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Long-term response of yellow-poplar to thinning in the southern Appalachian Mountains

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ABSTRACT

As the focus of forest management on many public lands shifts away from timber production and extraction to habitat, restoration, and diversity-related objectives, it is important to understand the long-term effects that previous management activities have on structure and composition to better inform current management decisions. In this paper, we analyzed 40 years of growth data to quantify (1) the long-term response of yellow-poplar to thinning across an age and site quality gradient, and (2) the longevity of any growth response yellow-poplar may have to thinning throughout the southern Appalachian Mountains. Between 1960 and 1963, 134–0.1 ha plots were established across an age and site quality gradient in yellow-poplar (*Liriodendron tulipifera* L.) stands throughout the southern Appalachian Mountains. All plots were thinned from below, with post-thinning relative density categorized into three classes: low (relative density <0.25), moderate (relative density $\geqslant$0.25 but <0.35), and high (relative density $\geqslant$0.35 but <0.60). Using plot-level annual basal area increment (BAI; $cm^2\ yr^{-1}$) chronologies reconstructed from tree cores, average annual BAI was calculated for 10 years prior to thinning (BAI_{pre}) and each following 10 year period thereafter (BAI_{post}).

Site index and age at the time of thinning had a positive effect on BAI_{post}. During the first 10 year period following thinning, annual BAI (at a site index = 32.3 m and age = 43) averaged (SE) 33.7 (1.6), 26.3 (1.3), and 21.6 (1.1) $cm^2\ yr^{-1}$ in the low, moderate, and high density classes, respectively. Significant differences between low and moderate and low and high density classes remained throughout the duration of the study. During the 10 years post-thinning the ratio of BAI_{post} to BAI_{pre} (RBAI) was >1.0 in 92%, 86%, and 57% of plots in the low, moderate, and high density classes, respectively indicating an overall increase in growth relative to pre-thinning growth rates. By the fourth decade post-thinning the percentage of stands containing trees that possessed RBAI values >1.0 had fallen; however trees in 71% of the plots in the low density class continued to experience growth rates greater than those prior to thinning. We conclude the increase in growth is short-lived when density is reduced to moderate and high levels whereas the response of trees to more intense thinnings is long-lasting.

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1. Introduction

Goals and objectives associated with forest management on public lands in the United States have evolved over the past few decades from timber production and extraction to habitat, restoration, and diversity-related objectives. In light of these ecologically-oriented objectives, thinning may prove to be a particularly useful management activity because of the flexibility in developing thinning prescriptions to meet a variety of objectives associated with stand structure and/or composition (Curits, 1997). For example, thinning prescriptions can be specifically developed to enhance, create, and maintain wildlife habitat (Beck, 1983; Haveri and Carey, 2000), accelerate the development of late structural characteristics (O'Hara et al., 2010; Dodson et al., 2012), and restore or enhance structural and/or biological complexity (Carey, 2003). In the upland hardwood region of the southeastern United States, thinning treatments designed to achieve timber-related goals and objectives on public lands were once commonplace across a region comprised of maturing forests. Current management efforts on public lands in the region, however, are now guided by longer rotations, restoration or habitat objectives, and rarely include precommercial or commercial thinning operations specific to timber management objectives. Quantitative information regarding the development of these previously thinned stands over the long-term may prove to be particularly useful in addressing whether past silvicultural treatments, often guided by timber management objectives, are effective at addressing contemporary forest management issues.

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Numerous studies report on the effects of thinning over short time frames, with some of the earliest and most visible effects of thinning on stand structure and development related to individual tree growth. In the short-term, diameter growth of individual trees commonly increases in response to decreases in stand density (Mayor and Rodà, 1993; Bebber et al., 2004; Mäkinen and Isomäki, 2004a), with the magnitude of response often varying with age at the time of thinning (Hilt, 1979; Medhurst et al., 2001; Skov et al., 2005), species (Plaugorg, 2004; Latham and Tapeiner, 2002; Plummer et al., 2012), initial tree size (Pukkala et al., 1998; Mäkinen and Isomäki, 2004c; Boncina et al., 2007), and thinning intensity (Beck and Della-Bianca, 1975; Harrington and Reukema, 1983; Simard et al., 2004).

Information regarding the long-term response of tree growth to thinning is less abundant, and results are inconsistent across studies. Although some studies suggest any increase in diameter growth immediately following thinning can be short-lived for some species (e.g., Auchmoody, 1985; Cutter et al., 1991; Mayor and Rodà, 1993), other studies indicate tree growth is affected for decades following thinning. In the Pacific Northwest, Latham and Tapeiner (2002) documented that basal area increment of almost 45% of old-growth conifer trees sampled (most of which were Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was 50% greater than prior to thinning 20 years post-thinning. Similarly, Bebber et al. (2004) report that after 10 years, thinned old-growth eastern white pine (*Pinus strobus* L.), continued to experience an increase in growth relative to trees in unthinned stands.

Yellow-poplar (*Liriodendron tulipifera* L.) is the most abundant individual tree species (in terms of volume) in the Blue Ridge physiographic province of the southern Appalachian Mountains, with forest inventories documenting a continuous increase of this species over the recent years (e.g., Thompson, 1998; Schweitzer, 1999; Brown, 2003). As a consequence of a shift in management objectives, previously thinned stands originally managed on a timber- or financially-related rotation length are no longer actively managed within the original silvicultural prescription. As such, the current age of many of these stands meet or exceed the traditional stand rotation age used to achieve timber-related goals and objectives for yellow-poplar (Beck and Della-Bianca, 1981). Because many of these stands were, in the past, harvested at their biological rotation age, there is limited quantitative data regarding the effects of previous management activities on long-term growth patterns over time. The long-term effects that past management has on stand structure and composition can influence a variety of forest resources, and may be used to inform management guidelines aimed at meeting current goals and objectives (e.g., guide current restoration prescriptions). In this paper, we analyzed 40 years of growth data to quantify (1) the long-term response of yellow-poplar to thinning across an age and site quality gradient, and (2) the longevity of any growth response yellow-poplar may have to thinning throughout the southern Appalachian Mountains.

2. Methods

2.1. Study area

This study was conducted in the Blue Ridge and Northern Ridge and Valley Physiographic provinces of the southern Appalachian Mountains. Study sites were located throughout northern Georgia, western North Carolina, and southwestern Virginia. Soils present were either ultisols or inceptisols, and encompassed six major soil series (Tusquitee, Brevard, Ashe, Haywood, Watuga, and Porters soil series), indicating a range of site productivity. Soils were well-drained, coarse or fine-loamy in texture, and possessed high soil moisture water holding capacity. Temperatures in the intermountain basin of Asheville, NC, which is centrally located within the geographic range of the study area, range from 2.3 °C in January to 22.3 °C in July (McNab et al., 2004). The altitude of the study sites range from approximately 340 to 1150 m. Average annual precipitation, which increases with altitude, is evenly distributed throughout the year and ranges from 1000 mm to 1500 mm (but can be as high as 2500 mm in some areas) across the study sites (McNab, 2011). As a reference, in the Asheville Basin, which is approximately 600 m above sea level, annual precipitation averages 1200 mm (McNab et al., 2004).

2.2. Experimental design and data collection

Between 1960 and 1963, 141–0.1 ha permanent plots were established in yellow-poplar stands throughout the study area. This study utilized 134 of the original 141 plots. Seven of the original 141 plots were completely or partially harvested and removed from this study. All plots were established in even-aged stands in which yellow-poplar comprised >75% of the overstory basal area. Plots were primarily located on north and east aspects and ecologically mapped as primarily rich cove forests (Simon et al., 2005).

At the time of plot establishment and prior to thinning, all live trees >11.4 cm diameter at breast height (DBH; 1.37 m above ground line) within each plot were tagged and stem-mapped. For all tagged trees, species, DBH (cm), and total height (m) were recorded. One increment core at stump height was obtained from five dominant/co-dominant yellow-poplar trees per plot. Age at stump height was obtained from the increment cores in the lab under magnification. Using age and height data, site index (base-age 50) was calculated using yellow-poplar site index equations (Beck, 1962) for each of the five trees per plot. Plot-level site index (m) was calculated as the average site index of the five sample trees.

Following plot establishment and the pre-thinning inventory, all plots (in addition to a 20 m buffer around each plot) were thinned to a randomly assigned basal area ($m^2\ ha^{-1}$). Post-thinning basal area corresponded to residual relative densities ranging from 12% to 56%, with relative density calculated as a function of stand density index (SDI) (Reineke, 1933). Specifically, relative density was calculated as plot-level $SDI_{observed}/SDI_{maximum}$. Thinning was accomplished via low thinning. After the second inventory cycle (1965 to 1968) was complete, 13 of the 134 plots used in this study received a second low thinning to the originally assigned residual density. The second thinning was extremely light. Across all plots, only 0.1 $m^2\ ha^{-1}$ of basal area was removed during the second thinning, which equated to an average reduction in relative density of 1% from the level observed following the initial thinning. Because this thinning was so minor and did little to further alter structure, it was not considered during data analysis. No further management activities ensued.

Between October and December, 2009, increment cores were collected at approximately 1.37 m above ground line from five randomly selected dominant/co-dominant yellow-poplar trees from each of the 134 plots. Cores were dried, mounted, and sanded with progressively finer sandpaper until cell structure was clearly visible within rings. Rings were visually crossdated against other trees in each plot. Radial growth was then measured to the nearest 0.001 mm using a linearly controlled stage and microscope attached to a digital encoder (Velmex, Inc.). Accuracy of visual crossdating was supported statistically using the program COFECHA (Holmes, 1983). Crossdated ring-width chronologies were converted to chronologies of annual basal area increment (BAI; $cm^2\ yr^{-1}$) assuming circularity for each sample tree. The use of BAI in lieu of radial growth eliminates variation in growth observed due to the negative correlation between raw ring width and tree circumference (Biondi and Qeadan, 2008). Annual BAI of the five sample trees were averaged by plot, thereby providing plot-level BAI chronologies. Using the plot-level BAI chronologies, average annual BAI for five time periods was calculated: (1) average annual BAI during the 10 years prior to thinning (BAI_{pre}); (2) average annual BAI between 1 and 10 years after the initial thinning (BAI_{post10}); (3) average annual BAI between 11 and 20 years after the initial thinning (BAI_{post20}); (4) average annual BAI between 21 and 30 years after the initial thinning (BAI_{post30}); and (5) average annual BAI between 31 and 40 years following the initial thinning (BAI_{post40}).

2.3. Statistical analysis

Plots were classified into three density classes: low ($n = 39$), moderate ($n = 42$), and high density ($n = 53$) based on either the pre-thinning relative density (for analysis of pre-thinning growth) or relative density immediately following the initial thinning (for the analyses related to post-thinning growth). Low density was defined as pre- or post-thinning relative densities <0.25, moderate density was defined as pre- or post-relative densities ⩾0.25 but <0.35, and high density was defined as pre- or post-thinning relative densities ⩾0.35 but <0.6. An additional density class, overstocked, where relative density was ⩾0.60, was used to classify pre-thinning relative density. Low, moderate, high, and overstocked density classes correspond to various stages of stand development, including free-to-grow conditions (no tree-to-tree competition), crown closure and the onset of inter-tree competition, full-site occupancy, and the lower limit to when density-dependent mortality occurs, respectively (Long and Smith, 1984; Long and Shaw, 2005).

We used an analysis of covariance (ANCOVA) to determine differences in BAI_{pre} among pre-thinning density classes, where pre-thinning density was the categorical variable (low, moderate, high, and overstocked) and site index and average age of sample trees at the time of the initial thinning were the continuous covariates. For the analysis of post-thinning BAI, we used ANCOVA with repeated measures to determine the effects of post-thinning density class, site index, average age of sample trees at the time of thinning, and years post-thinning (10, 20, 30, and 40 years post-thinning) on two separate dependent variables (1) BAI_{post}, which corresponded to average annual BAI observed during the four, 10-year periods after thinning; and (2) $RBAI_{post}$, which was relative annual BAI. Relative BAI is unitless and is defined as average annual BAI_{post10}, BAI_{post20}, BAI_{post30}, and BAI_{post40} divided by the average annual BAI during the 10 year period prior to thinning (BAI_{pre}). By using relativized growth data, each plot serves as its own control (Salonius et al., 1982) and represents a proportional change in BAI based on pre-thinning growth patterns (Latham and Tapeiner, 2002; Keyser et al., 2010). Values of $RBAI_{post} < 1.0$ signify a slow-down in growth relative to pre-thinning rates, whereas values of $RBAI_{post} > 1.0$ indicate an increase in growth.

When the interaction between density class and years post-thinning was statistically significant ($P < 0.05$) in the repeated measures ANCOVA, the significance of the effect of density class and time period post-thinning was determined using the SLICE option in PROC MIXED (SAS Institute, Inc.). The partitioned F-tests in the SLICE analysis were significant at a Bonferonni-adjusted $\alpha = 0.0125$ (0.05/4) for the analysis of the effects of density class within a given time period, and at a Bonferonni-adjusted $\alpha = 0.0167$ (0.05/3) for the effect of time on $RBAI_{post}$ and BAI_{post} within a given density class. Following significant F-tests in the SLICE analysis, differences in Least Squares Means for BAI_{post} and $RBAI_{post}$ were compared using a Bonferonni-adjustment to the Least Squares Means tests, where $\alpha = 0.0083$ (0.05/6) for comparisons among time periods within a density class, and $\alpha = 0.0167$ (0.05/3) for comparisons among density classes within a given time period. The $RBAI_{post}$ and BAI_{post} data were ln-transformed and square-root transformed to achieve normality and homoscedasticity, respectively.

In all ANCOVAs, assumptions, including the test that the slopes describing the effects of the covariate(s) (i.e., age and site index) across density classes were equal, were tested as outlined by Milliken and Johnson (2002). All analyses were performed using the PROC MIXED procedure in SAS v. 9.2 (SAS Institute, 2011). The Least Squares Means and standard errors (SE) reported represent back-transformed data.

3. Results

3.1. Pre-thinning growth

Pre- and post-thinning attribute data are presented in Table 1. On average, 23% (range 5–43%), 38% (range 19–56%), and 56% (range 17–74%), of the pre-thinning basal area was removed from low, moderate, and high density classes during the initial thinning, respectively.

A common slope model in the ANCOVA adequately described the positive and significant effect of site index on BAI_{pre} (i.e., the effect of site index was similar across density classes). Average age of the sample trees at the time of thinning, was not a significant covariate in the analysis of BAI_{pre} ($P > 0.05$). After controlling for the effects of site index, we found no significant effect of pre-thinning density on BAI_{pre} (Table 2). Across pre-thinning density classes, Least Squares Means for BAI_{pre} averaged (SE) 12.8 (1.2), 17.2 (1.1), and 21.6 (1.2) $cm^2\ yr^{-1}$ on low (site index = 27.4 m), moderate (site index = 32.3 m), and high quality (site index = 36.0 m) sites, respectively.

3.2. Post-thinning growth

Site index and average age of sample trees at the time of the initial thinning were significant covariates in the repeated measures ANCOVA of BAI_{post} (Table 2), with a common slope model adequately describing the positive effects of site index and age on BAI_{post}. In all time periods, BAI_{post} in the low density class was significantly greater than BAI_{post} in moderate and high density classes (Table 3). In comparison, for moderate and high density classes, significant differences in BAI_{post} were only observed during the first 10 year period following the initial thinning. Within the low and moderate density classes, BAI_{post} was similar during the 10 and 20 year time periods following thinning (Table 3). In the high density class, however, BAI_{post} during the 20 year time period was significantly greater than during the first 10 years post-thinning (Table 3). Regardless of density class, we observed a significant decrease in BAI_{post} (relative to the first 10 year period post-thinning)

Table 1
Stand and tree-level attributes immediately prior to and following the initial thinning ($n = 134$).

Attribute	Mean	Standard deviation	Minimum	Maximum
Pre-thinning				
Trees ha^{-1}	571	175	270	1080
Basal area ($m^2\ ha^{-1}$)	31.4	7.2	10.2	48.2
Relative density ($SDI_{obs}/SDI_{maximum}$)	0.54	0.10	0.22	0.71
Age of sample trees	41	13	16	67
Site index (m)	31.9	3.3	22.9	40.2
Post-thinning				
Trees ha^{-1}	252	141	80	800
Basal area ($m^2\ ha^{-1}$)	19.7	7.0	5.9	35.4
Relative density	0.31	0.11	0.12	0.56

Table 2
Results of the reduced ANCOVA for average annual BAI during the 10 year period prior to thinning (BAI_{pre}), average annual BAI post-thinning (BAI_{post}), and relative average annual BAI ($RBAI_{post}$).

Source	df	*F*-value	*P*-value
BAI_{pre}			
Density class	3129	1.34	0.2629
Site index	1129	42.87	<0.0001
BAI_{post}			
Density class	2129	18.08	<0.0001
Time period	3392	99.61	<0.0001
Density class × time period	6392	4.78	0.0001
Site index	1129	38.35	<0.0001
Age at thinning	1129	6.04	0.0153
$RBAI_{post}$			
Density class	2130	13.69	<0.0001
Time period	3392	94.87	<0.0001
Density class × time period	6392	4.66	0.0001
Site index	1130	5.60	0.0195

Table 3
Mean (SE) annual basal area increment (BAIpost, $cm^2\ yr^{-1}$) (SE) during four, 10-year time periods post-thinning in low, moderate, and high density classes. Values followed by the same letter are not significantly different. Uppercase letters indicate differences across density classes within a given time period. Lowercase letters indicate differences among time periods within a given density class. Values represent the back-transformed Least Squares Means and standard errors at the median site index and age values in the dataset (site index = 32.3, age = 43).

Years post-thinning	Low density ($cm^2\ yr^{-1}$)	Moderate density ($cm^2\ yr^{-1}$)	High density ($cm^2\ yr^{-1}$)
10	33.7 (1.6)^{Aa}	26.3 (1.3)^{Ba}	21.6 (1.1)^{Ca}
20	34.6 (1.7)^{Aa}	26.8 (1.4)^{Ba}	23.8 (1.1)^{Bb}
30	24.4 (1.4)^{Ab}	17.5 (1.1)^{Bb}	17.3 (1.0)^{Bc}
40	28.0 (1.5)^{Ac}	19.1 (1.1)^{Bb}	20.6 (1.1)^{Ba}

during the 30 year time period post-thinning, with a slight recovery of BAI_{post} occurring during the fourth decade post-thinning.

Across time periods, $RBAI_{post}$ ranged between 0.48 and 3.22 in the low density class, 0.41 and 2.99 in the moderate density class, and 0.25 and 2.55 in the high density class. Overall, 92%, 86%, and 57% of plots in the low, moderate, and high density classes, respectively displayed RBA_{post} values ⩾1.0 during the first 10 year period post-thinning (Table 4), with 23% and 14% of plots in the low and moderate density classes displaying $RBAI_{post}$ values ⩾2.0. The proportion of plots containing trees that displayed an increase in growth relative to pre-thinning rates increased between 11 and 20 years post-thinning. Between 31 and 40 years post-thinning, 71%, 33%, and 45% of plots in the low, moderate, and high density classes, respectively still possessed RBA_{post} values ⩾1.0.

In the repeated measures ANCOVA of $RBAI_{post}$, site index was a significant covariate, with a common slope model adequately describing the effect of site index on $RBAI_{post}$ (Table 2). Unlike BAI_{post}, site index was negatively correlated with $RBAI_{post}$, suggesting on a relativized basis, trees on plots of lower site quality benefited from the thinning disproportionally more than trees on higher quality sites. Age at the time of thinning did not influence $RBAI_{post}$ ($P > 0.05$) and was, therefore, not included in the analysis of $RBAI_{post}$. During the 10 year time period following thinning the only significant differences in $RBAI_{post}$ among density classes were between the low and high and moderate and high density classes (Fig. 1a). As time progressed, $RBAI_{post}$ in low density class was significantly greater than in the moderate and high density classes. By the third decade following thinning, however, the initial increase in $RBAI_{post}$ observed in the moderate density class relative to the high density class was absent. For the low and moderate density classes, no significant differences in $RBAI_{post}$ were observed between the 10 and 20 year time periods post-thinning (Fig. 1b). As seen with BAI_{post}, a significant decrease in $RBAI_{post}$ occurred during the third decade post-thinning, with a slight recovery occurring in the low and high density classes during the fourth decade post-thinning.

4. Discussion

In this study, we sought to identify whether thinnings conducted over 40 years ago continue to influence tree growth in even-aged yellow-poplar stands across a broad age and site quality gradient. Unfortunately, no unthinned controls were established at the start of this study. However, analysis of BAI_{pre} revealed no significant differences in BAI among the density classes prior to thinning. Consequently, the differences in BAI_{post} are likely attributable to reductions in stand density. Not unexpected, the results of this study are consistent with others that found an increase in individual tree growth with greater reductions in density (e.g., Beck and Della-Bianca, 1975; Mäkinen and Isomäki, 2004a; Sullivan et al., 2006). However, in contrast to most other studies, we were also

Table 4
Percentage of plots (average BAI of five sample trees per plot) in low, moderate, and high density classes in each $RBAI_{post}$ category during the 10, 20, 30, and 40 year growth periods post-thinning. Percentages in each category are cumulative.

Relative basal area increment categories										
Density class	⩽1.0	⩾1.0	⩾1.1	⩾1.2	⩾1.3	⩾1.4	⩾1.5	⩾2.0	⩾2.5	⩾3.0
10 Years post-thinning										
Low	8	92	87	82	69	67	67	23	10	3
Moderate	14	86	81	71	64	55	45	14	0	0
High	43	57	38	25	25	15	11	0	0	0
20 Years post-thinning										
Low	5	95	92	79	77	64	56	33	10	3
Moderate	12	88	81	64	57	55	43	12	5	0
High	30	70	62	47	34	28	23	2	0	0
30 Years post-thinning										
Low	36	64	59	46	36	26	21	8	5	3
Moderate	62	38	26	17	17	14	7	0	0	0
High	72	28	17	11	8	6	4	0	0	0
40 Years post-thinning										
Low	29	71	71	68	58	47	37	5	8	3
Moderate	67	33	26	21	19	14	14	2	2	0
High	55	45	32	30	25	17	13	2	2	0

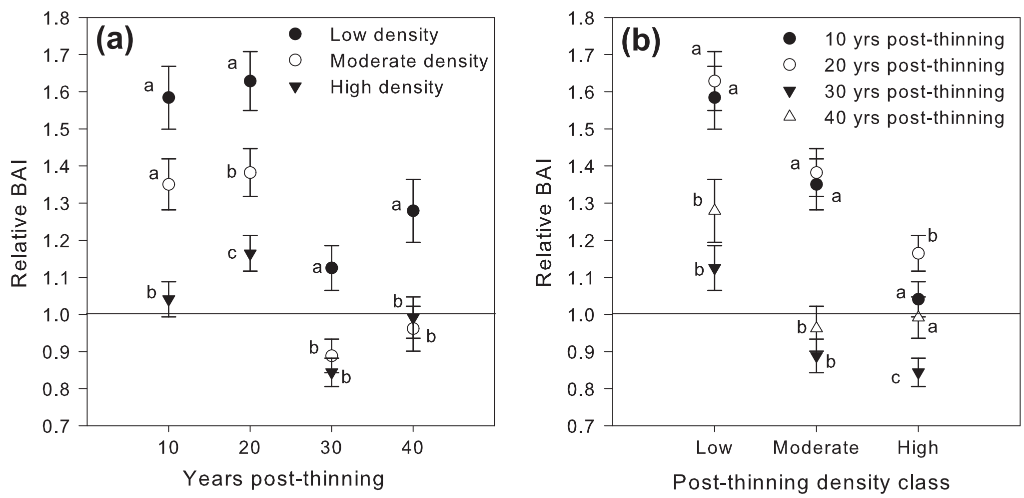

Fig. 1. Differences in post-thinning relative basal area increment ($RBAI_{post}$), adjusted for site index, among time periods within a given density class (panel a) and among density classes within a given time period (panel b). Values represent the back-transformed Least Squares Means and standard errors at the median site index value in the dataset (site index = 32.3).Values followed by the same letter are not significantly different. The solid line ($y = 1$) represents no change between pre- and post-thinning BAI.

able to examine the effects of reductions in density over a 40 year period since initial treatment.

As age at the time of thinning and site index increased, BAI_{post} increased across density classes. This positive relationship between BAI_{post} and age is similar to that reported by Johnson and Abrams (2009) who found BAI of numerous eastern US tree species increased up through even the oldest (e.g.,>300 years) age classes. In contrast, other studies have found tree size, rather than age, as one of the primary factors influencing tree growth, with larger trees displaying greater increases in growth following thinning than smaller trees (Mäkinen and Isomäki, 2004b,c). Simple linear regression using the data in this study revealed a positive relationship between diameter inside bark (determined from BAI chronologies) and age at the time of thinning ($R^2 = 0.49$; data not presented). Consequently, the age effect on BAI_{post} may be more of a function of relative competitive pressures associated with tree size rather than age alone. Furthermore, diameter increment has been shown to be related to sapwood area (Latham and Tapeiner, 2002; Galván et al., 2012), with sapwood area greater in larger than smaller trees (Martin et al., 1998; Bond-Lamberty et al., 2002; Powers et al., 2009), which may explain, along with the positive age-diameter relationship for yellow-poplar, the effect of age on BAI_{post}.

The analysis of $RBAI_{post}$ displayed the magnitude as well as the longevity of the post-thinning growth response. Regardless of density class, $RBAI_{post}$ was greatest 10 and 20 years post-thinning. Across density classes, $RBAI_{post}$ 30 and 40 years post-thinning suggested a slow-down in growth. Despite the decrease, on average, trees in low density plots continued to possess BAI 45% greater than pre-thinning BAI 40 years post-thinning, whereas average BAI_{post} of trees in plots in the moderate and high density classes was similar to BAI_{pre}. Compared to this study, the increase in growth following thinning reported for other temperate hardwood tree species is short-lived. For example, Cutter et al. (1991) documented only a 10–12 year period of increased growth following thinning for black oak (*Quercus velutina* Lam.) and white oak (*Quercus coccinea* Muench.). Similarly, the increase in tree growth observed by Mayor and Rodà (1993) following commercial thinning of Holm oak (*Quercus ilex* L.) diminished concomitantly with canopy closure, which occurred as early as nine years post-thinning. The sustained increase in tree growth reported in this study, particularly in the low density class, is more similar to the results found following thinning in temperate coniferous species. For example, the increase in BAI following precommercial thinning in western redcedar (*Thuja plicata* Conn ex D. Don) was found to last 25 years by Devine and Harrington (2009), while Latham and Tapeiner (2002) report an increase in growth that was sustained for at least 20 years following density reductions for individual Douglas-fir and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) trees in western Oregon.

Regardless of density class, a significant decrease in growth was observed during the third decade following thinning (Table 3, Fig. 1). During this decade, drought was widespread across the study area, with the Palmer Drought Severity Index (PDSI) in western North Carolina averaging -0.418. Although the average decadal PDSI indicates only mild drought conditions, PDSI during six of the 10 years was negative, with more severe drought conditions occurring in 1986 (PDSI = -2.416) and 1988 (PDSI = -1.711). Despite this apparent climate-related reduction in growth, trees in the majority of plots in low density classes continued to possess $RBAI_{post} > 1.0$ while $RBAI_{post}$ of trees in moderate and high density classes suggested trees were growing at rates similar to the ten years prior to thinning, which is consistent with the few studies to quantify the interactions of density and climate on tree growth and resilience/resistant to drought (e.g., Misson et al., 2003; Kohler et al., 2010).

5. Conclusions

Intermediate silvicultural treatments can have long-lasting effects on stand structure and composition (e.g., Hansen et al., 1995; Busing and Garman, 2002; D'Amato et al., 2011). For yellow-poplar, where timber-related objectives include production of large, veneer-quality sawlogs, the increase in tree growth at the lowest residual densities was sustained over the 40 year period encompassed by this study regardless of the age at the time of the thinning. As these stands approach, or in some cases exceed, the traditional (i.e., biological) rotation age, it is apparent that potential crop trees (from a timber resource perspective) continue to benefit from previous thinnings. Beyond traditional timber objectives, the thinning conducted 40 years ago accelerated the development of large trees, which is one of the key attributes associated with the mixed-mesophytic forests in the later stages of stand development (Greenberg et al., 1997).

Increasing structural and compositional complexity in these even-aged yellow-poplar forests is a key restoration effort in the southern Appalachians. It is clear that thinning, across a wide range of ages, can accelerate tree growth, and hence, be used as a preliminary restoration treatment in these relatively simple, homogenous stands. Monitoring of how other attributes, including the accumulation of downed woody debris, species composition, vertical canopy stratification, and snags develop over time and in response to thinnings should be a future focus.

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