, such as thinning and initial stand density, can promote climatic resiliency and moderate decreased productivity through the reduction of tree competition. In terms of thinning, it was found that climatic resiliency was predominantly influenced by thinning intensity (a more intense thinning generally led to a higher climatic resilience) with thinning method having a less significant role (thinning from below increased climatic resiliency more than thinning from above). Overall, the thinning from below to a residual basal area of 21 square meters per hectare (90 square feet per acre) was the best compromise to maximize tree size, biomass per hectare, and climatic resiliency. In a separate study, initial stand density was considered as an forest management technique to generate climatic resilience across multiple sites. It was found that low initial density stands (988 trees per hectare) (400 trees per acre) had equal or great measures of productivity while maintaining a greater climatic resilience, particularly to summer drought, compared to high initial density stands (1977 trees per hectare) (800 trees per acre).

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

Climate change is predicted to increase the frequency and persistence of stressful growing conditions resulting in a decrease of forest productivity in many regions (Kling et al., 2003). Forest management techniques may have the potential to increase resiliency to climatic stress by moderating the degree of tree competition for environmental resources and thus maintain productivity (Cescatti and Pitutti, 1998; Laurent et al., 2003; Spittlehouse and Stewart, 2003). Productivity of trees is a general term that can describe a variety of commercially desirable traits including height, diameter, biomass, and stand density. A dominant variable of productivity is climate, particularly the aspects of temperature and precipitation. Objectives of this chapter are to provide an overview of the impact of climate on tree growth, examine the potential impact of climate change on forest productivity, describe several methods of forest management, outline methods of tree growth analysis, and examine the interactive effects of forest management on the climatic sensitivity of forests.

1.2. Changing Climate and Its Effect on Tree Growth

Climate regulates many important variables of tree growth including the availability of water (through precipitation). Water is the medium for most biochemical reactions (including photosynthesis) and is required for maintaining cell turgor and cell expansion. Summer drought stress has been shown to have a significant impact on tree growth of many species including red pine (*Pinus resinosa* Ait.) (Koop, 1985; St. George et al., 2008). Air temperature is also a growth

factor as it affects a tree's metabolic growth rate (winter dormancy of trees in temperate climates) (Graumlich, 1993; Keep, 1985), as well as evapotranspiration (warmer temperatures increase water lost from plants and soil) (Pallardy, 2007; Raven et al., 1999).

The degree to which each aspect of climate (precipitation and temperature) impacts growth will vary by tree species and location. The variation is due to ecophysiological differences that are related to the species and/or the climate at the growing site. For instance, Miyamoto et al. (2010) noted variation in growth - climate responses between three different conifer species (*Picea glauca*, *Pinus contorta* var. *latifolia*, and *Abies lasiocarpa*) which was attributed to different degrees of shade tolerance. It was found that species with a higher shade tolerance were less susceptible to growth variation from changes in climate, indicating that the development of shade tolerance also can help a tree survive other climatic stresses such as drought.

De Luis et al. (2009) studied two conifer species (*Pinus halepensis* and *Pinus pinea*) and found that the size or crown class of the trees was a more important variable in the climate-growth relationship than the species of the tree. The growth of smaller trees was more sensitive to changes in climate than that of larger trees, indicating that larger tree have better access to resources, which will moderate the effects of climatic growth stressors. However, these results cannot be generalized as they only represent specific species and locations and other researchers have found results that indicate that tree size of different species in different locations can have no or the reverse effect on size - climate relationships (Carrer and Urbinati, 2004; Chhin et al., 2008; Esper et al., 2008; Vieira et al., 2009). Another variable that affects climate-growth response is competition, which is described in a study on European beech (*Fagus sylvatica* L.)

by Piutti and Cescatti (1997). The proximity of one tree to another determines the amount of resources that are available for each individual and thus will change the climate-growth response.

The local climate within the distributional range of a species can impact the sensitivity of the climate-growth relationship. Miyamoto et al. (2010) found that three species of conifer (*Picea glauca*, *Pinus contorta* var. *latifolia*, and *Abies lasiocarpa*) had similar growth - climate relationships within one climatic region. For example, temperature was found to be the most notable climatic variable at the northernmost sites in the Yukon. These sites mark the northernmost range of these species in which temperature is the most prominent growth factor as it controls when the growing season can begin. Another example from Kipfmüller et al. (2010) shows that red pine (*Pinus resinosa*), white pine (*Pinus strobus*), and white cedar (*Thuja occidentalis*) in northern Minnesota all had a similar growth response to June-July precipitation. This indicates that the presence or absence of water during the summer months is the most limiting climatic/growth variable for all of these species.

In addition to climatic variation among sample sites along a latitudinal gradient, the elevation gradient must also be considered because it can cause significant climatic differences over a relatively short distance. Chhin et al. (2008) observed that lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) growing at higher elevations in the Canadian Rocky Mountains were susceptible to damage by the Chinook winds, which do not occur to the same degree at lower elevations. These winds are both strong and dry, which can lead to the loss of foliage from crown collisions as well as winter desiccation due to increased evapotranspiration, both of which can cause stress and reduced growth.

1.2.1. Anthropogenic climate change

The anthropogenic production of greenhouse gases caused primarily by fossil fuel use and land use change (i.e. tropical deforestation) has become a matter of great interest with respect to long-term climate projections. With excess greenhouse gases in the atmosphere, more heat from the sun is retained, creating an overall warmer global climate, which will also impact atmospheric processes like wind and precipitation (e.g., Chmura et al., 2011). Worldwide the average annual temperature are projected to increase by 1.8 to 4.0° C by the end of the century (IPCC, 2007). In the Great Lakes region of the United States the average annual temperature is expected to increase by 3 - 11 °C by the end of the century (Kling et al., 2003). In this region, the average annual precipitation is not expected to change during this time, but the seasonal distribution is expected to shift with an increase in precipitation in the winter and a decrease in the summer. The combination of the seasonal shift in precipitation and the increase in temperature will cause more evapotranspiration and will create an overall drier climate particularly in the summer months (Kling et al., 2003). The amount of moisture available in the summer is a dominant factor in tree growth in the Great Lakes region (Kipfmueller et al., 2010).

In addition to the general changes expected in the Great Lakes region, Michigan is expected to experience an 8 to 10 week increase in the length of the growing season. It is also predicted that there will be a 50 - 100% increase in the occurrence of extreme weather events such as droughts, floods, strong winds, and heavy snows, which could damage trees (Kling et al., 2003). Such changes are predicted to eventually shift the optimal climatic range of red pine 600 to 800 km northeast as well as decrease the total area in which red pine is found (Flannigan and Woodward, 1994). In order to predict tree productivity under future climatic conditions it will require an understanding of historical climate-growth relationships (Dombroskie et al., 2010).

Sequestration of carbon dioxide by trees is being studied in order to quantify the potential of trees to mitigate global warming (Jackson and Schlesinger, 2004; Pohjola and Valsta, 2007). Since the rate of carbon dioxide sequestration is directly related to the rate of photosynthesis, any stress on a tree's photosynthetic rate and thus growth will reduce the amount of carbon that it can sequester (Bradford and Kastendick, 2010). There is great interest in how effective trees can be as a natural sink of carbon dioxide as it is the most abundant anthropogenic greenhouse gas. Carbon content or the carbon fraction of a tree can be calculated as a ratio of a tree's total biomass. This ratio can range from 46% to 55% in North American species but an approximation of 50% is commonly used across a variety of species (Jenkins et al., 2003; Lamtom and Savidge, 2003). To ensure carbon retention in forests, programs such as REDD (reducing emissions from deforestation and forest degradation) have been created. REDD limits deforestation by providing financial incentives to landowners based on carbon stored in a forest (Kaimowitz, 2008).

1.3. Forest Management

An integral goal of forest management is regulating competition for limited resources (light, water, mineral nutrients) between trees. Competition can result in diminished growth on both an individual and stand scale as well as cause mortality of less vigorous individuals. (e.g., Raven et al., 1999). In order to manage forest resources with the goal of maximizing productivity it is imperative to relieve competitive stress (Zhu et al., 2006). This can be done by either reducing the demand for resources (which will be discussed in terms of thinning) or adding resources to the system (which will be described in terms of fertilization and irrigation).

1.3.1. Intermediate Stand Tending Treatments

There are two variables of thinning that can impact tree growth. The first is thinning method which determines which trees to remove. Many common thinning methods are based on crown classification and include thinning from above (some of the upper crown classes are removed), thinning from below (lower crown classes are removed), and combination thinning (both upper and lower crown classes are removed). The effectiveness of different thinning methods vary for different species and productivity goals. The second variable is thinning intensity which has a more standard impact on growth. This is based on the principle that as more trees are removed, more resources become available to the residual trees which increases their growth (Nyland, 2007).

It has been shown that no one thinning method and intensity will maximize all types of productivity (Bradford and Palik, 2009; Powers et al., 2010; Smith 2003). Therefore, research must be done to identify specific management treatments that achieve specific productivity effects. Bradford and Palik (2009) found that red pine (in Minnesota) had a greater basal area growth rate when thinned from above compared to when thinned from below. This difference was the result of the thinning from above treatment increasing growing space around more individuals than the thinning from below treatment. Conflicting results were reported by Smith et al. (2003) who found that the same thinning methods (thinning from above and thinning from below) caused no large or consistent effect on basal area productivity in the stand in New Hampshire. As both studies used red pine as the test species and compared the same thinning methods, the difference in response is most likely due to the different age of the stand in each study and growth - climate response between the two locations.

An alternative measure of productivity is considered by Powers et al. (2010) who looked at how thinning reduced natural mortality in a stand of red pine. It was found that mortality

decreased with more intense thinning but was also dependant on the thinning method. For example, mortality in the thinning from below treatment decreased as the thinning intensity increased. In contrast, mortality only decreased in the light and moderate intensity of the thinning from above treatment. The most intense thinnings reversed this trend and exhibited an increase in mortality. The difference is due to smaller residual trees in the thinning from above treatment not being able to handle the stress of disturbances from a heavy harvest.

Irrigation and fertilization are commonly used in silviculture to increase the vigor of nursery grown seedlings. Miller and Timmer (1994) found that a combination of well irrigated and heavy nutrient loading of red pine seedlings resulted in an increase of 421% in growth rate after being planted compared to the control. The nutrient loaded seedlings were able to induce a steady state nutrient condition which rationed internal nutrient levels in order to sustain growth.

The effectiveness of irrigation and fertilization to increasing productivity in a middle aged stand has also been studied. Leaf et al. (1975) studied growth responses of 35 - 40 year old red pine and found that fertilization alone significantly increased many values of productivity including height and basal area. However, irrigation did not cause any significant difference in productivity. This is not always the case as Albaugh (2004) demonstrated with a study on a young stand of loblolly pine (*Pinus taeda*). Here the application of both irrigation and fertilization had a compounding increase in growth as compared to each on its own as long as there is enough growing space for the tree. Overall the optimal levels of irrigation and fertilization are situationally dependent based on species, tree age, nutrient requirements, and nutrient availability (Pallardy, 2007).

1.3.2. Interactions of Forest Management and Climate

Both forest management and climate have been shown to have independent effects on productivity. In order to determine climatic resiliency, both variables must be considered simultaneously. Climatic resiliency is an expression of the effectiveness of a forest management technique to maintain productivity in spite of climatic conditions that would otherwise result in a decrease in productivity. Most studies that examine the effects of forest management and climate on productivity, do not directly address climatic resiliency. For example, Chhin et al., (2008) considered interactions of lodgepole pine between climate, diameter size class, and elevational ecoregions in Canada and found general trends of decreased growth related to temperature and moisture stress. Piutti and Cescatti (1997) reported that relationships between European beech growth and temperature changed from positive to negative with increasing levels of competition, whereas precipitation had the opposite trend. It was postulated that forest management could be used to partially counterbalance the effects of climate change on tree growth. More direct comparisons of specific forest management practices, climate, and productivity, are rare and provide additional detail of productivity in terms of climatic resiliency. For example, Cescatti and Piutti (1998) incorporated various thinning treatments into their analysis of European beech and found that an intermediate thinning intensity resulted in resiliency to drought and temperature stress while maintaining a valuable yield. Laurent et al. (2003) reported more intense thinnings increased the drought resiliency of Norway spruce (*Picea abies* (L.) Karst.) but also increased susceptibility to other limiting factors that may include atmospheric pollution.

1.4. Sampling Methodology

To understand the growth dynamics of a forested stand, field sampling must be done to collect historical growth data. This data will reveal changing growth patterns that highlight the

past growing conditions. Predictions of how future conditions will affect tree productivity can then be made based on that historical data. This discussion will focus on both nondestructive and destructive sampling methods in terms of quantifying aspects of tree productivity in a stand.

1.4.1. Forest Inventories on Permanent Sample Plots

Forest inventories on permanent sample plots are a traditional method of calculating productivity within a stand of trees. Productivity in permanent sample plots is commonly measured in terms of basal area which is expressed in terms of square meters per hectare (Biondi, 1999). This makes basal area a function of tree size as well as stand density. The mean annual increment (MAI) is another measure used to quantify productivity in a permanent sample plot. MAI is the annual growth average and is determined by dividing the basal area per hectare by the age of the stand. In order to achieve a more accurate estimation of productivity, another set of basal area measurements can be collected, usually on a 5- to 10- year cycle. The difference in growth between samplings is represented as an average annual value and expressed as periodic annual increment (PAI). Growth patterns found in the PAI can then be used to project future growth. (D'Amato et al., 2010; Metsaranta and Lieffers, 2009)

Destructive sampling has been shown to be effective in obtaining accurate biomass and volume measurements for a stand. This requires cutting down and measuring disk segments of a number of trees in order to represent all of the trees in a stand (Rodriguez, 2003). This data can be used to develop allometric equations which can estimate tree mass and volume based on the diameter of the tree (Bradford and Palik, 2009).

1.4.2. Dendrochronology

Dendrochronology is an alternative method of measuring productivity and is based on the analysis of the pattern of internal ring formation in the stem of trees, (Speer, 2010; Yamaguchi, 1991). Samples are commonly collected through the use of an increment bore which removes a narrow cylinder of wood from the tree. The level of cambial activity that forms the annual ring is not equal around the entire circumference of the trunk, creating a small variation of ring width on different axes of the tree (Cherubini, 1998). In order to sample the best representative of growth at least two cores should be taken from opposite side of a tree away from any branches and perpendicular to any ground slope. The more cores taken from a tree the higher number of samples per ring and a more representative width can be measured. Coring is not considered destructive sampling for softwoods as they are able to quickly recover from the damage. However, there are some hardwood species that can sustain major internal damage from coring (Grissino-Mayer, 2003).

A key step in dendrochronology is using the principle of cross-dating (Speer, 2010; Yamaguchi, 1991). This is done by comparing ring width patterns between trees in order to indentify times of a common and significant stand-wide growth reductions. Kipfmuehler et al. (2010) used such methods to compare historical climatic data with ring width patterns and indicated aspects of climate that significantly impacted red pine, white pine, and white cedar in Minnesota. It is also possible to convert ring width measurements to a conventional measures of productivity with allometric equations. With every ring measured, productivity in terms of biomass can be determined on an annual basis (Jenkins et al., 2003).

1.4.3. Advantages of Dendrochronology over Forest Inventories

Dendrochronology features several sampling and data collection advantages over forest inventories. In terms of sampling technique, a forest inventory requires repeated sampling over many years and possibly decades in order to collect enough data to generate a PAI which is only indicates growth in between samplings and not before. Dendrochronological sampling does not require repeated sampling and provides annual growth rates data for the entire past growth history of the tree. This is significant as it provides more data in a shorter amount of time as well reduces the cost of sampling (Metsaranta and Lieffers, 2009; Piutti and Cescatti, 1997).

Growth data on an annual scale is a level of detail provided by dendrochronology that cannot be matched by PAI. The PAI that is measured using a forest inventory averages out the growth over many years which reduces the measurement's sensitivity to both climate and management growth variables. In addition, PAI loses sensitivity when describing a stand of trees: i.e., it is a measure of both the number and size of trees in question but does not address either specifically. Finally, the equipment used for each method of sampling are not equal in terms of accuracy. PAI is calculated based on the DBH which is measured with a diameter tape with an accuracy of only ± 0.01 centimeters. Dendrochronology on the other hand can be measured up to an accuracy of ± 0.001 millimeters either through a stage micrometer or a image analysis program (Metsaranta and Lieffers, 2009; Piutti and Cescatti, 1997).

1.5. Study Area and Red Pine Autecology

Forestland covers 7.8 million hectares or 53 percent of Michigan (Dickmann and Leefers, 2003). The distribution of forestland is not uniform within the state, and ranges from 21 percent in the southern region of the lower peninsula to 88 percent in the western region of the upper peninsula (Dickmann and Leefers, 2003). The state's current forest landscape contains many

forest cover types but is dominated by pine (i.e. *Pinus banksiana*, *Pinus Resinosa*), aspen (i.e. *Populus tremuloides*, *Populus grandidentata*), and northern hardwoods (i.e. *Acer saccharum*, *Acer rubrum*) (Johnson, 1995). The geologic structure of Michigan is based on Pleistocene glacial retreat, approximately 18,000 years ago, creating a topography featuring moraines and outwash plains (Dickmann and Leefers, 2003). Additionally, minerals and sediments were transported via glacial activity and was a contributing factor of soil development in Michigan. Common Michigan soil types include xeric entisols, mesic alfisols and spodosols, and hydric histosols (Johnson, 1995).

Michigan's prevailing climate is influenced by its mid-continental location and latitude as well as the proximity of the Great Lakes. Heat retained in the lakes moderates winter temperatures of coastal regions and can add approximately 50 additional days to the growing season compared to inland regions (Dickmann and Leefers, 2003). Another effect the lakes have on the local climate is the increase of coastal precipitation. These lake effect storms are most notable during the winter months, usually manifesting as snow, and impact up to 80 km inland along the northern border of the upper peninsula and the western boarder of the lower peninsula (Henne et al., 2007).

Red pine is a shade-intolerant native conifer with approximately 769,000 hectares of forest cover in Michigan (Gilmore and Palik, 2005). It can be found as both pure and mixed natural stands but due to its commercial significance most stands are plantations (Johnson, 1995). Thinning is a common management tool used by forest managers to increase the size and production value of residual red pine trees. Prescribed surface fires are also used to maintain red pine dominance in mature stands though suppression of the woody understory (Gilmore and Palik, 2005). Red pine maintains its greatest increases in productivity between the ages of 0- to

50- years, but productivity significantly decreases from 100- to 150- years and growth is minimal after 150 years. Average lifespan is approximately 200 years but under optimal conditions trees can survive as long as 300- to 400- years (Rudolph, 1990). Red pine is typically harvested after 40 years for pulpwood and from 60- to 120- years for sawtimber (Johnson, 1995).

1.6. Thesis Objectives and Structure

The overall objective of this thesis is to quantify the effects that forest management has on red pine productivity and climatic resiliency. Chapter two expresses forest management in terms of various thinning treatments and addresses the thesis objective by reporting correlations between tree growth, climate, and thinning treatments. This study took place at an experimental forest research site located within Manistee National Forest. Chapter three considers the impact of initial stand density on climatic resiliency and productivity of red pine across multiple sample sites within Huron National Forest. Chapter four summarizes the findings of chapters two and three and discusses future research directions.

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CHAPTER 2

EFFECTS OF THINNING AND CLIMATE ON THE PRODUCTIVITY OF RED PINE WITHIN MANISTEE NATIONAL FOREST, MICHIGAN

2.1. Introduction

Future climate change is expected to cause a significant impact to tree growth through changes in temperature and precipitation (Chmura et al., 2011; Spittlehouse and Stewart, 2003). Such changes are predicted to shift the range of red pine (*Pinus resinosa* Ait.) 600 to 800 km northeast as well as decrease the total area in which red pine is found (Flannigan and Woodward, 1994). Current forest management techniques must adapt in order to maintain productivity of forest resources under future conditions (Dombroskie et al., 2010). Adaptation of thinning management will promote proactive forest management to maintain productivity as opposed to relying on reactive forest management to salvage lost productivity.

The effects of climate (particularly the aspects of temperature and precipitation) have been shown to have a significant effect on tree productivity (Chhin et al., 2008; DeLuis et al., 2009; Kilgore and Telewski, 2004; Miyamoto et al., 2010; Pichler and Oberhuber, 2007). Similar region wide climatic conditions can illicit similar productive responses between different species and locations (Chhin et al., 2008; Miyamoto et al., 2010). For example, both of these studies reported the influence of summer temperature to generate drought stress and reduced tree productivity. Site specific studies provide details of localized conditions and variables of trees that differ from the general region-wide climatic conditions. Pichler and Oberhuber (2007) reported how a heat wave caused different growth responses of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) in a single stand based on the tree's canopy position. Similarly,

DeLuis et al. (2009) described how larger Aleppo pine (*Pinus halepensis*) and Stone pine (*Pinus pinea*) are less susceptible to temperature and precipitation stress compared to their smaller counterparts. Graumlich, (1993) used a principle component analysis to determine that climate is the single most significant variable of growth of trees in the Great Lakes region. Red pine at the Grayling Beal Plantation in Michigan has been reported to respond to April temperature but not to precipitation at any point in the year. It was postulated that this was because of local conditions that caused low amounts of evaporative water loss and root development that granted access to more consistent stores of water (Kilgore and Telewski, 2004).

Thinning is an effective forest management technique used to reduce competition and promote growth in the remaining individuals (Nyland, 2007). The number of trees removed is a factor of thinning intensity and is expressed in terms of residual basal area. Generally speaking, increased thinning intensity results in increased measures of tree-level productivity (Bradford and Palik, 2009; Powers et al., 2010; Smith, 2003). Once a residual basal area that provides sufficient growing space has been achieved, further increases of thinning intensity will not increase tree-level productivity as residual trees already have adequate access to resources. (Nyland, 2007). Furthermore, high intensity thinnings can decrease productivity under certain circumstances. For example, tree crowns are more susceptible to wind damage in a stand with a low residual basal area (Everham and Brokaw, 1996). Additionally, with more trees removed from a stand there is a greater change of logging damage to the remaining trees (Heitzman and Grell, 2002). The most common thinning intensity for red pine is to thin to a residual basal area of 21- to 25- square meters per hectare after the stand reaches 32 square meters per hectare (Gilmore and Palik, 2005).

Thinning is further expressed in terms of thinning method which is a factor of selecting the trees to be removed (Nyland, 2007). Several thinning methods are based on trees crown classifications. For example, thinning from above removes some of the dominant and codominant trees to promote growth of the best trees of the same classes while the understory trees are left in order to provide even stand density. Thinning from below removes the intermediate and overtopped trees to promote growth of the trees in the dominant and codominant crown classifications (Buckman et al., 2006). Thinning method does not have the same standard impact on productivity as thinning intensity. In terms of red pine, there are conflicting results in which some report thinning method has no effect on productivity (Smith, 2003; Gilmore et al., 2005), while other indicate that it does effect productivity (Bradford and Palik, 2009; Powers et al., 2010). Such variation is most likely due to differences in region, age of the stand, and unit of productivity in question.

Pitutti and Cescatti (1997) identified that in the interest of maintaining tree productivity in the future, there is a need to study the relationship between forest management, climate and productivity. Of the few studies that have directly addressed the relationship between all three of these variables, the common theme is that forest management is able to maintain productivity in spite of stressful climatic conditions. For example, Cescatti and Pitutti (1998) found that an intermediate thinning intensity of European beech (*Fagus sylvatica* L.) resulted in resiliency to drought and temperature stress while maintaining a valuable yield. Laurent et al. (2003) reported more intense thinnings increased the drought resiliency of Norway spruce but also increased susceptibility to other limiting factors that may include atmospheric pollution. With additional research including more species and regions it is possible to predict growth patterns under future

climate conditions and help maintain productivity (Chmura, 2011; Dombroskie et al., 2009; Spittlehouse and Stewart, 2003).

There are two objectives of this study of red pine sampled in Manistee National Forest, Michigan: 1) Quantify the effects of thinning method (thinning from above and thinning from below) as well as thinning intensity (residual basal areas of 14, 21, and 28 square meters per hectare) on red pine productivity; and 2) Examine which thinning treatment will result in a high climatic resiliency for red pine.

2.2. Methods

2.2.1. Study site

The study was conducted on a forest research plantation in the northern range of the Manistee National Forest near the towns of Wellston and Cadillac, Michigan (44°17'45" N 85°47'00" W). The site is commonly referred to as the Sooner Club and is managed by the USDA Forest Service (Figure 2.1 A). The stand was planted with 2 - 0 red pine planting stock in 1931 on approximately 14 hectares (35 acres). The site was divided into 46 plots in which a range of thinning treatments were applied (Figure 2.1 B). Each thinning treatment was replicated up to three times. Central to each plot, a 0.04 hectare (0.1 acre) sub-plot was marked in which future samples would be collected to avoid growth variation caused by edge effects. The stand was initially thinned in 1960 to specifications of each thinning treatment of each plot, and had additional thinnings in 1965, 1986, and 2000 to maintain the integrity of each treatment as required. Soil at the site is a Montcalm-Graycalm complex, which is a well drained loamy sand (Natural Resources Conservation Service, 2012).

Annual mean temperature averaged 6.13° C from 1931 to 2010 in Cadillac, Michigan. In the same time frame the total annual precipitation averaged 819.0 mm and the total annual climatic moisture index averaged 231.6 mm (National Climatic Data Center, 2012). Temperature and precipitation are greatest from April to October which marks the length of the growing season (Figure 2.2 A). However, the increase in temperature from May to August also increases evapotranspiration negating the influx of water into the system and causing a net loss of water available for growth. This typical summer drought is demonstrated in Figure 2.2 (B) by a negative climatic moisture index (precipitation minus potential evapotranspiration) (Hogg, 1997). The study site is under the influence of lake effect snow which results in greater quantities of winter precipitation within approximately 80 km of the western shoreline of the Michigan's lower peninsula (Henne et al., 2007).

2.2.2. Field Sampling

A total of 21 plots were chosen from the USDA forest research plantation to represent three replicates of six different thinning treatments and one control treatment (Figure 2.1 B). The six thinning treatments considered consisted of a combination of two thinning methods and three thinning intensities. The two thinning methods represented in this study are thinning from above, in which the larger diameter trees are removed, and thinning from below, in which the smaller diameter trees are removed. The three thinning intensities considered in this study represent heavy, moderate, and light thinnings, with residual basal areas of 14, square meters per hectare (60 square feet per acre), 21 square meters per hectare (90 square feet per acre), and 28 square meters per hectare (120 square feet per acre), respectively. A control treatment which was never thinned was also included in the study. Each thinning treatment is denoted by a combination of

thinning method and intensity parameters, e.g. Above 60 (AB60), Above 90 (AB90), Above 120 (AB120), Below 60 (BL60), Below 90 (BL90), and Below 120 (BL120), while the control plot is referred to as "Uncut".

Measurements and samples were taken from 21 plots in June of 2011. Each plot covered 0.2 hectare (0.5 acre) and samples were collected inside the 0.04 hectare (0.1 acre) sub-plot that was center to each plot. Each sub-plot was divided into four equal quadrants and the tree closest to the center of each quadrant was selected for sampling. The nearest neighbor of the center tree in each quadrant was also selected for sampling, totaling eight trees per sub-plot. In sub-plots with fewer than eight trees, all trees were sampled. For each of the selected trees, total height, height to live crown, diameter at breast height (1.37 m) (DBH), and bark thickness at breast height were measured. In addition, two cores were collected from each tree with an increment bore at breast height (1.37 m). Cores were taken from the north and south face of each tree. Additionally, DBH was measured for all trees in each sub-plot.

2.2.3. Sample Processing

Tree cores were processed using standard dendrochronological techniques (Stokes and Smiley, 1996). Tree cores were glued onto grooved wood strips to act as a stable base. Samples were then sanded with progressively finer sandpaper up to 600 grit to achieve a polished surface in which the rings were clearly visible. Sanded cores were then scanned into a computer at an optical resolution of 1200 dpi.

2.2.4. Cross-Dating and Tree-Ring Measurement

Cores were cross-dated with the list method to accurately assign a calendar date to each tree ring (Yamaguchi, 1991). In addition to relative width of rings, characteristic ring structures such as missing rings, frost rings, and latewood width were also used to ensure maximum accuracy of the crossdating. Additional statistical quality control was provided through the use of the program COFECHA (Holmes, 1983; Holmes, 1994). COFECHA identifies samples that should be checked for cross dating errors based on a poor correlation between individual ring widths series and an average sub-plot chronology. Ring widths were measured using the programs CooRecorder and CDendro (Cybis Elektronik & Data AB, Saltsjöbaden, Sweden). A stage micrometer (Velmex: Bloomfield, New York) was used as a supplemental tool to measure sections of cores with very narrow rings that were unclear in the scanned image.

2.2.5. Data Analysis

2.2.5.1. Biomass Calculations

Allometric equations were used to calculate tree biomass as a function of DBH. Total aboveground tree biomass (Equation 2.1) was determined using the following equation that is specific to pine species (Jenkins et al. 2003):

$$T_{bm} = \text{Exp} (-2.5356 + 2.4349 \ln \text{DBH}) \quad (2.1)$$

Where

T_{bm} = total aboveground biomass

Exp = exponential function

ln = natural log base e (2.718282)

DBH = diameter at breast height

A tree component equation was used to calculate the ratio of stem biomass to total aboveground biomass (Equation 2.2) (Jenkins et al. 2003):

$$\text{Ratio} = \text{Exp} [-0.3737 + (-1.8055 / \text{DBH})] \quad (2.2)$$

Where

Ratio = ratio of stem biomass to total aboveground biomass

Exp = exponential function

DBH = diameter at breast height

The ratio was multiplied by the total aboveground biomass to calculate the stem biomass. Total and stem biomass were summarized as an average of the eight trees sampled in each sub-plot. Separate calculations summarized the total and stem biomass on a per hectare basis based on the DBH of all trees in a sub-plot as of June 2011.

2.2.5.2.Red Pine Form and Productivity

Slenderness coefficient is a dimensionless value based on the ratio of the diameter and height of a tree and is calculated as the height divided by the DBH in the same units (m). Greater values indicate a taller and narrower tree, and trees with values over a threshold of 80 are prone to wind-induced breakage (Watt et al., 2008). Crown ratio represents the ratio of the crown length to the total height of a tree and is calculated as the height of the lowest dominant branch

divided by the total height of the tree. All measures of tree-level productivity (DBH, total height, crown ratio, slenderness coefficient, basal area, total biomass, and stem biomass) were subjugated to an one-factor analysis of variance (ANOVA) to indentify significant thinning treatments effects using the program SYSTAT 10.2. Furthermore, stand-level productivity (i.e. per hectare basis) was also compared between the treatments using a one-way ANOVA. Fisher's LSD was used to examine pairwise comparisons between thinning treatments (SYSTAT, 2002). Any comparison with a P value that was less than 0.05 was considered significant.

2.2.5.3.Dendrochronological Analysis

Ring widths were standardized to generate a radial growth index through the statistical program ARSTAN (Cook, 1985; Holmes, 1994). A radial growth index is a dimensionless expression of ring width and was calculated by dividing the observed ring width by the ring widths predicted from a 40 year cubic smoothing spline. Radial growth index values that are greater than one represent above average growth while values less than one represent below average growth. Ring widths were detrended to standardize the raw ring width measurements though the removal of size and age related effects on ring width. Remaining variation in the radial growth index between trees is the result of stand-wide effects like climate and management (Biondi, 1999). The radial growth index of each tree and year was averaged to create a standard chronology for each thinning treatment which could then be compared to historical climate data. ARSTAN calculated an expressed population signal (EPS) to exceed 0.85 for all thinning treatments from 1948 to 2010 so all climatic analysis is based on that timeframe (Briffa and Jones, 1990). The EPS quantifies how well a chronology based on a finite number of trees represents a hypothetically perfect chronology (Wigley et al., 1984).

Historical climate data was obtained from by the National Climatic Data Center at the Cadillac Municipal Airport (Station ID 201176) (44°16'50" N 85°25'02" W) and Cadillac station (Station ID 201176) (44°15'55" N 85°23'47" W) in Cadillac, Michigan. Data collected included monthly averages of minimum, mean, and maximum daily temperature, and total monthly precipitation. Minimum and maximum monthly temperature and precipitation measurements were further combined into a climatic moisture index (CMI) representing estimated net water availability to trees. CMI was calculated based on the following equation (Hogg, 1997):

$$\text{CMI} = \text{P} - \text{PET} \quad (2.3)$$

Where

CMI = climatic moisture index (mm)

P = precipitation (mm)

PET = potential evapotranspiration (mm)

Potential evapotranspiration (PET) was calculated based on mean temperature (Hogg, 1997):

$$\text{When } T_{\text{mean}} > 10^{\circ} \text{ C: } \text{PET} = 93 * D * \text{Exp} (A / 9300) \quad (2.4 \text{ a})$$

$$\text{When } 10^{\circ} \text{ C} > T_{\text{mean}} > -5^{\circ} \text{ C: } \text{PET} = (6.2 * T_{\text{mean}} + 31) D * \text{Exp} (A / 9300) \quad (2.4 \text{ b})$$

$$\text{When } T_{\text{mean}} < -5^{\circ} \text{ C: } \text{PET} = 0 \quad (2.4 \text{ c})$$

Where

T_{mean} = mean temperature ($^{\circ}$ C)

PET = potential evapotranspiration (mm)

D = vapor pressure deficit (kPa)

Exp = exponential function

A = altitude of climate station (m)

The vapor pressure deficit (D) was calculated as (Hogg, 1997):

$$D = 0.5 (eT_{\text{max}} - eT_{\text{min}}) - eT_{\text{dew}} \quad (2.5)$$

Where

D = vapor pressure deficit (kPa)

eT_{max} = saturation vapor pressure at maximum temperature

eT_{min} = saturation vapor pressure at minimum temperature

eT_{dew} = saturation vapor pressure at mean dewpoint temperature

Missing climate data-points were extrapolated based on data from nearby climate stations at the Tippy Dam Pond (Station ID 208772) (44°15'31" N 85°56'21" W) in Wellston, Michigan and the Manistee 3SE station (Station ID 205065) (44°12'40" N 86°17'37" W) in Manistee Michigan. Additionally, monthly climate data was seasonalized into 3 month periods (averages of temperature and sums of precipitation and CMI) to represent longer term climatic trends.

The standard chronology and each individual set of climate data were run through the program DendroClim (Biondi and Waikul, 2004) to identify significant monthly correlations between each climatic variable and tree growth from April of the previous year to October of the current year. Analysis begins in April of the previous year as growing conditions of the previous year can affect the current year's growth by how much carbon they store and how many needle buds are formed (Garrett and Zahner, 1973; Pallardy, 2007). Significant correlations are determined through bootstrapped samples, which are drawn at random with replacement from each year in the data set (Biondi and Waikul, 2004). For every data set, Pearson correlation coefficients were calculated between growth and each of the monthly and seasonal climate variables. A total of 1000 bootstrapped samples are calculated to compute correlation coefficients. Statistical significance is determined from the correlation coefficients from the original data set that fall outside of the 95% range of 1000 bootstrapped data sets (Biondi and Waikul, 2004).

2.3. Results

2.3.1. Red Pine Form and Productivity

For both thinning methods, mean tree DBH increases as thinning intensity increases (Table 2.1). Given the same thinning intensity, thinning from below generally has a greater mean tree DBH and tree height than thinning from above (Table 2.1). For both thinning methods, crown ratio was significantly affected by thinning intensity with the moderate intensity thinnings generating the largest crown ratio. The slenderness coefficient generally increased with low intensity thinnings for both thinning methods; furthermore, given the same thinning intensity, the

slenderness coefficient was greater when thinned from above versus when thinned from below (Table 2.1).

Tree-level basal area, total biomass, and stem biomass show a similar pattern between the thinning treatments. For both thinning methods, increased thinning intensity favored increased tree-level basal area and biomass; furthermore, given the same thinning intensity the thinning from below treatment generated larger average tree basal area and biomass than the thinning from above treatment (Table 2.2). According to stand-level productivity measures on a per hectare basis there was no significant difference in basal area and biomass between the two thinning methods given the same thinning intensity (Table 2.3). For both thinning methods, thinning intensity is the dominant influence with the low intensity thinnings generating a higher stand-level basal area and biomass per hectare. The uncut plots had the greatest variability (i.e. standard deviation) of basal area and biomass per hectare (Table 2.3).

2.3.2. Tree-Ring Chronologies

Basic patterns of relative ring width can be seen across all seven thinning treatments (Figure 2.3). For example, lower than average ring widths from long term stressful growing conditions are seen in the early to mid 1960s, 1977, and the late 1980s, while ring widths were greater than average in the early 1970s and early 1980s. The radial growth index was more influenced by thinning intensity than thinning method. This is prevalent in the mid 1960s when increasing thinning intensity results in greater moderation of growth stressors, as well as in the 1990s when decreasing thinning intensity results in greater moderation of growth stressors.

2.3.3. Growth-Climate Relationships

2.3.3.1.Responses to Temperature

All significant monthly correlations between temperature and radial growth are negative and many thinning treatments have significant correlations in the same months (Figure 2.4). For example, periods of significance are primarily found in late spring and mid-summer of the previous year and early and later summer of the current year. Trees found in low intensity thinnings that were thinned from above and the unthinned control plots (Above 120, Uncut) had radial growth that was significantly associated with temperature in April of the previous year. Trees found in moderate and high intensity thinnings that were thinned from above (Above 90, Above 60) and low and moderate intensity thinnings that were thinned from below (Below 90, Below 120) had radial growth that was correlated with temperature in May of the previous year. Trees found in high intensity thinnings of both thinning methods (Above 60, Below 60) had radial growth that was correlated with temperature in July of the previous year. Trees found in moderate intensity thinnings of both thinning methods (Above 90, Below 90) as well as low intensity thinnings that were thinned from above (Above 120) had radial growth that was correlated to temperature in May of the current year. Trees found in the unthinned control (Uncut) had radial growth that was correlated with temperature in June of the current year. Lastly, trees found in low intensity thinnings of both thinning methods (Above 120, Below 120) and the moderate intensity thinnings that were thinned from above (Above 90) had radial growth that was correlated with temperature in September of the current year.

Similar growth-climate relationships are present for the seasonal temperature correlations (Figure 2.5). Trees found in moderate and low intensity thinnings of both thinning methods (Above 90, Above 120, Below 90, Below 120) and the unthinned control (Uncut) had radial growth that was correlated with temperature in the Apr-May-Jun period of the previous year.

Trees found in every thinning treatment except for the moderate intensity thinnings that were thinned from below (Above 60, Above 90, Above 120, Below 60, Below 120, Uncut) had radial growth that was correlated with temperature in the May-Jun-Jul period of the previous year. Trees found in low intensity thinnings of both thinning methods, moderate intensity thinnings that were thinned from above, and the unthinned control (Above 90, Above 120, Below 120, Uncut) had radial growth that was correlated with temperature in the Apr-May-Jun period of the current year. Trees found in low intensity thinnings of both thinning methods and the unthinned control (Above 120, Below 120, Uncut) had radial growth that was correlated with temperature in the May-Jun-Jul period of the current year. Finally, trees found in the low intensity thinnings that were thinned from above (Above 120) had radial growth that was correlated with temperature in the Aug-Sept-Oct period of the current year.

2.3.3.2.Responses to Precipitation

Radial growth was positively correlated with December and June precipitation of the current year for high intensity thinnings of both thinning methods (Above 60, Below 60) (Figure 2.6). Additional positive correlations to precipitation are seen in June of the current year for radial growth of trees in low intensity thinnings that were thinned from below (Below 120) and July for radial growth of trees in moderate intensity thinnings that were thinned from below (Below 90). The final positive correlation with precipitation was in April of the previous year with the radial growth of trees in plots that were thinned from below to a low intensity (Below 120). All negative precipitation correlations were found to be with the radial growth of trees in the thinning from above treatment. Trees found in low and moderate intensity thinnings (Above 90, Above 120) had radial growth that was negatively correlated with precipitation in September

of both the previous and current year, trees found in while high intensity thinnings (Above 60) had radial growth that was negatively correlated to precipitation in August of the current year.

Seasonal precipitation correlations reveal that the radial growth of trees in high intensity thinnings that were thinned from above (Above 60) was positively correlated with precipitation in two winter seasonal periods (Nov-Dec-Jan and Dec-Jan-Feb) (Figure 2.7). Trees found in moderate intensity thinnings of both thinning methods (Above 90, Below 90) and low intensity thinnings that were thinned from below (Below 120) had radial growth that was positively correlated to precipitation in the May-Jun-Jul period of the current year. The radial growth of trees found in the unthinned control (Uncut) showed no significant correlation to monthly or seasonal precipitation

2.3.3.3. Responses to Climatic Moisture Index

Combining the factors of precipitation and temperature on growth is shown through the growth response to climatic moisture index (CMI) (Figure 2.8). Growth responses to CMI closely resemble those of the precipitation correlations including the positive relationships in December and June of the current year for the radial growth of trees found in high intensity thinnings of both thinning methods (Above 60, Below 60). Trees found in low intensity thinnings that were thinned from below (Below 120) had radial growth that was also positively correlated with CMI in June of the current year. Trees found in moderate intensity thinnings that were thinned from above, low intensity thinnings that were thinning from below, and the unthinned control (Above 90, Below 120, Uncut) had radial growth that was positively correlated with CMI in April of the previous year. Trees found in moderate intensity thinnings that were thinned from above (Above 90) had radial growth that was negatively correlated with CMI in September of

the previous year. Radial growth of trees found in moderate intensity thinnings that were thinned from above (Above 90) exhibited a positive correlation to CMI in July of the current year. Lastly, trees found in high intensity thinnings of both thinning methods (Above 60, Below 60) had radial growth that was negatively correlated to CMI in August of the current year.

All seasonal climatic moisture index correlations with radial growth were positive (Figure 2.9). Trees found in high intensity thinnings of both thinning methods (Above 60, Below 60) had radial growth that was correlated with CMI in the Nov-Dec-Jan period, and trees found in the High intensity thinnings that were thinned from above (Above 60) had radial growth that was also correlated with CMI in the Dec-Jan-Feb period. Trees found in low intensity thinnings that were thinned from below (Below 120) had radial growth that was correlated with CMI in the Apr-May-Jun and May-Jun-Jul periods while trees found in the moderate intensity thinnings that were thinned from above (Above 90) had radial growth that was also correlated with the May-Jun-Jul period. The radial growth of trees found in the unthinned control (Uncut) was not correlated with any seasonal CMI period.

2.4. Discussion

2.4.1. Red Pine Form and Productivity

Thinning intensity is a significant variable to all measured units of productivity and tree form except tree height. As thinning intensity increases there is a subsequent decrease in competition between trees. Less competition allows additional resource allocation for growth and results in greater tree-level productivity (increased DBH, basal area, and biomass and decreased slenderness) (Nyland, 2007). We found that moderate thinning intensities generate the largest crown ratio as it optimizes factors of light penetration through the canopy as well as space for the

canopy to grow. Low intensity thinnings have smaller crown ratios as a dense canopy persists in which light does not penetrate far enough for the tree to create a large crown-ratio. High intensity thinnings have smaller crown-ratios because they create an open canopy in which trees have the opportunity to fill out in lateral space which is more efficient to capture light compared to a more vertical crown structure (Larocque and Marshall, 1994). The effect of greater thinning intensities resulting in greater tree-level red pine productivity is a common theme in many managed red pine forests in the Great Lakes region (Bradford and Palik, 2009; D'Amato et al., 2010; Powers et al., 2010). Greater thinning intensities resulted in a greater tree-level productivity which was seen at a thinning intensity of 14 m² per hectare residual basal area as high growth rate of basal area and biomass (Bradford and Palik, 2009) as well as a high quadratic mean diameter (Powers et al., 2010). However, extremely high thinning intensities (7 square meters per hectare) can be detrimental to tree-level productivity as the residual trees are susceptible to damage from the thinning process as well as windthrow (Bradford and Palik, 2009; Powers et al., 2010). Increasing thinning intensity has also seen success in reinvigorating growth in older red pine stands (> 90 years) (Bradford and Palik, 2009; D'Amato et al., 2010).

Thinning method is a less significant variable of productivity as it minimally affects tree-level productivity (slenderness, basal area, and biomass) and does not affect stand-level productivity. Thinning method is less effective than thinning intensity at increasing productivity because the number of trees removed and not which trees are removed is the dominant factor in reducing competition (Nyland, 2007). The degree to which thinning method impacts productivity is a matter of contention. Some studies suggest that thinning method has a negligible impact on productivity (Gilmore et al., 2005; Smith, 2003) while others suggest a limited but still significant impact (Bradford and Palik, 2009; Powers et al., 2010). One potential reason for

these differences in these studies is the unit of productivity that was considered. All four studies express productivity as growth rate except for Powers et al. (2010) who used natural mortality as a measure of productivity. Powers et al., (2010) found that thinning from below was more effective at reducing natural mortality than thinning from above at equal thinning densities. Bradford and Palik (2009) reported that thinning from above generated greater growth rates than thinning from below which is contrary to the results reported by Gilmore et al. (2005) and Smith (2003) who reported no difference between the two thinning methods. Tree age is another potential factor for differences in the studies. Bradford and Palik (2009) worked with older trees (80- to 130- years) while Gilmore et al. (2005) and Smith (2003) studied stands that were much younger (35- to 50- years). The higher growth rate of younger trees potentially dominates any impact of thinning method. Conversely, the reduced growth rate of older trees is more sensitive to management and will respond to thinning method (Bradford and Palik, 2009). Combining the results regarding growth rate (Bradford and Palik, 2009) and tree-level and stand-level total productivity in this current study, it is concluded that thinning method is an effective tool to achieve particular productivity traits and can be a factor of growth rate in more mature stands.

Which thinning treatment is best to maximize productivity is an arbitrary measure that differs depending on what values of productivity are most desired. No one thinning treatment is able to maximize all values of tree-level and stand-level productivity therefore a compromise must be found (Zeide, 2001). We found that Below 60 and Below 90 maintained the largest average tree size in terms of height, diameter, crown ratio, slenderness, basal area and biomass. Not only did increasing the thinning intensity beyond Below 90 to Below 60 not result in an increase in tree-level productivity but it presented low stand-level basal area and biomass. Therefore, the Below 90 is the best overall thinning treatment to focus on a high tree-level

productivity while maintaining average stand-level productivity. Similar findings by D'Amato et al., (2010) indicate an above average basal area and volume per hectare in a plot that was thinned to 23.0 square meters per hectare compared to alternative thinning intensities that range from 13.8 square meters per hectare to 32.1 square meters per hectare. Additionally, Bradford and Palik (2009) reported that thinning to residual basal areas of 14 square meters per hectare and 21 square meters per hectare generated the two largest quadratic mean diameters compared to higher and lower intensity thinnings.

Alternatively, if maximum biomass per hectare is a desired outcome, this current study found that Above 120 and Below 120 are the best options. Unthinned plots also have the potential to exhibit very high stand-level productivity but it is at the expense of tree-level productivity and a high rate of natural mortality. Below 120 results in significantly larger trees than the Uncut and Above 120, so the Below 120 is the best compromise in this case. Similar findings were reported by D'Amato et al., (2010), Garcia-Gonzalo et al., 2007, and Powers et al., (2011) which indicate that low thinning intensities like 27.5 square meters per hectare and 32.1 square meters per hectare maintain a greater basal area and volume per hectare than moderate and high intensity thinnings. Another consideration is in the economic value of forest products extracted from a stand. Thinning from below is focused on developing a final high value stand with little value earned from each thinning, while thinning from above is focused on a more even rate of value extraction with larger and higher value trees being removed in each thinning (Gilmore and Palik, 2005; Nyland, 2007).

2.4.2. Growth-Climate Relationships

The significant positive correlations between radial growth and monthly precipitation in June and July of the current year represent drought stress reducing growth (Mäkinen et al., 2002; Martín-Benito et al., 2008; Pallardy, 2007). The same pattern and reasoning applies for the correlation between radial growth and climatic moisture index (CMI). Seasonal correlations between radial growth and both precipitation and CMI indicate that summer drought stress is a persistent climatic variable. Red pine has been reported to respond to summer drought by Kipfmüller et al. (2010) and St. George et al. (2008). In contrast, Kilgore and Telewski (2004) found no significant correlation with precipitation at any point in the year. It is assumed that in Kilgore and Telewski's (2004) study that sufficient water storage capacity in the soil at their study site buffered the trees from drought and allows them to grow independently from precipitation events (Kipfmüller et al., 2010).

In April of the previous year the significant positive correlations between radial growth and both precipitation and CMI signify the reliance on water availability in early spring at the start of the growing season. Sufficient water availability at this time is a key factor in the formation of buds for needles that will leaf-out in the following growing season (Garrett and Zahner, 1973; Pallardy, 2007). This correlation could also indicate a reliance on water availability to build-up carbohydrate reserves that can be used to drive growth in the following year (Pallardy, 2007). Such correlations between radial growth and both precipitation and CMI in the previous year are not persistent as no seasonal correlation was found.

Negative monthly temperature correlations with radial growth in both the previous and current year are a factor of increasing temperature causing an increase in the tree's respiration rate. Excessive respiration consumes carbon stores that had the potential to be used to increase productivity (Adams et al., 2009; Mäkinen et al., 2002; Pallardy, 2007). The influence of

temperature on growth is persistent as these same patterns were observed in the seasonal temperature correlation. Other studies have also shown that red pine growth is negatively correlated with summer temperature (Kipfmüller et al., 2010; St. George et al., 2008). This commonality indicates that summer temperature uniformly affects red pine across a wide area. Temperature at other times of the year has been reported to have less uniform effect on tree growth within the Great Lakes region. Graumlich (1993) and Kilgore and Telewski (2004) reported a positive correlation between red pine growth and temperature in April of the current year which was attributed to increased growth elicited by warming temperatures that promoted an early start to the growing season. Continental climatic conditions prevail in Minnesota (Graumlich, 1993) and central Michigan (Kilgore and Telewski, 2004) resulting in lower winter temperatures that may delay the start of the growing season (Scott and Huff, 1996). Conversely, the results of the current study indicate no correlation between radial growth and temperature in April of the current year. It is theorized that this lack of correlation is the result the proximity of the Great Lakes moderating winter temperature to the point that temperature in April is no longer a limiting growth factor (Scott and Huff, 1996).

Radial growth of red pine was positively correlated to monthly precipitation and CMI in December for the high thinning intensity plots. A potential ecophysiological based explanation for this is that more snow is able to reach the ground of the high thinning intensity plots, insulating the soil by a few extra degrees (Brown and DeGaetano, 2011). Greater soil temperature leads to earlier growth initiation in the spring and reduces the incidences of xylem cavitations in frozen tissue (Jyske et al., 2012). Growth responses to seasonal precipitation and CMI highlight winter snow insulation as a persistent climatic variable.

We speculate that the negative correlations between radial growth and precipitation exhibited by thinning from above in late summer of the previous and current year represent the influence of storm induced wind that can cause canopy damage (Everham and Brokaw, 1996; Peterson, 2000; Scott and Huff, 1996). This would result in decreased radial growth as resource allocation would be prioritized to repair the damaged crown (Pallardy, 2007). This reasoning also applies to the negative correlations between radial growth and CMI within the same timeframe.

2.4.3. Competition and Climatic Resiliency

The level of climatic resiliency is determined by the degree to which a thinning treatment is significantly correlated with a climatic variable. Generally, the fewer significant correlations between growth and climate, the greater the climatic resiliency that thinning treatment is to that climatic variable (Kilgore and Telewski, 2004). The exception to this is when another growth variable (such as competition) is a more limiting factor to growth than the climatic variable in question (Castagneri et al., 2012). Such a scenario would initially appear to indicate climatic resiliency, with little to no correlation between growth and climate, but if the tree's growth rate is very low due to limited access to light then it will not respond to changes in climate (Pallardy, 2007). Such cases are possible in high density stands where competition is greatest.

The lack of correlation between radial growth and both precipitation and CMI of the uncut control and low thinning intensity plots is likely due to high levels of competition and not an inherent high resilience of red pine to precipitation and CMI. Due to the high density and competition in these plots, light is the likely the most limiting factor to productivity instead of precipitation and CMI (Castagneri et al., 2012; Pallardy, 2007). Significant relationships with

precipitation is seen in higher intensity thinned plots in which competition was reduced enough for light to no longer be the most limiting growth factor (Above 60, Above 90, Below 60, and Below 90). Of these treatments, Below 90 exhibits the greatest resilience to monthly precipitation with only 1 month of significance, while Below 60 exhibits the greatest resilience to seasonal precipitation with no periods of significance (Table 2.4). Below 90 exhibits the greatest resiliency to CMI as it is the only moderate or high intensity thinning treatment that has no significant correlation with either monthly or seasonal CMI. Below 60 was also expected to be resilient to monthly CMI however this was not the case. This is in part due to the more open canopy which allows more snow to reach the ground increasing the insulating effect that increases soil temperature (winter correlation) (Brown and DeGaetano, 2011; Jyske et al., 2012). The open canopy also increases tree susceptibility to damage from windthrow (late summer correlation) (Evans et al., 2007), and allows greater solar radiation and wind penetration that results in an increase of evapotranspiration which can induce drought stress (early summer correlation) (Bladon et al., 2006).

Red pine resilience to temperature is seen as both a factor of thinning method and intensity. Larger trees, which are found in more intensely thinned plots and/or in the thinning from below plots, are more resilient to temperature. This is due to larger carbon stores maintained by larger trees which allow the tree to continue normal productivity rates in spite of loss of carbon from excess respiration rates (Adams et al., 2009; Pallardy, 2007). Smaller trees found in less intense thinnings and the thinning from above plots do not maintain large carbon stores and thus radial growth is more susceptible to excessive temperature induced respiration (Adams et al., 2009; Pallardy, 2007). Below 60 has the greatest climatic resiliency to monthly temperature as only one month is significantly correlated. Both Below 60 and Below 90 show the

greatest climatic resilience in terms of seasonal temperature with only one seasonal period each with a significant correlation. Plots that were thinned to 28 square meters per hectare (120 square feet per acre) and the uncut control exhibit the lowest climatic resiliency with four to five seasonal periods of significant correlation.

Climate-growth relationships for a variety of species and regions have been well researched (Chhin et al., 2008; DeLuis et al., 2009; Kilgore and Telewski, 2004; Mérian and Lebourgeois, 2011; Miyamoto et al., 2010; Pichler and Oberhuber, 2007). Such studies are mostly based on natural stands and can indirectly address climatic resiliency. Models have been used to predict climatic resiliency with the general consensus that it is possible for forest management to mediate changes in growth caused by climate change (Jacobson and Thorsen, 2003; Yousefpour et al., 2012). In order to directly approach quantifying climatic resiliency generated by forest management in terms of productivity a retrospective analysis of forest research sites and silvicultural experiments is generally used. Such studies are rare but a few examples are as follows. Laurent et al. (2003) reported on the relationships between thinning intensity and drought resilience of Norway spruce. It was found that increased thinning intensity resulted in greater resilience to drought stress. Another example is from Cescatti and Piutti (1998) who considered various thinning treatments of European beech and found that an intermediate thinning intensity resulted in resiliency to drought and temperature stress while maintaining a valuable yield. The results of these studies are corroborated by the current study which found that thinning from below to a moderate thinning intensity resulted in an increased resilience to precipitation, CMI, and temperature while maintaining high tree-level productivity and moderate stand-level productivity. In order to sustain climatic resiliency, forest management

techniques must be maintained, otherwise climatic resiliency will diminish over time (Vayreda et al., (2012).

2.5. Conclusions

Thinning intensity was found to be a stronger influence on productivity and climatic resilience than thinning method. Overall the thinning from below to a residual basal area of 21 square meters per hectare (90 square feet per acre) was the best compromise to maximize tree size, biomass per hectare, and climatic resiliency. This data is particularly applicable to red pine productivity as it describes red pine stands at an age (79 years) in which they are commonly harvested for sawtimber. (Johnson, 1995). Additionally, the potential to use climatic resilience as a guide in adapting future forest management techniques will give long term relevance to the findings of this study (Dombroskie et al., 2009).

APPENDICES

Table 2.1. Number of trees sampled per treatment (n). Average (standard deviation) tree-level productivity (DBH, tree height, crown ratio, and slenderness) of red pine in Michigan managed under seven thinning treatments. Treatments with different letters are significantly different ($p < 0.05$).

Treatment	n	DBH (cm)	Tree Height (m)	Crown Ratio	Slenderness
Uncut	24	24.04 (4.67) a	23.81 (1.33) b	0.325 (0.113) ab	103.39 (19.77) d
Above 60	24	29.9 (4.81) b	22.54 (1.67) ab	0.397 (0.078) b	76.64 (13.47) b
Above 90	24	25.89 (3.92) ab	20.98 (2.08) a	0.485 (0.09) c	82.6 (10.94) bc
Above 120	24	23.91 (4.41) a	21.91 (2.55) a	0.392 (0.072) b	91.92 (14.44) cd
Below 60	21	34.5 (2.12) c	23.99 (0.69) b	0.437 (0.037) bc	68.83 (5.02) ab
Below 90	24	34.33 (2.8) c	23.9 (1.39) b	0.484 (0.067) c	69.17 (3.6) a
Below 120	24	27.71 (1.94) b	24.33 (0.81) b	0.299 (0.05) a	86.28 (5.95) c

Table 2.2. Average (standard deviation) tree-level productivity (basal area, total above ground biomass, and total stem biomass) of red pine in Michigan managed under seven thinning treatments. Treatments with different letters are significantly different ($p < 0.05$).

Treatment	Basal Area (m²)	Total Above-Ground Biomass (kg)	Total Stem Biomass (kg)
Uncut	0.0471 (0.0177) a	194.32 (87.99) a	124.53 (57.97) a
Above 60	0.0720 (0.0219) b	324.01 (116.91) b	210.35 (77.56) b
Above 90	0.0538 (0.0147) ab	226.79 (73.15) ab	145.87 (48.2) ab
Above 120	0.0464 (0.0156) a	190.43 (74.93) a	121.93 (49.21) a
Below 60	0.0939 (0.0116) c	443.01 (66.92) c	289.42 (44.67) c
Below 90	0.0932 (0.0148) c	439.8 (84.24) c	287.31 (56.16) c
Below 120	0.0606 (0.0086) b	260.44 (45.04) b	168.01 (29.84) b

Table 2.3. Average (standard deviation) stand-level productivity (basal area per hectare, above ground biomass per hectare, and stem biomass per hectare of red pine in Michigan managed under seven thinning treatments. Treatments with different letters are significantly different ($p < 0.05$).

Treatment	Basal Area (m²/hectare)	Total Above-Ground Biomass (Metric Tons/hectare)	Total Stem Biomass (Metric Tons/hectare)
Uncut	47.08 (11.97) abcd	187 (40.45) abc	119.05 (24.97) abc
Above 60	17.41 (0.33) a	77.62 (6.2) a	50.33 (4.46) a
Above 90	24.71 (1.33) b	104.69 (3.52) b	67.39 (2.06) b
Above 120	34.66 (0.41) d	141.2 (4.77) c	90.28 (3.73) c
Below 60	17.56 (2.49) ab	83.41 (10.63) ab	54.53 (6.85) ab
Below 90	25.69 (1.62) bc	121.47 (5.19) bc	79.37 (3.24) bc
Below 120	31.61 (1.37) cd	138.02 (3.99) c	89.25 (2.4) c

Table 2.4. Counts of significant bootstrapped correlation coefficients for monthly and seasonal periods between climatic variables (temperature, precipitation, and climatic moisture index) and different thinning treatments. Fewer counts indicate climatic resiliency or high competition in high density stands.

Treatment	Month Temp	Month Precip	Month CMI	Month Total	Season Temp	Season Precip	Season CMI	Season Total
Uncut	2	0	1	3	4	0	0	4
Above 60	2	3	3	8	1	2	2	5
Above 90	3	2	3	8	3	1	1	5
Above 120	3	2	0	5	5	0	0	5
Below 60	1	2	3	6	1	0	1	2
Below 90	2	1	0	3	1	1	0	2
Below 120	2	2	2	6	4	1	2	7

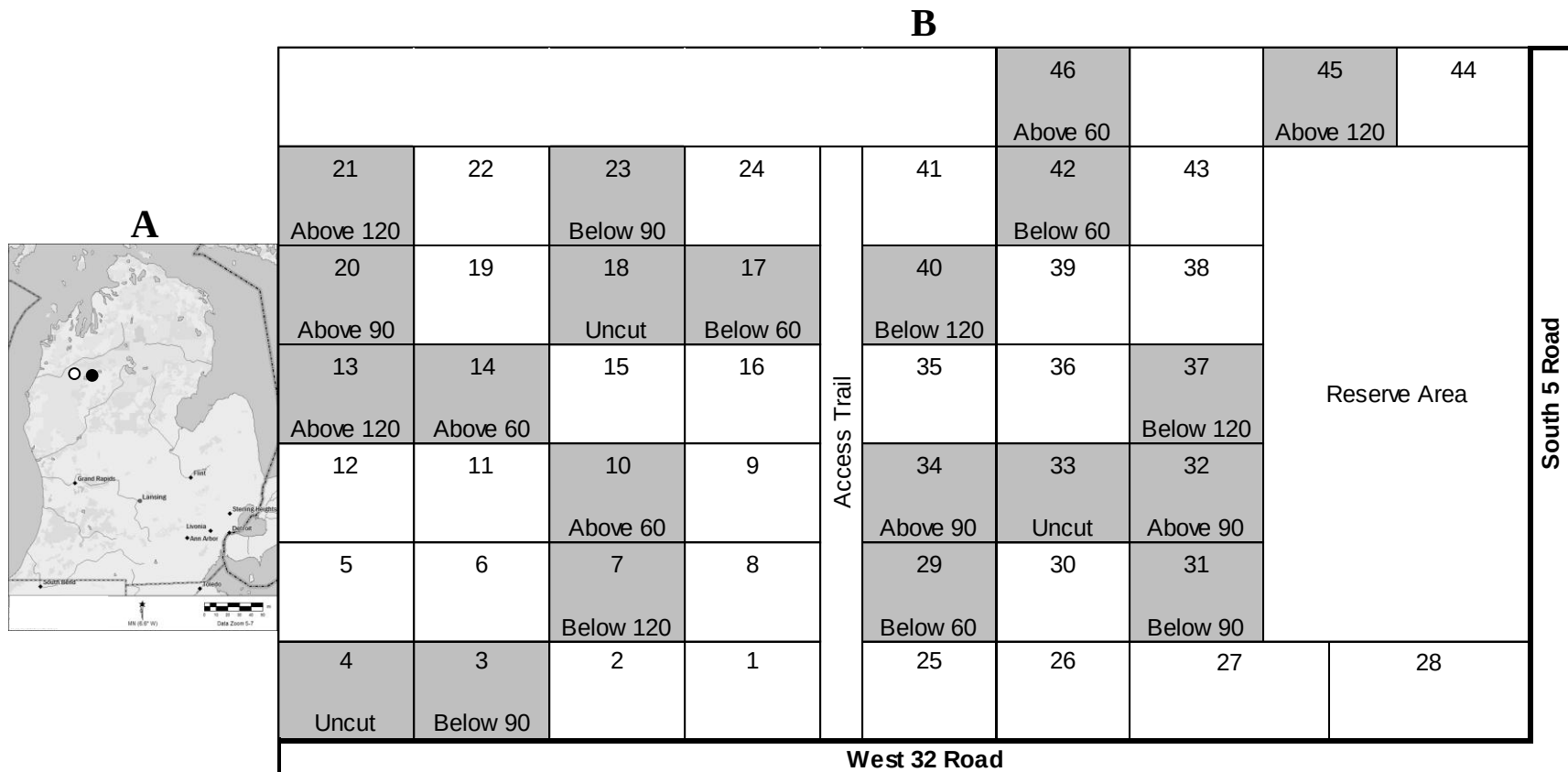


Figure 2.1. A) USDA research plantation sample site location marked by white dot (situated near Wellston, Michigan) and climate station marked by the black dot (Cadillac, Michigan) in Wexford County in the lower peninsula of Michigan. B) Site map of USDA research plantation. Shaded cells highlight plots used in study. Non-labeled cells represent thinning treatments that were not considered in this study. Plots covered 0.5 acre with a 0.1 acre sub-plot center to each plot in which samples were collected.

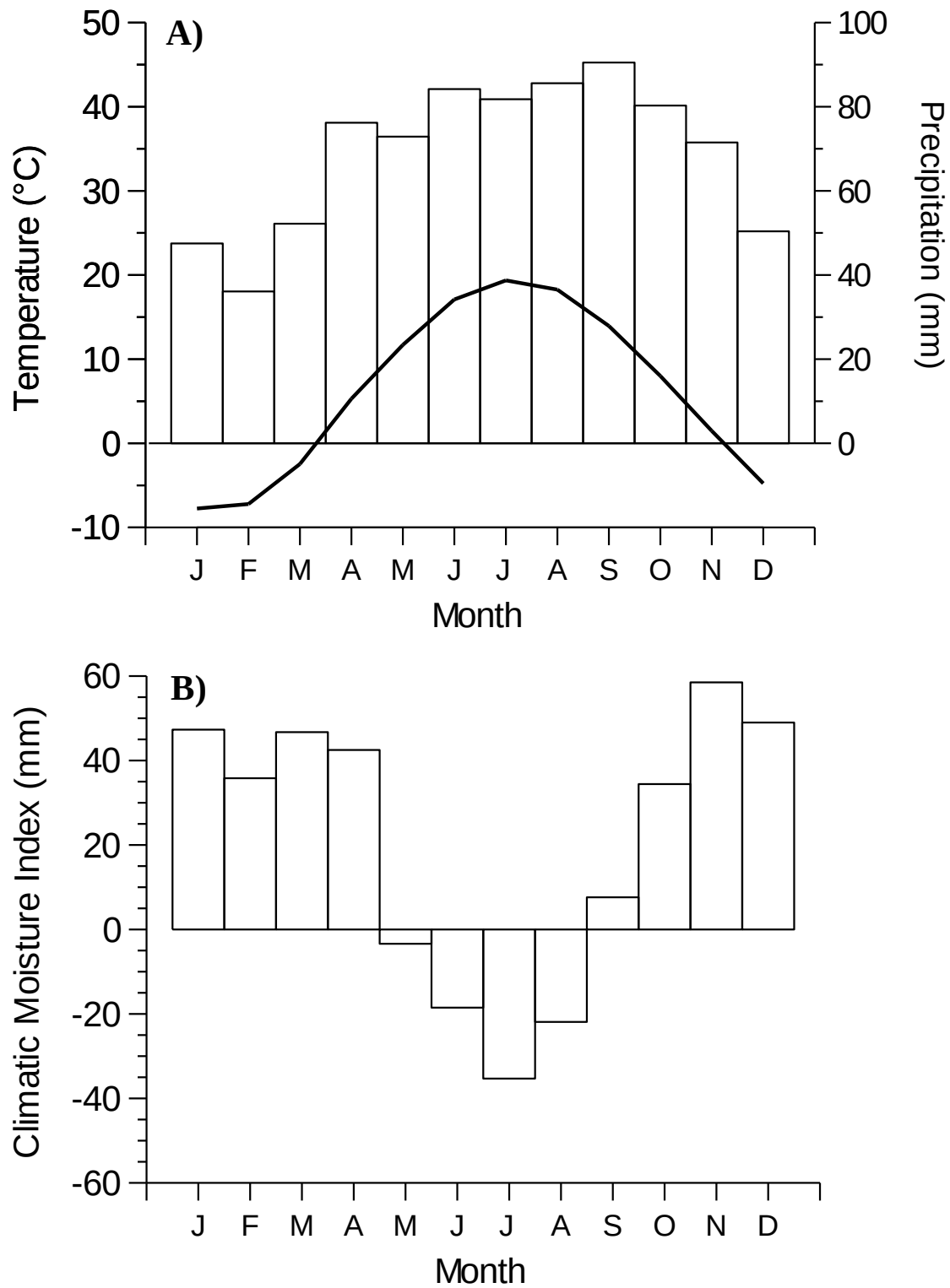


Figure 2.2. A) Mean monthly temperature and mean total monthly precipitation were averaged from 1948 - 2010 for Cadillac, Michigan. Line represents temperature and bars represent precipitation. B) Mean monthly climatic moisture index averaged from 1948 - 2010 in Cadillac, Michigan

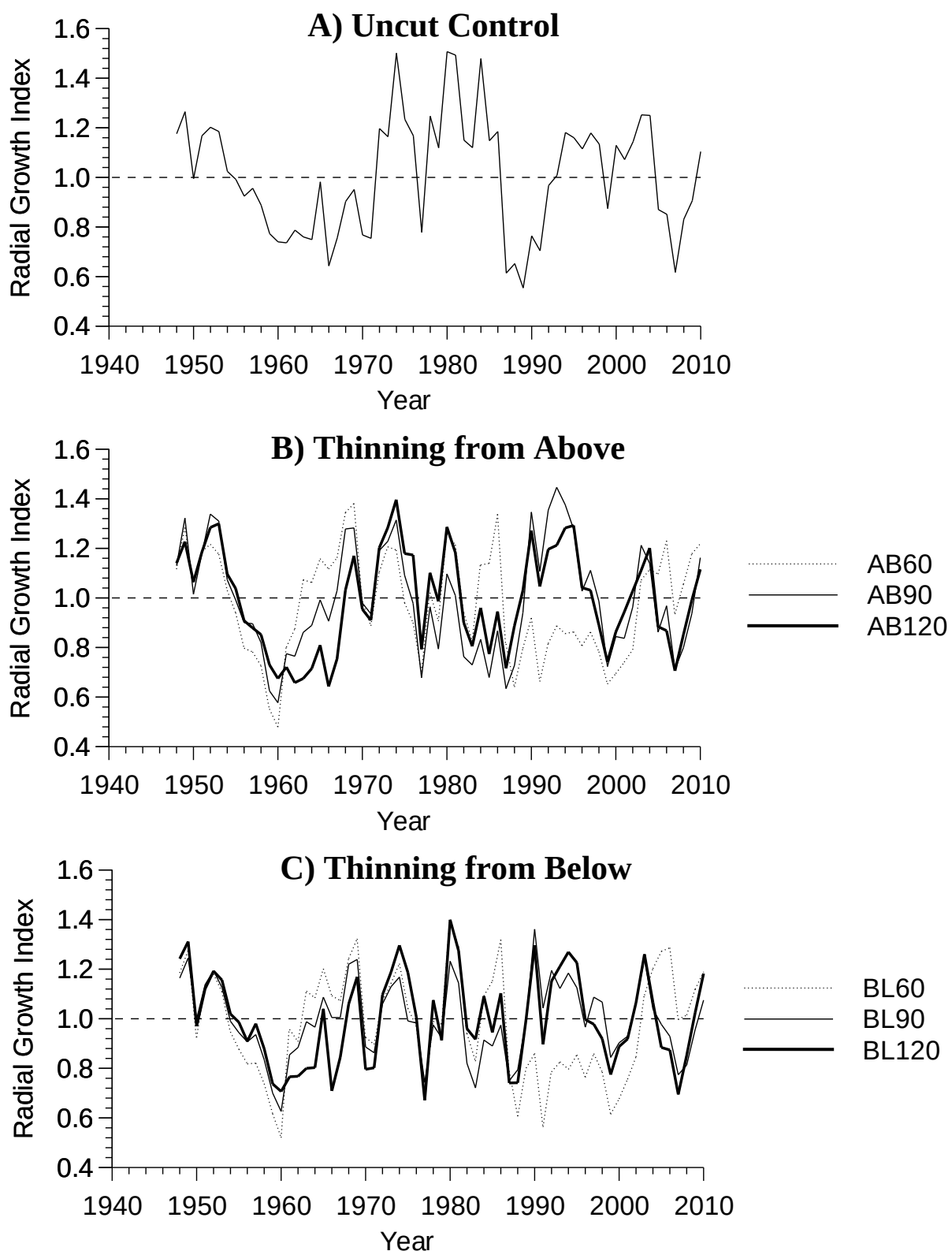


Figure 2.3. Detrended ring width chronologies of red pine grown in Wellston, Michigan. AB represents thinning from above and BL represents thinning from below and 60, 90, and 120 square feet per acre represent the residual basal area of each thinning treatment.

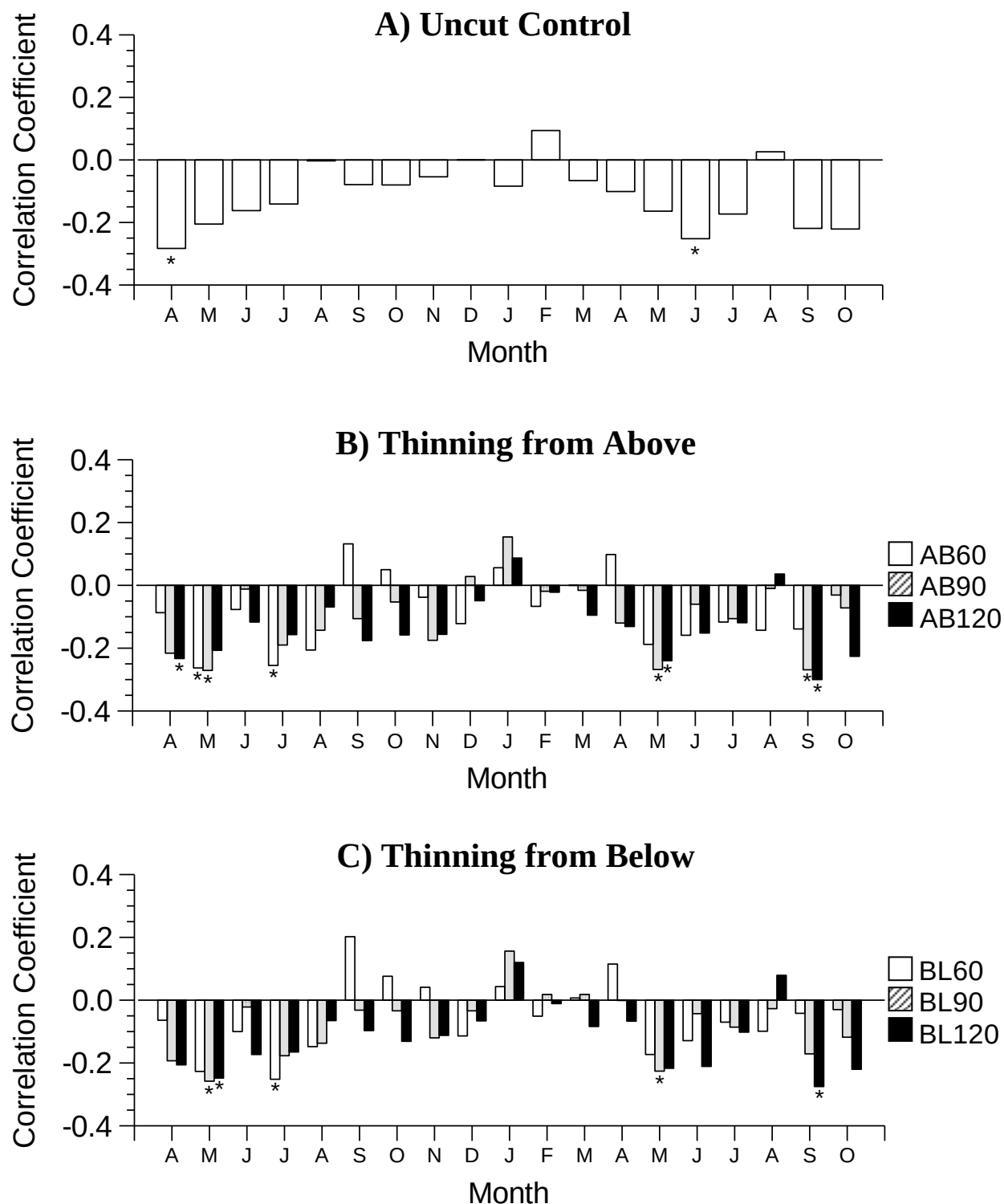


Figure 2.4. Monthly correlations between mean temperature and radial growth of red pine in Michigan based on climate from 1948 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations.

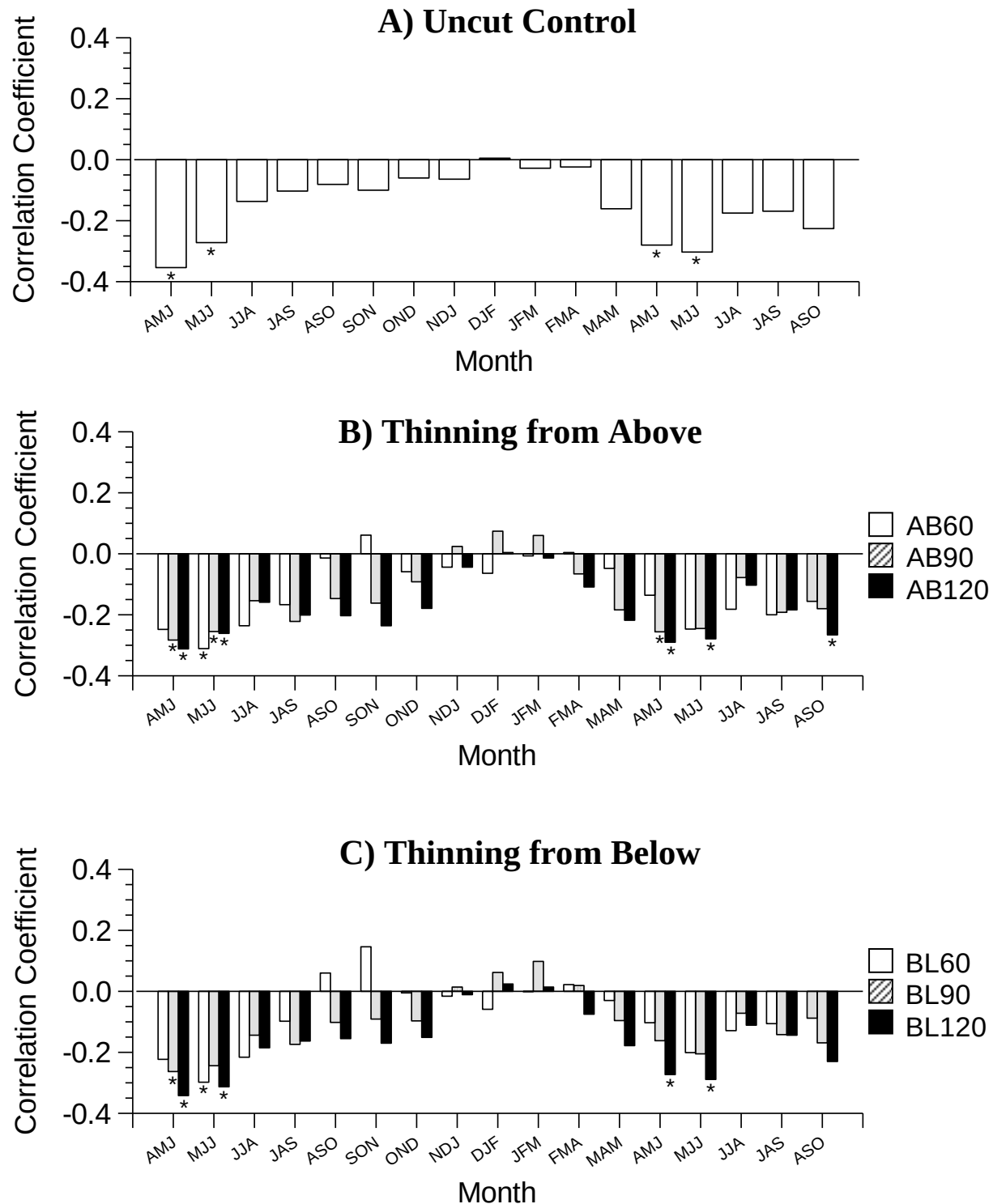


Figure 2.5. Seasonal correlations between mean temperature and radial growth of red pine in Michigan based on climate from 1948 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations.

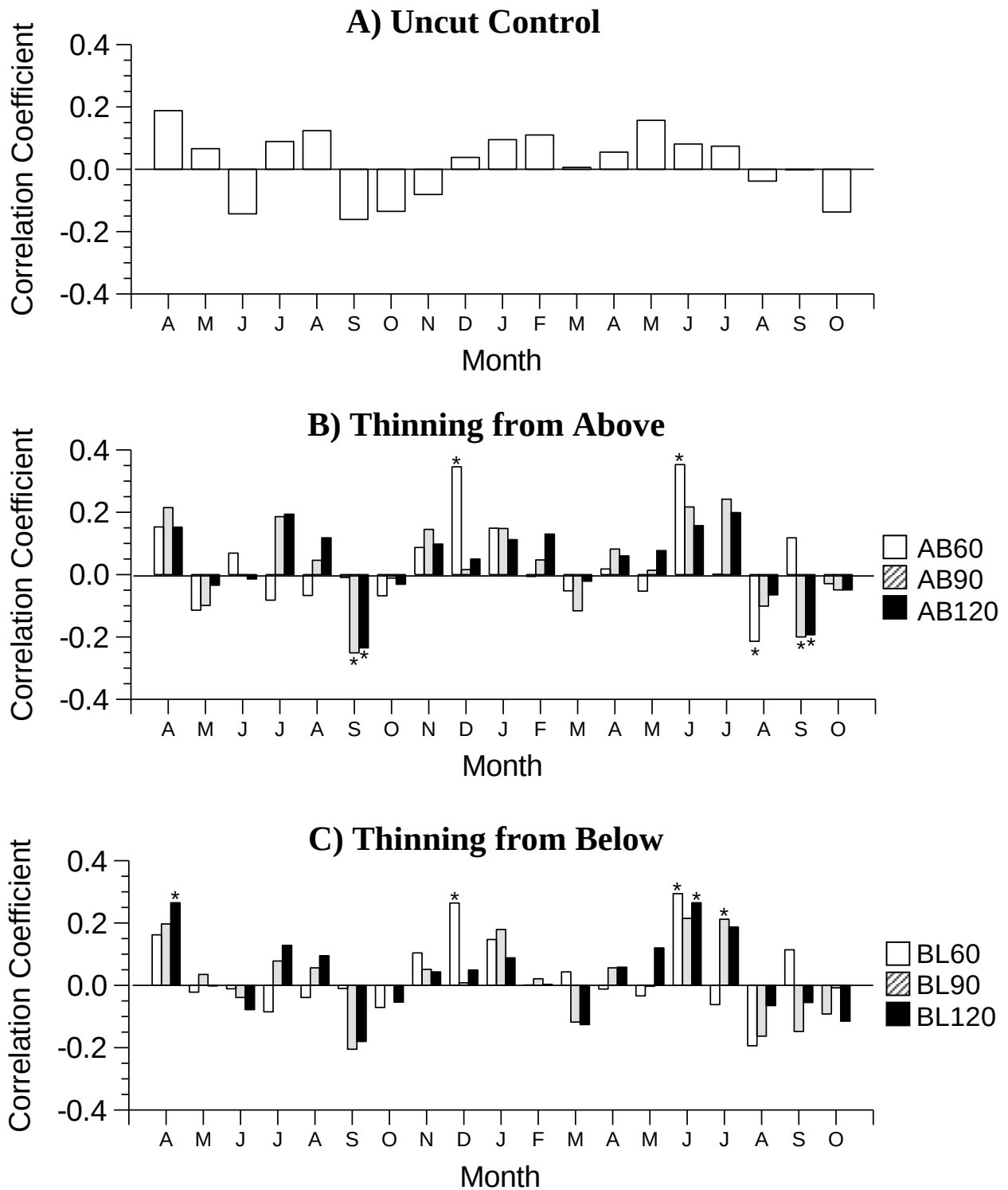


Figure 2.6. Monthly correlations between total precipitation and radial growth of red pine in Michigan based on climate from 1948 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations.

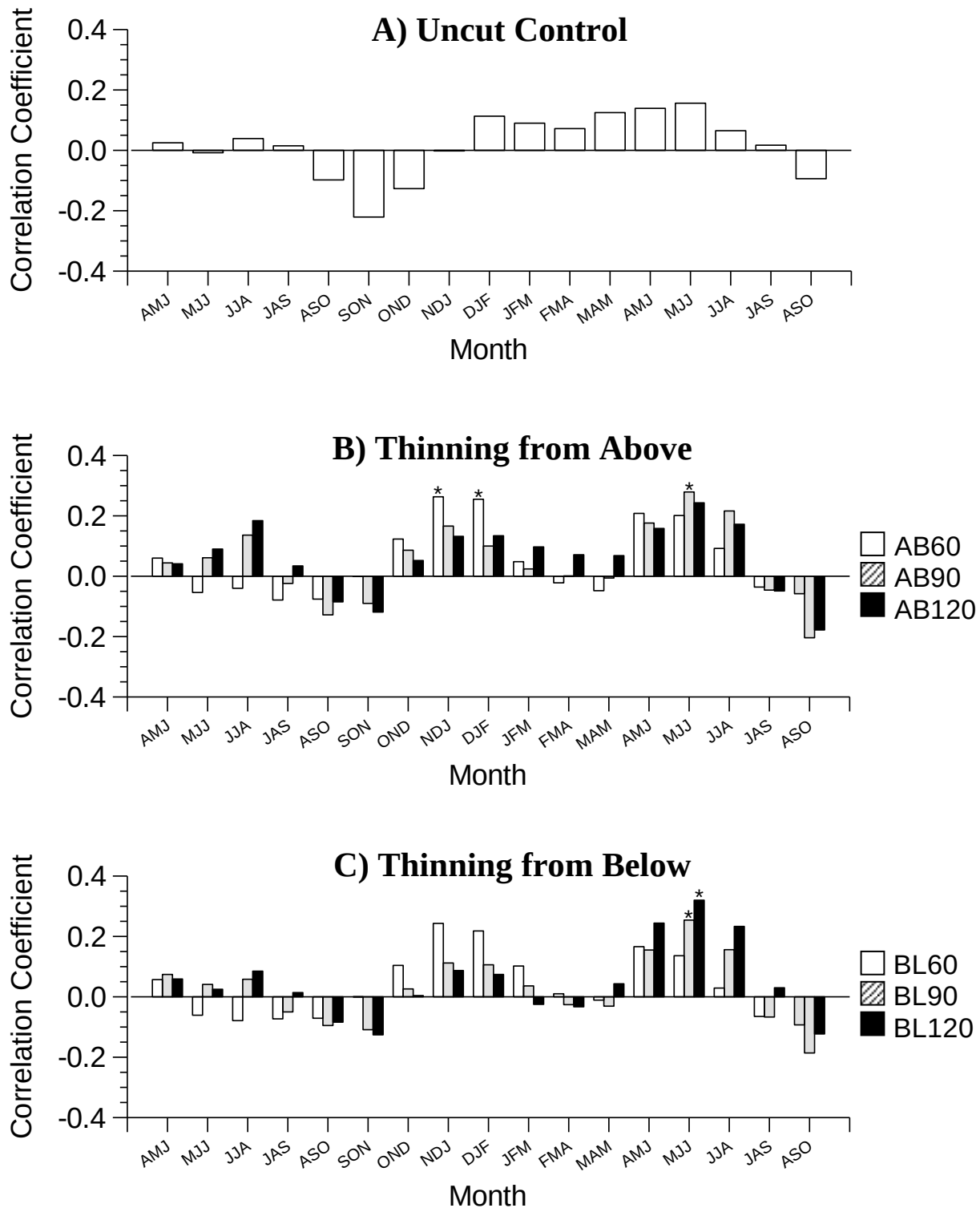


Figure 2.7. Seasonal correlations between total precipitation and radial growth of red pine in Michigan based on climate from 1948 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations.

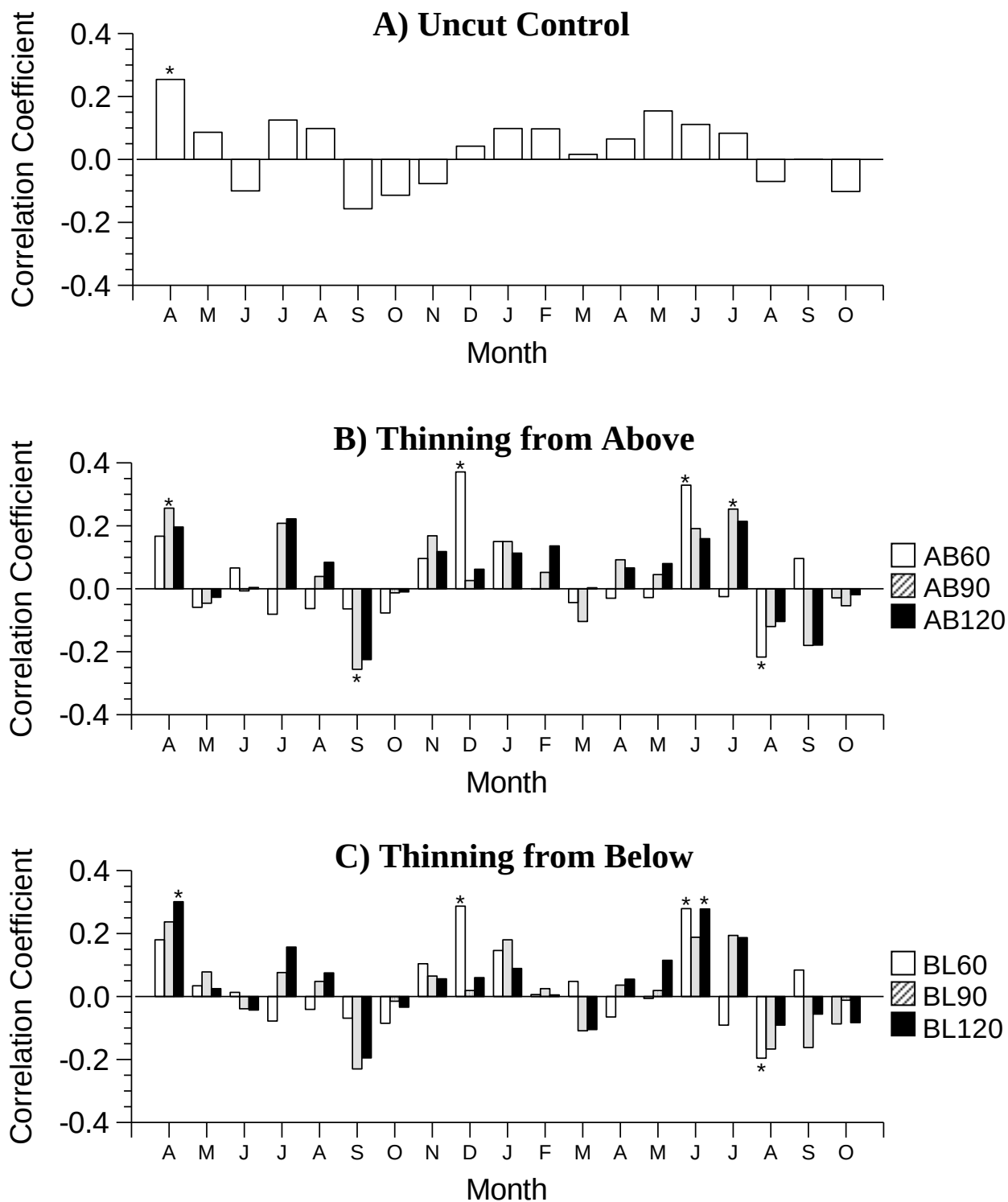


Figure 2.8. Monthly correlations between total climatic moisture index and radial growth of red pine in Michigan based on climate from 1948 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations.

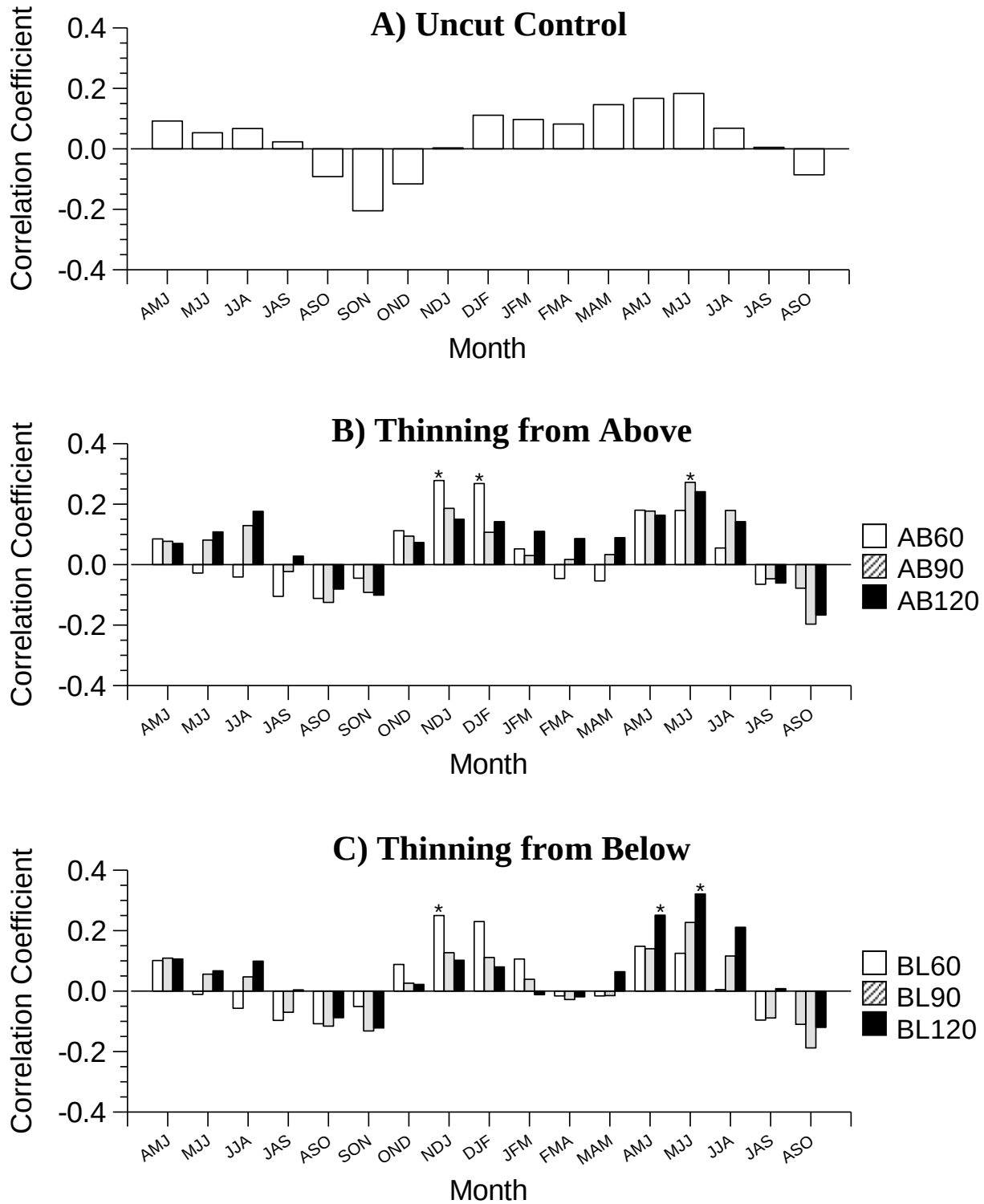


Figure 2.9. Seasonal correlations between total climatic moisture index and radial growth of red pine in Michigan based on climate from 1948 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations.

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CHAPTER 3

EFFECTS OF INITIAL STAND DENSITY AND CLIMATE ON RED PINE PRODUCTIVITY WITHIN HURON NATIONAL FOREST, MICHIGAN

3.1. Introduction

Future climate change is expected to cause a significant impact to tree growth through changes in temperature and precipitation (Chmura et al., 2011; Spittlehouse and Stewart, 2003). Current forest management techniques must adapt in order to maintain productivity of forest resources under future conditions (Dombroskie et al., 2010). Management adaptation will allow for proactive forest management to generate climatic resiliency and maintain productivity as opposed to relying on reactive forest management to salvage lost productivity.

Initial stand density is a possible proactive management technique to cope with changing climate. Two common planting regimes, 988 trees per hectare (400 trees per acre) (low density) and 1977 trees per hectare (800 trees per acre) (high density) have been generally used for managing red pine (*Pinus resinosa* Ait.) in the Great Lakes region (Gilmore and Palik, 2005). Planting 988 trees per hectare is less costly and trees grow more rapidly due to increased growing space compared to higher density plantings. Alternatively, planting 1977 trees per hectare promotes growth with less taper, smaller branches, and a larger stand volume per hectare. It also provides a greater selection of crop trees and more options for early stand development (Gilmore and Palik, 2005; Larocque, 2002; Penner et al., 2001).

Examining common growth responses to climate across multiple sites can be used to determine if a forest management technique can generate climatic resiliency uniformly across a region. Past research has indirectly identified common climatic responses across multiple sites

for several species in terms of tree productivity and forest management but generally have been focused on observational studies in natural forests (Chhin et al., 2008; Kipfmüller et al., 2010; Miyamoto et al., 2010). In contrast, there have been few studies that have examined the influence of climate in managed forests across a regional network of site (Lasch et al., 1999). New research that reports climatic resiliency in terms of direct correlations between tree productivity, forest management, and climate across a large region will provide data that can be used to adapt general management techniques to maintain tree productivity in the future.

The general objective of this study is to examine the influence of initial stand density on climatic responses of red pine across multiple sites within the Huron National Forest. Specifically, the first objective of this study is to quantify different aspects of productivity as caused by low and high initial stand densities (988 and 1977 trees per hectare, respectively) at the individual tree-level as well as stand-level on a per hectare basis. The second objective is to determine which initial stand density will result in a higher climatic resiliency while maintaining adequate productivity.

3.2. Methods

3.2.1. Study site

The study was implemented in the Huron National Forest of Michigan (Figure 3.1) where forest cover is dominantly comprised of white, red and jack pine (*Pinus strobus*, *Pinus resinosa*, and *Pinus banksiana* respectively) (Dickmann and Leefers, 2003; Johnson, 1995). White pine is the least common of the three species and most commonly occurs in mixed stands. Red pine is the most commercially important conifer in the region and is commonly found in managed plantations (Johnson, 1995). Jack pine is typically managed in the region as an early succession

stage to promote habitat for the endangered Kirtland's Warbler (Donner et al., 2009). Six sample sites were selected based on dominance of red pine (> 85% of stems), minimum age (30 years), general positive health of the stand, and density of the stand. Three sites were chosen to represent high density stands (>1977 trees per hectare) while the other three plots represent low density stands (< 988 trees per hectare). Differences in density were caused by management based adoption of different initial plantation densities. Intermediate stand management of red pine in the Huron National Forest is uniformly managed to be initially cut with a row thinning (cut two rows, leave two rows) (K. Lazda, USDA Forest Service, personal communication). This is followed by a free thinning approximately every 15 years to remove individuals with poor form and/or disease while maintaining a basal area of 21 square meters per hectare (90 square feet per acre) (Gilmore and Palik, 2005). All sites were plantations and incorporated a small variety of tree ages and sizes. Soil at all sites are very similar types of excessively drained sand (Natural Resources Conservation Service, 2012). Given that all other growth variables are not significantly different between sample sites, initial stand density is therefore the key independent variable of this study.

Annual mean temperature averaged 6.41° C from 1931 to 2010 in Mio, Michigan. In the same time frame the total annual precipitation averaged 678.2 mm and the total annual climatic moisture index averaged 31.1 mm (National Climatic Data Center, 2012). Temperature and precipitation significantly increased during the spring and summer months which marks the growing season from April to October (Figure 3.2 A). However, the increase in temperature from May to October also increases evapotranspiration offsetting the influx of water into the system and causing a net loss of water available for growth. This typical summer drought is

demonstrated in Figure 3.2 (B) by a negative climatic moisture index (measure of precipitation minus potential evapotranspiration) (Hogg, 1997).

3.2.2. Field sampling

Sample plots were established in October of 2011 by conducting a forest inventory within a plot with a 7.99 meter (high initial density stands) or 9.78 meter (low initial density stands) radius around a randomly selected focal tree a minimum of 30 m from the stand's boundary. Trees that were closest to half the radius of the plot along the bearings of NE, SE, SW, and NW were selected for sampling. For each of the selected trees, total height, height to live crown, diameter at breast height (DBH), and bark thickness were measured. In addition, two cores were collected from each tree with an increment bore at breast height (1.37 m) from the north and south face of each tree.

3.2.3. Sample Processing

Tree cores were processed using standard dendrochronological techniques (Stokes and Smiley, 1996). Tree cores were glued onto grooved wood strips to act as a stable base. Samples were then sanded with progressively finer sandpaper up to 600 grit to achieve a polished surface in which the rings were clearly visible. Sanded cores were then scanned into a computer at an optical resolution of 1200 dpi.

3.2.4. Cross-Dating and Tree-Ring Measurement

Cores were cross-dated with the list method to accurately assign a calendar date to each tree ring (Yamaguchi, 1991). In addition to relative width of rings, characteristic ring structures

such as missing rings, frost rings, and latewood width were also used to ensure maximum accuracy of the crossdating. Additional statistical quality control was provided through the use of the program COFECHA (Holmes, 1983; Holmes, 1994). COFECHA identifies samples that should be checked for cross dating errors based on a poor correlation between individual ring widths series and an average sub-plot chronology. Ring widths were measured using the programs CooRecorder and CDendro (Cybis Elektronik & Data AB, Saltsjöbaden, Sweden). A stage micrometer (Velmex: Bloomfield, New York) was used as a supplemental tool to measure sections of cores with very narrow rings that were unclear in the scanned image.

3.2.5. Data Analysis

3.2.5.1. Biomass Calculations

Allometric equations were used to calculate tree biomass as a function of DBH. Total aboveground tree biomass (Equation 3.1) was determined using the following equation that is specific to pine species (Jenkins et al. 2003):

$$T_{bm} = \text{Exp} (-2.5356 + 2.4349 \ln \text{DBH}) \quad (3.1)$$

Where

T_{bm} = total aboveground biomass

Exp = exponential function

ln = natural log base e (2.718282)

DBH = diameter at breast height

A tree component equation was used to calculate the ratio of stem biomass to total aboveground biomass (Equation 3.2) (Jenkins et al. 2003):

$$\text{Ratio} = \text{Exp} [-0.3737 + (-1.8055 / \text{DBH})] \quad (3.2)$$

Where

Ratio = ratio of stem biomass to total aboveground biomass

Exp = exponential function

DBH = diameter at breast height

The ratio was multiplied by the total aboveground biomass to calculate the stem biomass. Total and stem biomass were summarized as an average of the eight trees sampled in each sub-plot. Separate calculations summarized the total and stem biomass on a per hectare basis based on the DBH of all trees in a sub-plot as of October 2011.

3.2.5.2. Red Pine Form and Productivity

Slenderness coefficient is a dimensionless value based on the ratio of the diameter and height of a tree and is calculated as the height divided by the DBH in the same units (m). Greater values indicate a taller and narrower tree, and trees with values over a threshold of 80 are prone to wind-induced breakage (Watt et al., 2008). Crown ratio represents the ratio of the crown length to the total height of a tree and is calculated as the height of the lowest dominant branch divided by the total height of the tree. All collected measures of tree-level productivity (DBH, total height, crown ratio, slenderness coefficient, basal area, total biomass, and stem biomass)

were subjugated to an one-factor analysis of variance (ANOVA) to indentify significant thinning treatments effects using the program SYSTAT 10.2. Furthermore, stand-level productivity (i.e. per hectare basis) was also compared between the treatments using a one-way ANOVA. Fisher's LSD was used to examine pairwise comparisons between thinning treatments (SYSTAT, 2002). Any comparison with a P value that was less than 0.05 was considered significant.

3.2.5.3. Dendrochronological Analysis

Ring widths were detrended to generate a radial growth index through the statistical program ARSTAN (Cook, 1985; Holmes, 1994). A radial growth index is a dimensionless expression of ring width and was calculated by dividing the observed ring width by the ring widths predicted from a 40 year cubic smoothing spline. Radial growth index values that are greater than one represent above average growth while values less than one represent below average growth. Ring widths were detrended to standardize the raw ring width measurements though the removal of size and age related effects on ring width. Remaining variation in the radial growth index between trees is the result of stand-wide effects like climate and management (Biondi, 1999). The radial growth index of each tree and year was averaged to create a standard chronology for each thinning treatment which could then be compared to historical climate data. ARSTAN calculated an expressed population signal (EPS) to exceed 0.80 for all thinning treatments from 1965 to 2010 so all climatic analysis is based on that timeframe (Briffa and Jones, 1990). The EPS quantifies how well a chronology based on a finite number of trees represents a hypothetically perfect chronology (Wigley et al., 1984).

Historical climate data was obtained from by the National Climatic Data Center at the Mio Hydro Plant (Station ID 205531) (44°39'40" N 84°07'54" W) and the Mio Waste Water

Treatment Plant (Station ID 205533) (44°38'47" N 84°06'55" W) in Mio, Michigan. Data collected included monthly averages of minimum, mean, and maximum daily temperature, and total monthly precipitation. Minimum and maximum monthly temperature and precipitation measurements were further combined into a climatic moisture index (CMI) representing estimated net water availability to trees. CMI was calculated based on the following equation (Hogg, 1997):

$$\text{CMI} = \text{P} - \text{PET} \quad (3.3)$$

Where

CMI = climatic moisture index (mm)

P = precipitation (mm)

PET = potential evapotranspiration (mm)

Potential evapotranspiration (PET) was calculated based on mean temperature (Hogg, 1997):

$$\text{When } T_{\text{mean}} > 10^{\circ} \text{ C: } \text{PET} = 93 * D * \text{Exp} (A / 9300) \quad (3.4 \text{ a})$$

$$\text{When } 10^{\circ} \text{ C} > T_{\text{mean}} > -5^{\circ} \text{ C: } \text{PET} = (6.2 * T_{\text{mean}} + 31) D * \text{Exp} (A / 9300) \quad (3.4 \text{ b})$$

$$\text{When } T_{\text{mean}} < -5^{\circ} \text{ C: } \text{PET} = 0 \quad (3.4 \text{ c})$$

Where

T_{mean} = mean temperature ($^{\circ}$ C)

PET = potential evapotranspiration (mm)

D = vapor pressure deficit (kPa)

Exp = exponential function

A = altitude of climate station (m)

The vapor pressure deficit (D) was calculated as (Hogg, 1997):

$$D = 0.5 (eT_{\text{max}} - eT_{\text{min}}) - eT_{\text{dew}} \quad (3.5)$$

Where

D = vapor pressure deficit (kPa)

eT_{max} = saturation vapor pressure at maximum temperature

eT_{min} = saturation vapor pressure at minimum temperature

eT_{dew} = saturation vapor pressure at mean dewpoint temperature

Missing climate data-points were extrapolated based on data from nearby climate stations at the Hale Loud Dam (Station ID 203529) (44°27'49" N 83°43'18" W) near Glennie, Michigan. Additionally, monthly climate data was seasonalized into 3 month periods (averages of temperature and sums of precipitation and CMI) to represent long term climatic trends.

The standard chronology and each individual set of climate data were run through the program DendroClim (Biondi and Waikul, 2004) to identify significant monthly correlations between each climatic variable and tree growth from April of the previous year to October of the current year. Analysis begins in April of the previous year as growing conditions of the previous year can affect the current year's growth by how much carbon they store and how many needle buds are formed (Garrett and Zahner, 1973; Pallardy, 2007). Significant correlations are determined through bootstrapped samples, which are drawn at random with replacement from each year in the data set (Biondi and Waikul, 2004). For every data set, Pearson correlation coefficients were calculated between growth and each of the monthly and seasonal climate variables. A total of 1000 bootstrapped samples are calculated to compute correlation coefficients. Statistical significance is determined from the correlation coefficients from the original data set that fall outside of the 95% range of 1000 bootstrapped data sets (Biondi and Waikul, 2004).

3.3. Results

3.3.1. Red Pine Form and Productivity

Mean DBH and tree height were greater for trees planted at a low initial stand density versus the high initial stand density (Table 3.1). There was no significant difference in crown ratio and slenderness of trees between low initial stand density and high initial stand density plots (Table 3.1). There were also no significant differences in tree basal area but both total and stem biomass was greater in low density versus high density stands (Table 3.2). However, on a stand-level, there was no significant difference in basal area and biomass between the low and high initial stand density treatments (Table 3.3).

Ring width chronologies between high and low density plots feature many similar patterns as well as a few key differences. Low density plots generally have more consistent growth with fewer extreme values in the radial growth index (Low initial density standard deviation equaled 0.19 and high initial density standard deviation equaled 0.28). This is particularly evident in the late 1960s to early 1970s, and mid 1990s, and mid 2000s (Figure 3.3).

3.3.2. Growth-Climate Relationships

Monthly correlations between temperature and radial growth in Figure 3.4 (A) highlight significant negative relationships in May and July of the previous year for trees found in both high and low initial density stands. Monthly correlations between precipitation and radial growth for trees found in high initial density stands in Figure 3.4 (B) show a significant negative correlation in May of the previous year and a positive correlation in June of the current year. In contrast, the radial growth of trees found in low initial density stands was only correlated to precipitation negatively in August of the current year. Monthly CMI is positively correlated with radial growth in high initial density stands in June and July of the current year and negatively correlated with radial growth in low initial density stands in August of the current year (Figure 3.4 C).

Seasonal correlations between temperature and radial growth mirror the monthly correlations with significant negative relationships in Apr-May-Jun and May-Jun-Jul of the previous year (Figure 3.5 A). In contrast, the correlations between radial growth and seasonal precipitation (Figure 3.5 B) indicate no periods of significance for either high or low initial density stands. Finally, seasonal CMI is positively correlated to the radial growth of trees found in high initial density stands in May-Jun-Jul of the current year (Figure 3.5 C).

3.4. Discussion

3.4.1. Red Pine Form and Productivity

Low initial density stands had higher values of tree-level DBH, height, and biomass as compared to high initial density stands which is the result of lower levels of competition exhibited in low initial density stands. Less competition allows trees increased growing space and thus more access to resources (i.e. light, soil moisture) which in turn increases their productivity (Nyland, 2007). Tree-level crown ratio, slenderness and basal area as well as stand-level basal area and biomass were not significantly different between low and high initial density plots. This lack of significance indicates that such measures of productivity equalize as the stand ages if no additional forest management techniques differentiate the plots (Nyland, 2007). A model constructed by Li et al. (2011) predicted a loss of stand-level productivity through self-thinning in high initial density stands but not in low initial density stands. Such a loss was not recorded in this study as the plots were managed with thinning to prevent self thinning. The findings of the current study are supported by Penner et al. (2001) who reported that lower initial thinning density increased quadratic mean diameter, but reduced stand-level basal area and biomass compared to higher initial density plots. Additionally, Penner et al., (2001) reported no significant difference in tree height was found between treatments. Similarly, Larocque (2002) also reported no difference in tree height for any initial stand density. It is generally understood that tree height is not overly sensitive to changes in stand density (Nyland, 2007). However, it is still possible for stand density to influence height if comparing extreme stand densities, which is the case for the current study (Nyland, 2007).

3.4.2. Growth-Climate Relationships

The significant positive relationship for precipitation in June and CMI in June and July of the current year for the high initial density plots is the result of growth sensitivity to summer drought stress (Pallardy, 2007). Summer drought is a persistent variable affecting growth in high initial density stands as demonstrated by the seasonal correlation with CMI for May-Jun-Jul. Similar reports of red pine response to June-July drought have been made by Kipfmuehler et al. (2010). Different results were reported by Kilgore and Telewski (2004) who found no significant correlation between red pine radial growth and precipitation at any point in the year. It is postulated that there was sufficient water storage capacity in the soil at Kilgore and Telewski's (2004) study site that buffered the trees from drought and allows them to grow independently from precipitation events (Kipfmuehler et al., 2010).

The correlation between radial growth in high initial density stands and both temperature and precipitation in May of the previous year is indication of temperature induced drought stress (Pallardy, 2007). All other correlations in the previous year (May and July) are a factor of increasing temperature resulting in an increase in tree's respiration rate (Adams et al., 2009). Excessive respiration consumes carbon stores that had the potential to be used in the current years productivity (Pallardy, 2007). Excessive temperature induced respiration is a persistent growth variable as indicated by significant relationships in Apr-May-Jun and May-Jun-Jul of the previous year. Summer temperature has a widespread influence on red pine growth as negative correlations with June - July temperature have been reported across the Great Lake region (Kipfmuehler et al., 2010; St. George et al, 2008). Temperature at other times of the year has been reported to not have the same uniform influence across the Great Lakes region. Graumlich (1993) and Kilgore and Telewski (2004) reported that a positive correlation between red pine growth and temperature in April of the current year represented warming temperatures that

promote an early start to the growing season. Temperature in April is significant for these studies as continental climatic conditions prevail in Minnesota (Graumlich, 1993) and central Michigan (Kilgore and Telewski, 2004) resulting in lower winter temperatures that delay the start of the growing season (Scott and Huff, 1996). However, the correlation between red pine growth and temperature in April of the current year was not found by the current study. It is postulated that this lack of correlation is due to the proximity of the Great Lakes which can moderate winter temperature to the point that temperature in April is no longer a limiting growth factor (Scott and Huff, 1996).

Negative correlations between radial growth and both precipitation and CMI in low initial density stands in August of the current year correspond with storm events that can generate strong winds that can damage tree crowns (Everham and Brokaw, 1996; Peterson, 2000; Scott and Huff, 1996). Damaged trees exhibit reduced radial growth because they will prioritize growth resource allocation to crown repair over diameter growth (Pallardy, 2007). Storm damage is not a persistent growth variable as it is not present in the seasonal precipitation or CMI correlation.

3.4.3. Site Network

Growing conditions and corresponding productivity are not expected to be uniform across a region (Chhin et al., 2008; Graumlich, 1993; Kipfmüller et al., 2010), however general similarities in growth responses have been reported. Chhin et al. (2008) found common responses to heat, drought stress, harshness of winter, and length of growing season of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) in multiple eco-regions in Canada. Growth-climate relationships presented in the current study indicate that summer drought stress,

storm damage, and excess respiration from increased summer temperatures are common across multiple sites and likely represent persistent and widespread climatic-growth variables that effect red pine across Michigan. Compared to other red pine studies in the region the most widespread climatic variables of growth are summer drought (Kipfmueeller et al., 2010) and the timing of the start of the growing season in continental climates (Graumlich, 1993; Kilgore and Telewski, 2004).

3.4.4. Forest Management and Climatic Resilience

Models developed to predict red pine productivity based on initial stand density (Laroque, 2002; Li et al., 2011) can be considered indirect inferences of climatic resiliency. Few studies directly address climatic resiliency generated by initial stand density (Penner et al., 2001). The current study found that low initial density stands have a higher resilience to precipitation and CMI than high initial density stands. This is exhibited by low initial density stands having only one month of correlation between radial growth and both precipitation and CMI compared to two months of high initial density stands. Additionally, high initial density stands have one seasonal period of correlation between radial growth and CMI whereas low initial density stands have zero. High and low initial density stands exhibited no difference in resilience to temperature as both densities had significant correlations in May and June of the previous year. Both treatments were significantly related to the same periods of seasonal temperature in Apr-May-Jun and May-Jun-Jul of the previous year. Among all three climatic variables, the low initial density stands exhibit a better overall resilience particularly to summer drought. This resilience to drought stress of low initial density red pine stands in Michigan is similar to the resilience to drought stress of heavily thinned Norway spruce (*Picea abies*) in

Belgium (Laurent et al., 2003). Additionally, low initial density stands have been found to be more resilient to snow and ice damage than high initial density stands (Penner et al., 2001). While initial stand density may not be the most powerful management tool to increase climatic resiliency, its impact is still significant especially given its ease of application compared to other forest management practices, like thinning, that require sustained maintenance.

3.5. Conclusions

Trees in low initial stand density plots were found to have a greater climatic resiliency than trees in high initial stand density plots while generating greater tree-level productivity. The results of this study are applicable to red pine grown in the Huron National Forest of Michigan but common region wide growth-climate relationships of red pine (Kilgore and Telewski, 2004; Kipfmüller et al., 2010) indicate that these results can generally represent stands across the Great Lake region. Initial stand density has the potential to act as an easily implemented management technique in red pine plantations to generate climatic resilience. This gives the findings of this study long term relevance in the interest of maintaining red pine productivity under future climate change (Dombroskie et al., 2009).

APPENDICES

Table 3.1. Average (standard deviation) age, DBH, tree height, crown ratio, and slenderness of red pine in the Huron National Forest, Michigan between two density types. Different letters denote significant differences between density types ($p < 0.05$).

Treatment	Age	DBH (cm)	Tree Height (m)	Crown Ratio	Slenderness
High Density	57 (10.1) a	20.4 (3.35) a	14.12 (1.73) a	0.65 (0.135) a	70.53 (11.71) a
Low Density	64 (8.2) a	26.54 (4.54) b	17.84 (2.91) b	0.526 (0.207) a	67.96 (11.30) a

Table 3.2. Average (standard deviation) basal area, above ground biomass, and stem biomass of red pine in the Huron National Forest, Michigan between two density types. Different letters denote significant differences between density types ($p < 0.05$).

Treatment	Basal Area (m^2)	Total Above Ground Biomass (kg)	Total Stem Biomass (kg)
High Density	0.081 (0.022) a	127.6 (51.52) a	80.62 (33.52) a
Low Density	0.057 (0.019) a	243.47 (114.51) b	156.96 (76.05) b

Table 3.3. Average (standard deviation) stand-level basal area, above ground biomass, and stem biomass per hectare of red pine in the Huron National Forest, Michigan between two density types. Different letters denote significant differences between density types ($p < 0.05$).

Treatment	Basal Area (m^2/hectare)	Total Above Ground Biomass (Metric Tons/hectare)	Total Stem Biomass (Metric Tons/hectare)
High Density	44.91 (6.82) a	183.48 (38.76) a	115.99 (25.04) a
Low Density	34.48 (6.6) a	155.61 (20.16) a	95.02 (17.54) a

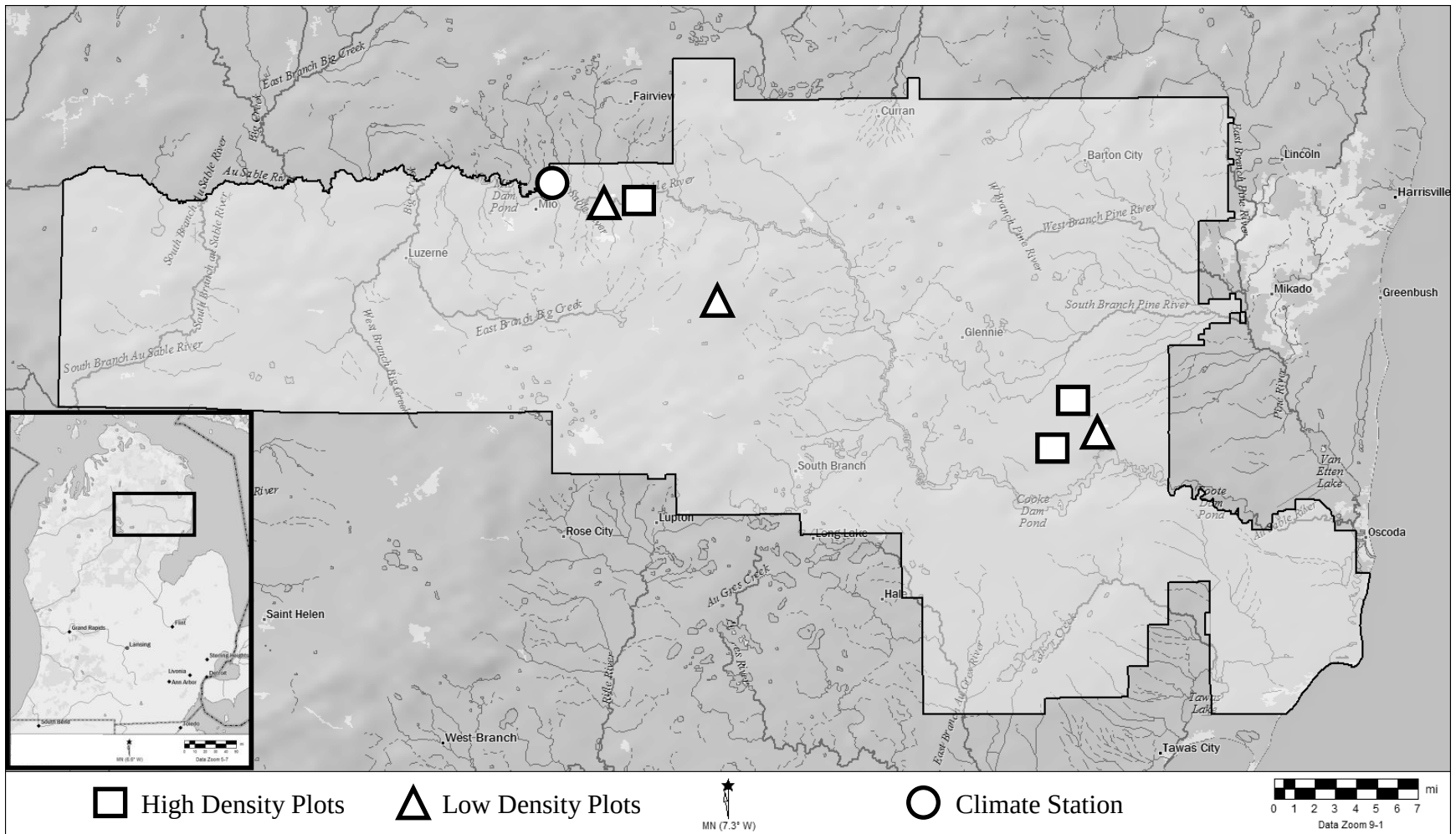


Figure 3.1. Locations of sample sites and climate station within the Huron National Forest in the lower peninsula of Michigan.

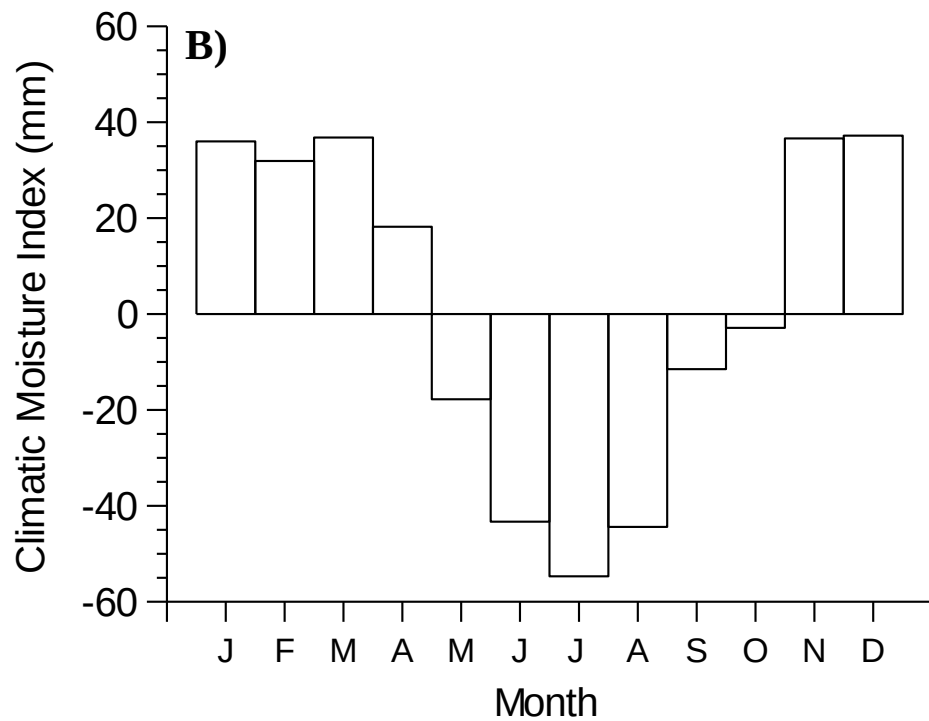
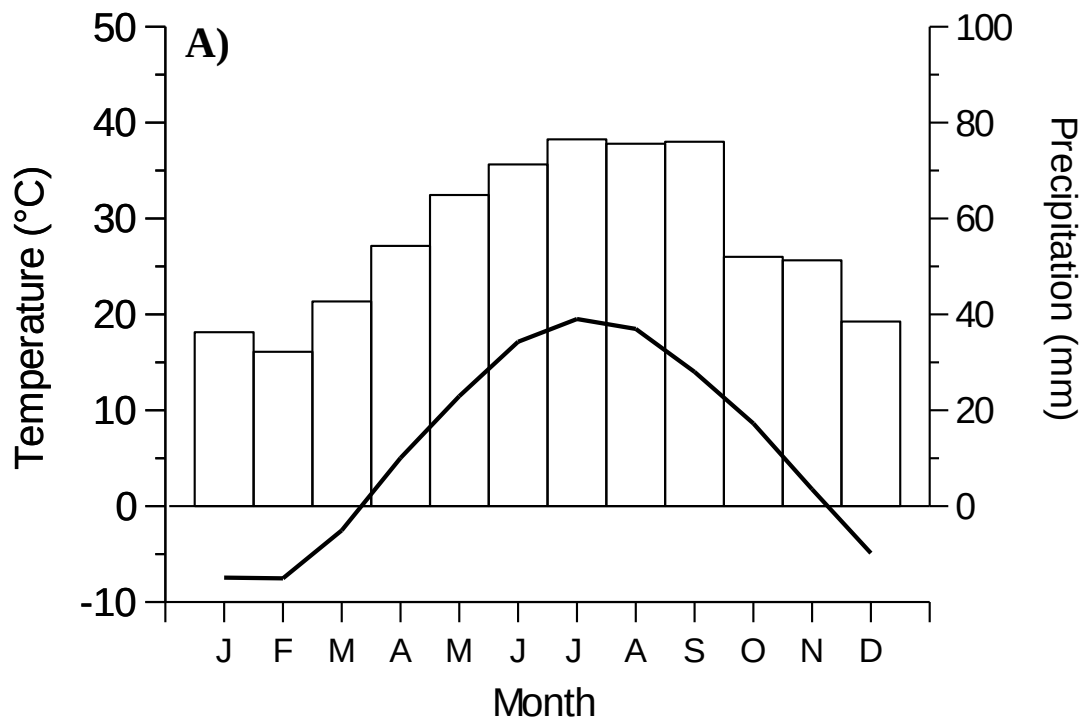


Figure 3.2 A) Mean monthly temperature and mean total monthly precipitation were averaged from 1965 - 2010 for Mio, Michigan. The line represents temperature and bars represent precipitation. B) Mean monthly climatic moisture index averaged from 1965 - 2010 in Mio, Michigan

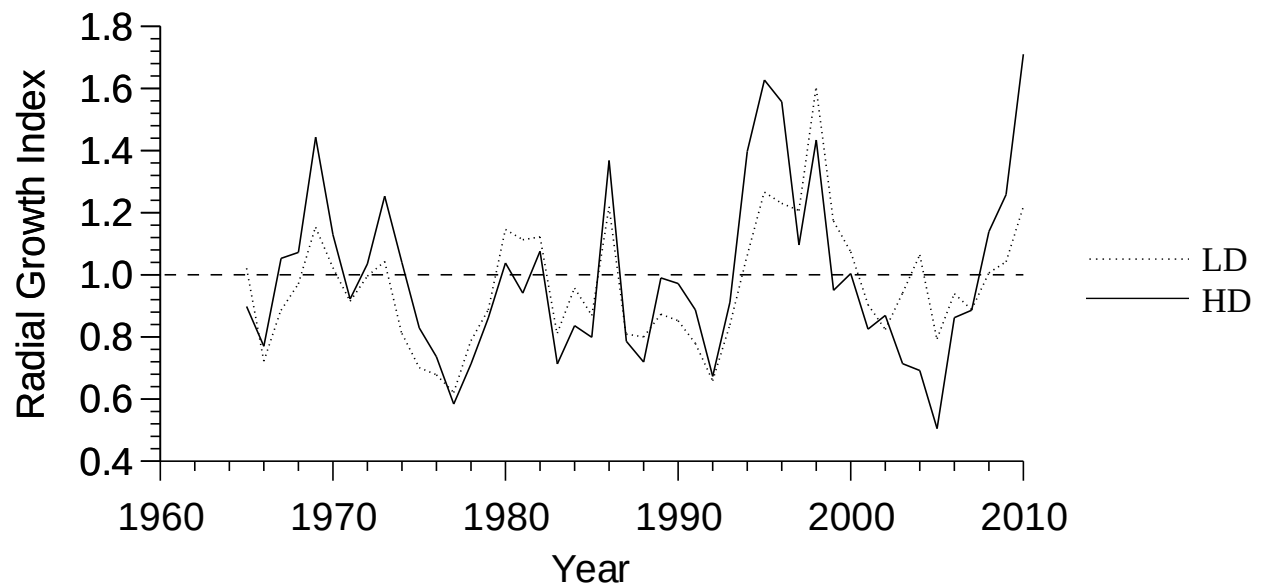


Figure 3.3. Detrended ring width chronologies of red pine grown in the Huron National Forest, Michigan. LD represents low density stands and HD represents high density stands.

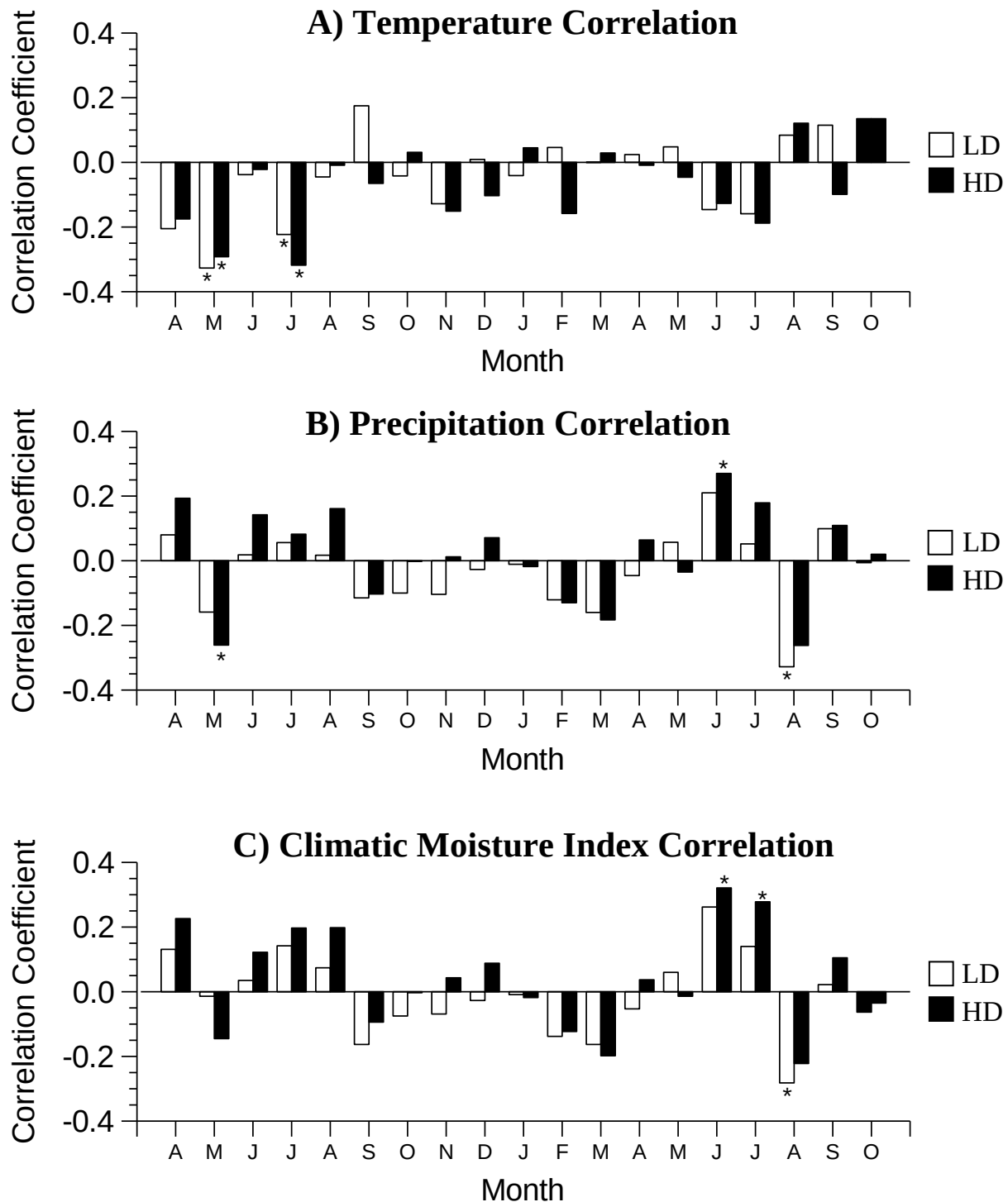


Figure 3.4. A) Monthly temperature correlation, B) monthly precipitation correlation, C) monthly climatic moisture index correlation to radial growth of red pine in the Huron National Forest, Michigan based on climate from 1965 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations. LD represents low density plots and HD represents high density plots.

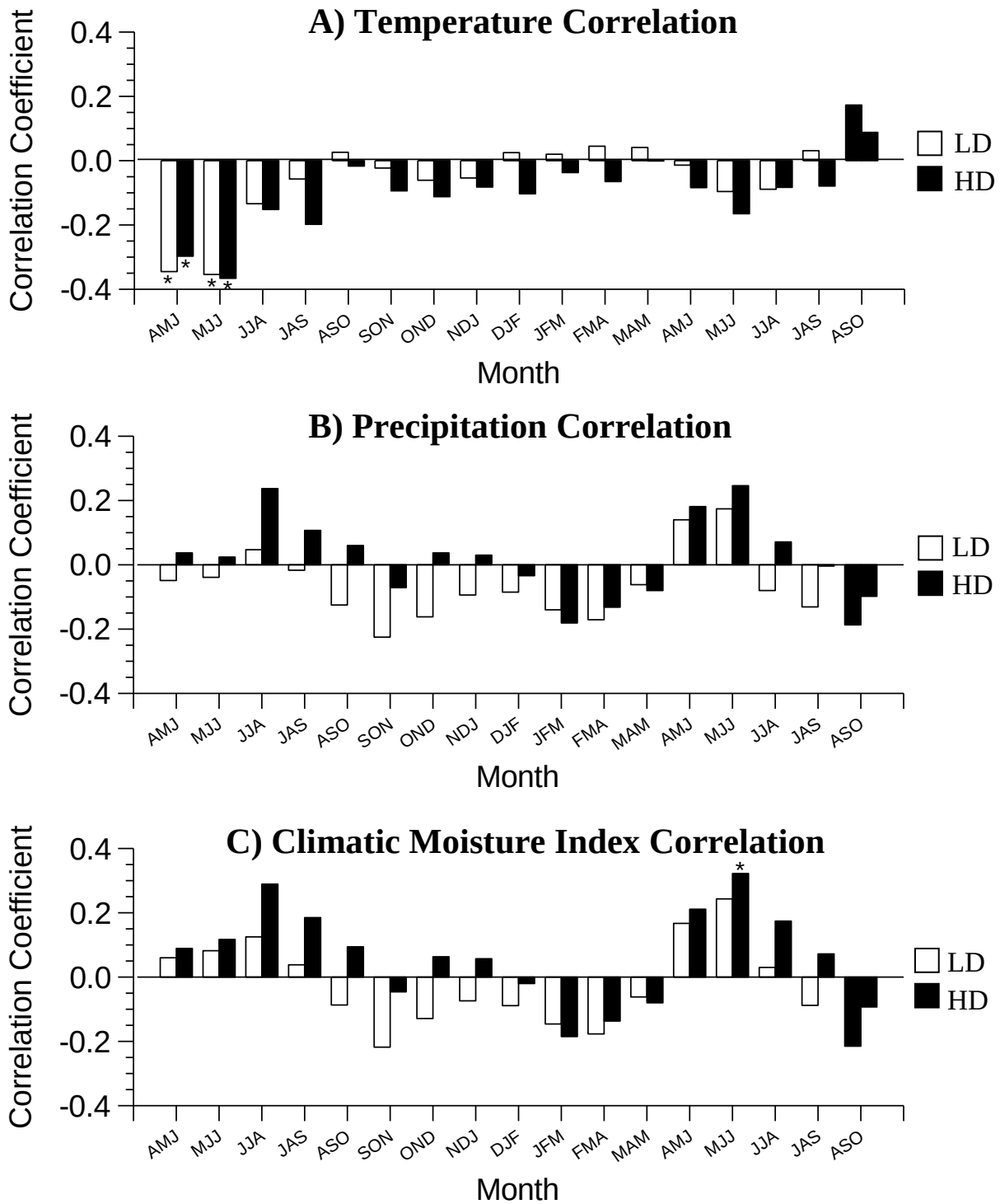


Figure 3.5. A) Seasonal temperature correlation, B) seasonal precipitation correlation, C) seasonal climatic moisture index correlation to radial growth of red pine in the Huron National Forest, Michigan based on climate from 1965 to 2010. Analysis begins in April of the previous year until October of the current year. An asterisk denotes a significant correlation coefficient that is outside the 95% range of coefficients derived from 1000 bootstrapped iterations. LD represents low density plots and HD represents high density plots.

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CHAPTER 4

CONCLUSIONS

In chapter two, it was found that the thinning intensity had a stronger influence on productivity and climatic resilience than thinning method. Overall the thinning from below to a residual basal area of 21 square meters per hectare (90 square feet per acre) was the best compromise to maximize tree size, biomass per hectare, and climatic resiliency. A different thinning treatment may be more appropriate for a specific management objective, but generally speaking, Below 90 is the best thinning treatment for red pine. As tree productivity in this study is reported in terms of cumulative growth, further analysis of the dendrochronologic data can provide information on the productivity and climatic resiliency in any year of the stand between the ages of 17- and 79- years. This timeframe is significant to red pine as it represents the range in which most stands are harvested for either pulpwood or sawtimber. This additional analysis will identify if another thinning treatment is a better option at a different stage of stand development and will highlight the effects of each thinning treatment over time.

In chapter three, widespread but more general red pine climatic correlations were found by sampling multiple sites within Huron National Forest. Stands initially planted to a lower density resulted in an equal or greater productivity and greater climatic resilience to summer drought than stands that were initially planted to a higher density. However, low initial density stands were also more susceptible to summer storm damage which high initial density stands were more resilient toward. Low density stands can remain the better management option through the use of additional proactive management techniques like thinning.

Ecophysiological explanations are inferred in this study and future research should directly examine the cause-effect relationships between climate and growth to truly understand how climatic resiliency is generated. Future research is also needed to expand our understanding of induced climatic resiliency by examining additional forest management techniques, (i.e. thinning options), species, and locations. Experimental forest research sites are optimal for such studies as they include multiple management techniques at one site which makes the management technique the dominant growth variable as the climatic conditions and soil profile are similar for all trees. In order to better express future climatic resiliency on a regional scale, more experimental forests need to be developed. Given the time required for an experimental forest to grow to a point where it can be sampled, sites created in this decade will not be available for sampling for a minimum of 20- to 30- years. Therefore, if we are to research the impact of forest management on climatic resiliency before stands decrease in productivity, we can afford to lose little time in developing such sites.