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Effects of Initial Stand Density and Climate on Red Pine Productivity within Huron National Forest, Michigan, USA

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Abstract: Changes in climate are predicted to significantly affect the productivity of trees in the Great Lakes region over the next century. Forest management decisions, such as initial stand density, can promote climatic resiliency and moderate decreased productivity through the reduction of tree competition. The influences of climate (temperature and precipitation) and forest management (initial stand density) on the productivity of red pine (*Pinus resinosa*) across multiple sites within Huron National Forest, Michigan, were examined using dendrochronological methods. Two common planting regimes were compared in this analysis; low initial density (<988 trees per hectare) and high initial density (>1977 trees per hectare). Low initial density stands were found to have a higher climatic resiliency by combining equal or greater measures of productivity, while having a reduced sensitivity to monthly and seasonal climate, particularly to summer drought.

Keywords: climatic resiliency; dendrochronology; initial stand density; *Pinus resinosa*; red pine; silviculture

1. Introduction

Future climate change is expected to cause a significant impact to tree growth through changes in temperature and precipitation [1,2]. Current forest management techniques must adapt in order to maintain productivity of forest resources under future conditions [3]. 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.

Manipulation of 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 establishing red pine (*Pinus resinosa* Ait.) in the Great Lakes region [4]. Planting 988 trees per hectare is less costly, and trees grow more rapidly because of 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 [4–6].

Ecosystem resilience is defined as the capacity of an ecosystem to absorb some disturbance (*i.e.*, drought), which in turn may induce some minor degree of ecosystem change, but still maintain its essential structure and functions [7]. In the context of forested ecosystems, forest management practices can moderate the degree of competition for environmental resources (*i.e.*, soil moisture, light), which in turn has the potential to buffer residual trees from stressful climatic conditions [1,8]. This resource buffering effect in turn may result in general decoupling of growth from the prevailing regional climate. From a growth and yield perspective, climatic resiliency, thus, is defined as the maintenance of an adequate degree of stand-level and tree-level productivity in spite of poor climatic conditions and a decoupling or reduced sensitivity between stand- and tree-level growth with climate conditions [1].

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, has been focused on observational studies in natural forests [9–11]. In contrast, there have been few studies that have examined the influence of climate in managed forests across a regional network of sites [12]. 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 the 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 a function of 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.

2. Methods

2.1. Study Site

The study was implemented in the Huron National Forest of Michigan (Figure 1), where forest cover is dominantly composed of white, red and jack pine (*Pinus strobus*, *Pinus resinosa* and *Pinus banksiana*, respectively) [13,14]. 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 [14]. Jack pine is typically managed in the region as an early succession stage to promote habitat for the endangered Kirtland's Warbler [15]. Six sample sites were selected based on the 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 and in the sites selected in this study is uniformly managed to be initially cut with row thinning (cut two rows, leave two rows) (K. Lazda, USDA Forest Service, personal communication [16]). 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 m² per hectare (90 ft² per acre) [4]. All sites were plantations with a limited variety of tree ages and sizes. Soils at all sites are very similar types of excessively drained sand [17]. For the purposes of this study, we have assumed that there are no environmental differences between sample sites and that initial stand density is the key independent variable impacting growth in this study.

Historical climate data was obtained from 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, and from the Hale Loud Dam (Station ID 203529) (44°27'49" N, 83°43'18" W) near Glennie, Michigan. Data collected included monthly averages of minimum, mean and maximum daily temperature and total monthly precipitation. Climate data from the Mio stations were combined with the climate data from the Hale Loud Dam station to provide a representative regional climatic data set. Minimum and maximum monthly temperature and precipitation measurements were further combined into a climatic moisture index (CMI) representing estimated net water availability to trees. 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. All monthly and seasonal climatic variables were screened, and no significant linear trends were observed using simple linear regression.

Annual mean temperature averaged 6.74 °C and 6.90 °C from 1965 to 2010 in Mio and Hale Loud Dam, Michigan, respectively [18]. In the same time frame, the total annual precipitation averaged 694 mm and 737 mm for Mio and Hale Loud Dam, respectively. The total annual climatic moisture index averaged 48.8 mm and 118.1 mm for Mio and Hale Loud Dam, respectively. Temperature and precipitation increased during the spring and summer months, which mark the growing season from April to October (Figure 2). 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 by a negative climatic moisture index (CMI) [19]. CMI is calculated as the total precipitation minus water lost due to evapotranspiration, which is a factor of increasing temperature [19]. Summer drought was less severe at the Hale Loud Dam station compared to the Mio station.

Figure 2. Mean monthly temperature and mean total monthly precipitation were averaged from 1965–2010 for Mio (dashed line, open bars) and Hale Loud Dam (solid line, gray bars), Michigan. The lines represent temperature, and bars represent precipitation.

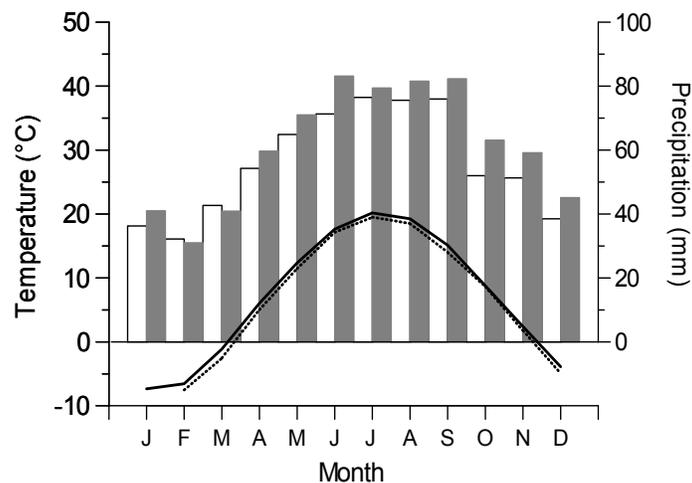
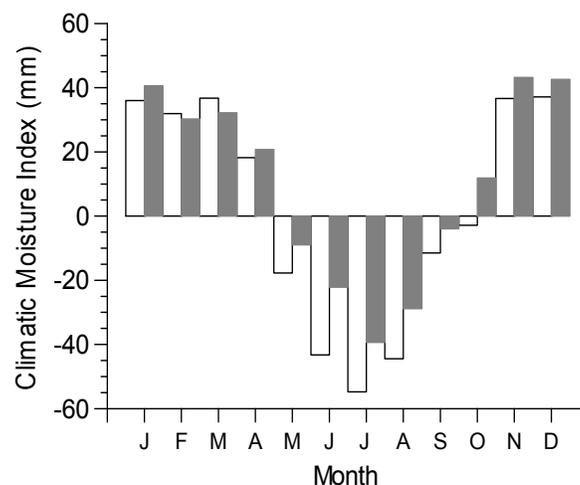


Figure 3. Mean monthly climatic moisture index averaged from 1965–2010 in Mio (open bars) and Hale Loud Dam (gray bars), Michigan.



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. It is common practice in conducting forest inventory sampling to modify the sampling radius based on tree density (*i.e.*, smaller radiuses are used for higher densities) as a way to optimize field sampling efficiency; in uniform populations (e.g., forest plantations), differences in plot size have little effect on plot measurements [20]. 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.

2.3. Sample Processing

Tree cores were processed using standard dendrochronological techniques [21]. 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.

2.4. Cross-Dating and Treering Measurement

Cores were cross-dated with the list method to accurately assign a calendar date to each tree ring [22]. 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 cross-dating. Additional statistical quality control was provided through the use of the program COFECHA [23,24]. 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, NY, USA) was used as a supplemental tool to measure sections of cores with very narrow rings that were unclear in the scanned image.

2.5. Data Analysis

2.5.1. Biomass Calculations

Allometric equations were used to calculate tree biomass as a function of DBH. Total aboveground tree biomass (Equation 1) was determined using the following equation that is specific to pine species [25]:

$$T_{\text{bm}} = \text{Exp} (-2.5356 + 2.4349 \ln \text{DBH}) \quad (1)$$

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) [25]:

$$\text{Ratio} = \text{Exp} [-0.3737 + (-1.8055/\text{DBH})] \quad (2)$$

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 four trees sampled in each sampling plot at the time of sampling in October 2011. The average annual total biomass of trees in each treatment plot was also determined for the time period of sufficient sample replication (1965–2011). Separate calculations summarized the total and stem biomass on a per hectare basis based on the DBH of all trees in a sampling plot as of October 2011.

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 [26]. Crown ratio represents the ratio of the crown length to the total height of a tree. All collected measures of tree-level productivity (DBH, total height, crown ratio, slenderness coefficient, basal area, total biomass and stem biomass) for the four trees in a sampling plot were treated as sub-samples and averaged before being subjected to a two-sample *t*-test (pooled variance) to identify significant thinning treatments effects using the program SYSTAT (version 10.2) [27]. Furthermore, stand-level productivity (*i.e.*, per hectare basis) was also compared between the treatments using a two-sample *t*-test. A P value that was less than 0.05 was considered statistically significant.

2.5.3. Dendrochronological Analysis

Ring widths were detrended to generate a radial growth index through the statistical program ARSTAN [24,28]. 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. A 40-year cubic spline still preserves 99% of the variation in each ring-width series at a wavelength of about 13 years. Consequently, common trends at decadal time scales (1–13 years) in radial growth between trees due to stand-wide effects, like climate and stand management practices, are still preserved [29]. 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 [30]. The EPS quantifies how well a chronology based on a finite number of trees represents a hypothetically perfect chronology [31].

The standard chronology and each individual set of climate data were run through the program DendroClim [32] to identify significant monthly correlations between each climatic variable and tree growth from April of the previous year to October of the current year. The analysis started 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 [33,34]. Significant correlations were determined through bootstrapped samples, which were drawn at random with a replacement from each year in the data set [32]. 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 were calculated to compute correlation coefficients. Statistical significance was determined from the correlation coefficients from the original data set that fall outside of the 95% range of 1000 bootstrapped data sets [32].

2.5.4. Climate Resilience Index (CRI)

A Climate Resilience Index (CRI) was determined for each thinning treatment by combining measures of productivity and sensitivity to climate using the following formula:

$$\text{CRI} = \text{SLP} + \text{TLP} - \text{SMC} - \text{SSC} \quad (3)$$

where SLP = Stand-Level Productivity, which is a relative index variable based on stand-level total above ground biomass; TLP = Tree-Level Productivity, which is a relative index variable based on tree-level total above ground biomass; SMC = Sensitivity to Monthly Climate, which is a relative index variable based on total number of significant correlations to temperature, precipitation and moisture index; and SSC = Sensitivity to Seasonal Climate, which is a relative index variable based on the total number of significant correlations to temperature, precipitation and moisture index. SLP, TLP, SMC and SSC are relative index variables, which were calculated by dividing their respective raw values for each treatment type by the management treatment with the smallest value. A relative index greater than one indicates a greater relative value for that variable (*i.e.*, higher productivity or higher sensitivity to climatic stress). Larger values of CRI indicate greater climatic resiliency.

3. Results

3.1. Red Pine Form and Productivity

There was no significant difference in tree age, DBH, tree height, crown ratio and slenderness of trees between low initial stand density and high initial stand density plots (Table 1). The tree basal area was greater in low density *versus* high density stands (Table 2). However, on stand-level, there was no significant difference in basal area and biomass between the low and high initial stand density treatments (Table 3).

Table 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	21.6 (3.2) a	14.12 (0.93) a	0.350 (0.121) a	70.5 (11.7) a
Low Density	64 (8.2) a	28.0 (8.5) a	17.84 (2.98) a	0.474 (0.229) a	68.0 (11.3) a

Table 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 ($p < 0.05$).

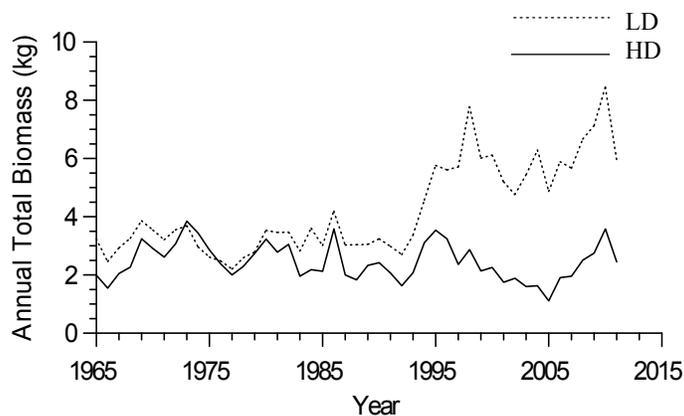
Treatment	Basal Area (m ²)	Total Above Ground Biomass (kg)	Total Stem Biomass (kg)
High Density	0.033 (0.002) a	127.6 (8.4) a	80.6 (5.59) a
Low Density	0.057 (0.015) b	243.5 (81.1) a	157.0 (53.8) a

Table 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	183.5 (38.8) a	116.0 (25.0) a
Low Density	34.48 (6.60) a	155.6 (20.2) a	95.0 (17.5) a

The average annual total biomass of trees in each treatment type for the time period for sufficient sample replication (1965–2011) is shown in Figure 4. Average annual total biomass of trees in low density plots was generally higher than trees in high density plots over this time period.

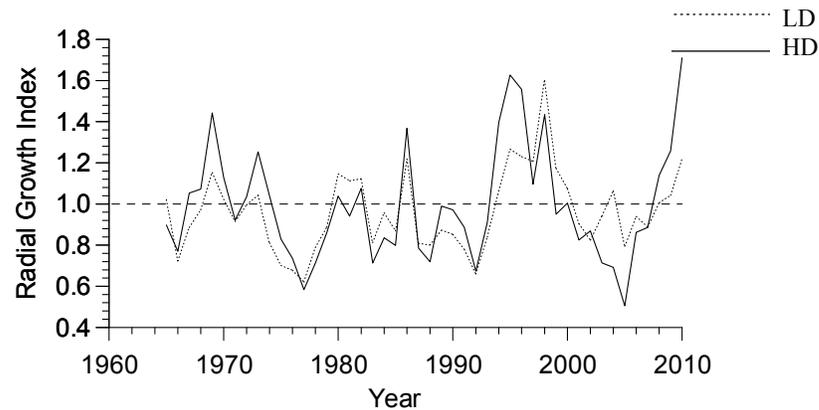
Figure 4. The average annual total aboveground biomass of trees in low density (dashed line) and high density (solid line) plots.



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, mid 1990s and mid 2000s (Figure 5).

Figure 5. 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.



3.2. Growth-Climate Relationships

Monthly correlations between temperature and radial growth in Figure 6A highlight significant negative relationships in May 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 6B show a significant negative correlation in May of the previous year and a positive correlation in both June and July of the current year. In contrast, the radial growth of trees found in low initial density stands was correlated to precipitation in June (positively) and August (negatively) 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 correlated with radial growth in low initial density stands in June (positively) and August (negatively) of the current year (Figure 6C).

Seasonal correlations between temperature and radial growth mirror the monthly correlations with significant negative relationships in April-May-June (for low density stands) and May-June-July (for both low density and high density stands) of the previous year (Figure 7A). In contrast, the correlations between radial growth and seasonal precipitation (Figure 7B) and seasonal CMI (Figure 7C) indicate positive associations with one seasonal period for low density stands (May-June-July) and for three seasonal periods for high density stands (April-May-June, May-June-July and June-July-August).

Figure 6. (A) Monthly temperature correlation, (B) monthly precipitation correlation and (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 (open bars) represents low density plots and HD (closed bars) represents high density plots.

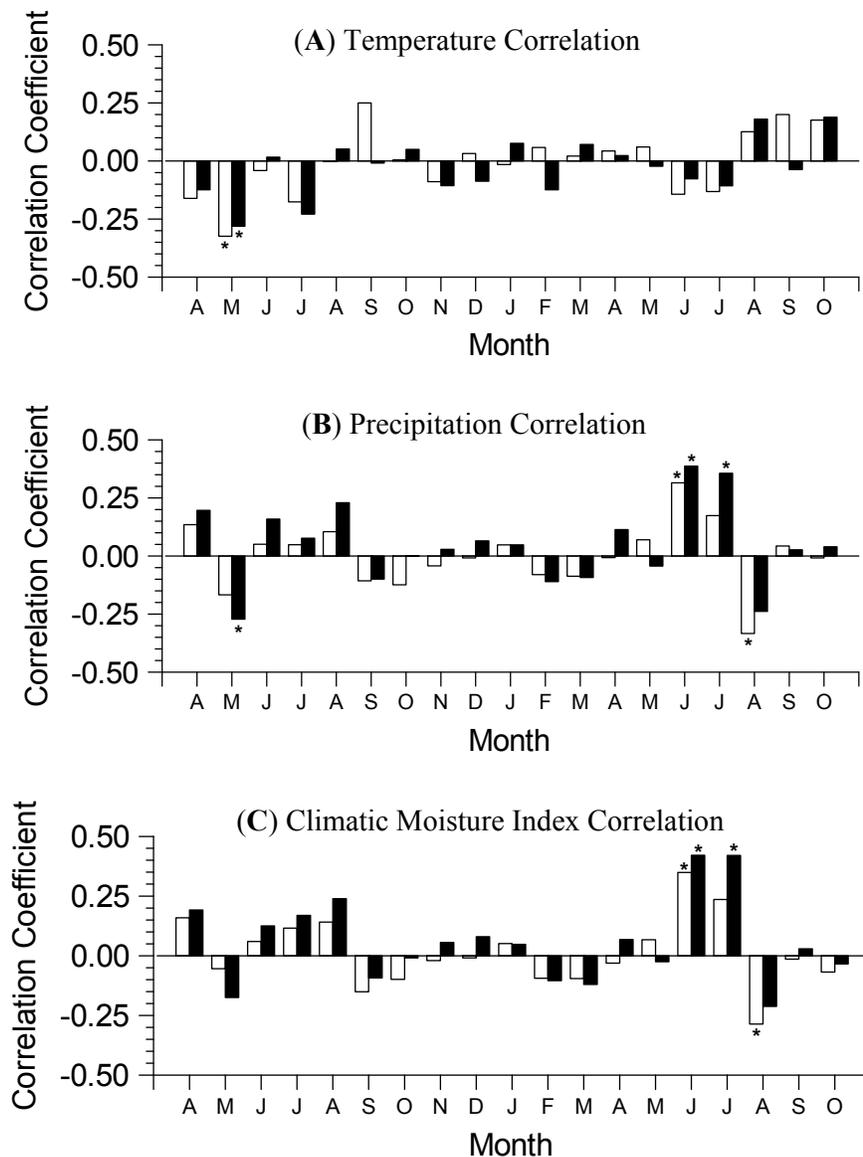
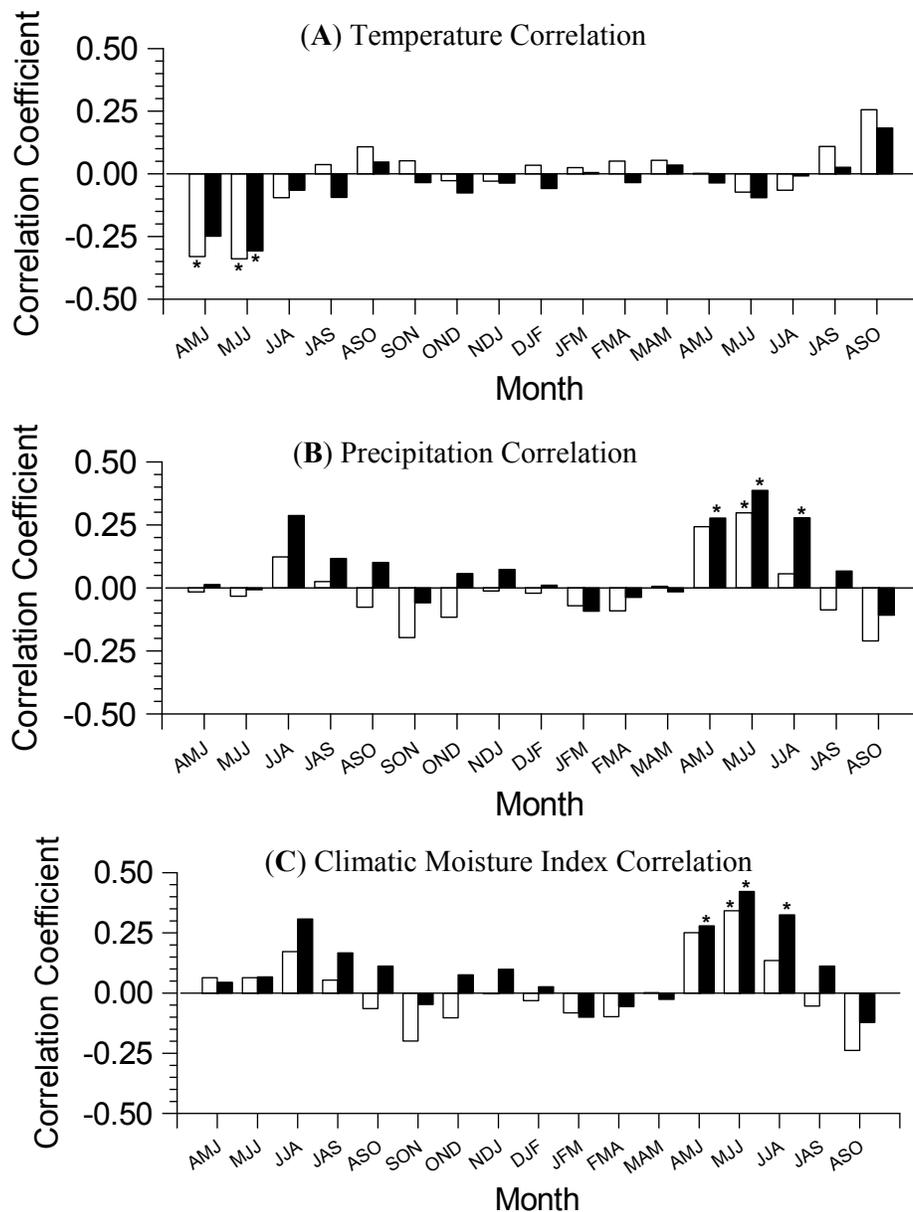


Figure 7. (A) Seasonal temperature correlation, (B) seasonal precipitation correlation and (C) seasonal climatic moisture index correlation to radial growth of red pine in the Huron National Forest, Michigan, based on climate from 1965 to 2010. Analysis begins in April of the previous year until October 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 (open bars) represents low density plots and HD (closed bars) represents high density plots.



3.3. Climate Resilience Index (CRI)

Low density stands had a higher Climate Resilience Index (CRI) than high density stands (Table 4). The higher CRI of low density stands was a result of higher tree-level productivity and reduced sensitivity to monthly and seasonal climatic variables.

Table 4. Climate Resilience Index (CRI) derived from a combination of relative indexes of productivity (Stand-Level Productivity (SLP), Tree-Level Productivity (TLP)) and sensitivity to climatic stress (Sensitivity to Monthly Climate (SMC) and Sensitivity to Seasonal Climate (SSC)) of red pine in Michigan managed under two initial density treatments. SLP, TLP, SMC, and SSC are relative index variables which were calculated by dividing raw values for each treatment type by thinning treatment with the smallest value. A relative index greater than 1 indicates greater relative value for that variable. $CRI = SLP + TLP - SMC - SSC$.

Treatment	Stand-Level Productivity (SLP)	Tree-Level Productivity (TLP)	Sensitivity to Monthly Climate (SMC)	Sensitivity to Seasonal Climate (SSC)	Climate Resilience Index (CRI)
High density	1.18	1.00	1.20	1.75	-0.77
Low density	1.00	1.91	1.00	1.00	0.91

4. Discussion

4.1. Red Pine Form and Productivity

Low initial density stands had higher values of tree-level basal area 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 [35]. Tree-level crown ratio and slenderness, 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 [35]. A model constructed by Li *et al.* [36] predicted a loss of stand-level productivity of red pine plantations in Ontario, Canada, 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 limit the degree of self-thinning. The findings of the current study are consistent with Penner *et al.* [37], who reported that lower initial thinning density of red pine plantations in Ontario, Canada, increased the quadratic mean diameter, but reduced stand-level basal area and biomass compared to higher initial density plots. Additionally, Penner *et al.* [37] reported that no significant difference in tree height was found between treatments. Similarly, Larocque [5] also reported no difference in tree height for any initial stand density for red pine growing in plantations in Ontario, Canada. It is generally understood that tree height is not overly sensitive to changes in stand density [35]. However, it is still possible for stand density to influence height if comparing extreme stand densities, which is the case for the current study [35].

It would have been ideal to have an allometric equation for different stand densities. Unfortunately, there are few allometric studies in general for determining biomass, because it is such a resource intensive (*i.e.*, financial and time) process [25]. Consequently, few studies have looked at the effect of initial stand density on allometric biomass equations. Studies that compare different management treatments on productivity of red pine generally use the same allometric biomass equation for all treatments [38].

4.2. Growth-Climate Relationships

The significant positive relationship for precipitation 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 [34]. Summer drought affected growth in high initial density stands, as demonstrated by the seasonal correlation with both precipitation and CMI for three seasonal summer periods (*i.e.*, April-May-June, May-June-July and June-July-August). Trees in low density plots also responded to summer drought, but to a more limited degree. Similar reports of red pine response to June-July drought have been made by Kipfmüller *et al.* [10]. Different results were reported by Kilgore and Telewski [39], 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 [39] study site that buffered the trees from drought and allows them to grow independently from precipitation events [10].

Correlations between radial growth and temperature in the previous year (May and July) may be a factor of increasing temperature resulting in an increase in tree's respiration rate [40]. Excessive respiration consumes carbon stores that had the potential to be used in the current years productivity [34]. Excessive temperature-induced respiration is a persistent growth variable, as indicated by significant relationships in April-May-June (low density stands) and May-June-July (low and high density stands) 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 [10,41]. Temperature at other times of the year has been reported to not have the same uniform influence across the Great Lakes region. Graumlich [42] and Kilgore and Telewski [39] 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 [42] and central Michigan [39], resulting in lower winter temperatures that delay the start of the growing season [43]. 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 [43].

Negative correlations between radial growth and both precipitation and CMI in low initial density stands in August of the current year likely correspond with storm events that can generate strong winds that can damage tree crowns [43–45]. Damaged trees exhibit reduced radial growth, because they will prioritize growth resource allocation to crown repair over diameter growth [34]. Storm damage appears

to be an episodic event that is confined to the month of August, since it is not present in the seasonal precipitation or CMI correlation.

4.3. Site Network

Growing conditions and corresponding productivity are not expected to be uniform across a region [7,8,36], however, general similarities in growth responses have been reported. Chhin *et al.* [9] 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 affect red pine across this region in Michigan. Compared to other red pine studies in the region, the most widespread climatic variables of growth are summer drought [10] and the timing of the start of the growing season in continental climates [39,42].

4.4. Forest Management and Climatic Resilience

Models developed to predict red pine productivity based on initial stand density [5,36] can be considered indirect inferences of climatic resiliency. Few studies directly address climatic resiliency generated by initial stand density [37]. The Climate Resilience Index (CRI) used in this study provided a composite measure of forest productivity (stand-level and tree-level) and sensitivity to climate (monthly and seasonal variables). The current study found that low initial density stands have a higher climatic resilience than high initial density stands. Although the high initial density stands had higher stand-level productivity, they had relatively lower tree-level productivity and more sensitivity to monthly and seasonal climate. In particular, the low initial density stands exhibit a reduced sensitivity to seasonal periods of 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 [46]. Additionally, low initial density stands have been found to be more resilient to snow and ice damage than high initial density stands [37]. 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.

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 by generating greater tree-level productivity and reduced sensitivity to monthly and seasonal climate. 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 [10,39] 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 [3].

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Conflict of Interest

The authors declare no conflict of interest.

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