Forest Ecology and Management 494 (2021) 119323

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Long-term growth effects of simulated-drought, mid-rotation fertilization, and thinning on a loblolly pine plantation in southeastern Oklahoma, USA

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ARTICLE INFO

Keywords:
Pinus taeda
Water availability
Nutrients
Stand density

ABSTRACT

Loblolly pine (*Pinus taeda* L.) is the most productive commercial softwood species in the southeastern USA. More frequent drought due to climate change will likely alter loblolly pine productivity, especially in areas where the climate is already highly variable such as the Upper Gulf region of the south-central USA. In a long-term study, we examined the effects of drought treatment (30% throughfall exclusion), fertilization, and thinning on a loblolly pine plantation growing in southeastern Oklahoma, USA to determine how nutrient availability and stand density interact with drier conditions to affect productivity. Our treatments were applied at mid-rotation: throughfall reduction ages 5 to 13, fertilizer ages 5 and 10, and thinning age 10. Treatment effects on diameter and height increment depended on year, with drought treatment tending to decrease diameter and height growth in drier years and fertilization having a stronger positive effects on diameter growth in the years closely following fertilization events. The net effect on standing volume was that fertilization (+7%) and simulated-drought (−8%) countered each other by age 13. Positive fertilization effects were supported by increased foliar nitrogen (N) and phosphorus (P) concentrations, along with increased leaf area index (LAI, +14% measured age 12). Three and four years after thinning, diameter increment increased by 38%, and positive fertilization effects on gross current annual increment were greater in thinned compared to non-thinned stands. Basal area increment in drought-treated stands relative to non-drought-treated stands decreased more during drier years and exhibited recovery during wetter years. The fairly small growth decline in response to 30% throughfall reduction, positive fertilizer effects, and possible post-drought recovery indicate continued plantation viability in the future even at the drier, western fringe of loblolly pine's commercial range.

1. Introduction

Loblolly pine (*Pinus taeda* L.) is the most important commercial timber species in the southeastern USA. Within the region, it is the largest single-species biomass contributor, composing a fifth of total live aboveground biomass and accounting for 87% of regional softwood production (Oswalt et al., 2019). Loblolly pine plantations occur on 21 million ha in the southeastern USA (Oswalt et al., 2019) and are typically managed using intensive silviculture (Fox et al., 2007a). However, loblolly pine productivity may be challenged by climate change-induced droughts (Vose et al., 2018).

Within the southeastern USA, climate change is predicted to bring increasingly variable precipitation events, marked by more intense rainfall and runoff, longer drought duration, and less growing season precipitation (Easterling et al., 2018). Higher temperatures (Kloesel et al., 2018) and subsequently higher vapor pressure deficits (VPD) are predicted for the region ((Will et al., 2013; Kloesel et al., 2018). Higher VPD leads to more severe drought conditions, caused by greater plant transpiration, soil evaporation, and soil moisture depletion (Breshears et al., 2013; Will et al., 2013). For timber-producing stands, drought can increase mortality (e.g., Vose et al., 2018), reduce stand-level growth (e.g., Maggard et al., 2017), alter biomass partitioning (Green et al., 1994), and decrease post-drought growth (Anderegg et al., 2015). Drought is predicted to be especially severe on loblolly pine's drier, western commercial fringe, such as in Oklahoma, where historical thousand-year droughts are now predicted to occur at hundred-year intervals (Cook et al., 2015).

Southern pine research has focused on positive benefits from increased resource availability (e.g., Jokela et al., 2004). Fertilization is commonly used to increase stem growth. Increased growth is driven in

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https://doi.org/10.1016/j.foreco.2021.119323
Received 4 February 2021; Received in revised form 25 April 2021; Accepted 27 April 2021

large part by increased foliar nutrients and LAI (Jokela and Martin, 2000; Will et al., 2002; Albaugh et al., 2003). Nitrogen (N) and phosphorus (P) fertilization at planting occurs when there are site-specific deficiencies (Allen et al., 1990; Fox et al., 2007b). At mid-rotation, fertilization is a common treatment with between 200,000 to 400,000 ha of southern timberlands annually fertilized (Albaugh et al., 2019).

While thinning reduces stand-level growth compared to non-thinned stands, it increases growth of residual trees and economic returns (Shephard et al., 2021). Thinning typically occurs after canopy closure and is often complemented by fertilization. Used together, thinning and fertilization produce synergistic effects, increasing diameter growth and live-crown length to a greater extent than each alone (Sayer et al., 2004). Thinning also may be important for recovery and resilience to drought. Thinning increases precipitation throughfall (Stogsdill et al., 1989), decreases stand-level water use (Teskey et al., 1987), and increases post-drought stem growth (D'Amato et al., 2013; Sohn et al., 2016). Fertilization was beneficial when precipitation was experimentally reduced because nutrient amendments can decrease stomatal conductance and leaf-level transpiration (Bartkowiak et al., 2015; Maggard et al., 2016), without decreasing net photosynthesis (Maggard et al., 2016), which increases water-use efficiency, i.e., carbon gain per water loss (Maggard et al., 2017).

With climate change likely, it is essential to determine the effects soil moisture limitation will have on loblolly pine plantation growth. The effects of reduced soil moisture, fertilization, and thinning appear to be dependent on site-specific conditions. At mesic locations like Georgia and Virginia, USA, experimental reductions in throughfall had inconsistent effects on net photosynthesis, stem volume production, and LAI (Samuelson et al., 2014; Ward et al., 2015). In contrast, an Oklahoma stand, with more variable growing season precipitation and higher summer VPD, showed decreased net photosynthesis, stem volume production, and LAI under reduced throughfall conditions (Maggard et al., 2016; 2017). In wetter locations, such as the Lower Coastal Plain of North Carolina, USA, thinning had little effect on water availability in loblolly pine stands (Sun et al., 2010; Liu et al., 2018). Dissimilarly, there was a strong correlation between thinning, soil moisture availability, and stem growth in the Upper Gulf region of Oklahoma (Hennessey et al., 1992; 2004). In wet locations or under moist conditions, fertilization increased stomatal conductance and water-use (Bongarten and Teskey, 1986; Samuelson et al., 2008). On the other hand, in drier interior locations or under water stress conditions, nutrient additions decreased stomatal conductance and water-use (Bongarten and Teskey, 1986; Maggard et al., 2016). These different responses suggest that there are important interactions between nutrient additions, water availability, and stand density on physiology and aboveground productivity.

To address the interaction between nutrient availability, reduced water availability, and stand density, we quantified nine-years of growth response to fertilization, drought, and thinning treatments of a loblolly pine plantation in southeastern Oklahoma. Our research contributes to understanding long-term loblolly pine production under a drier climate scenario, with the goal to inform landowner silvicultural decisions. This is an extension of the Oklahoma Tier III site installed as part of Pine Integrated Network: Education, Mitigation, and Adaption Project (PINEMAP; www.pinemap.org). Though treatment combinations of fertilization with thinning (e.g., Sayer et al., 2004) and fertilization with throughfall reduction (e.g., Maggard et al., 2017) have been studied, no research thus far has examined the three-way interaction between fertilization, thinning, and throughfall reduction. To the best of our knowledge our study presents the longest soil moisture reduction experiment for loblolly pine, and perhaps North American forest productivity research, although longer studies have been conducted elsewhere in South America and Europe (da Costa et al., 2014; Bogdziewicz et al., 2020). We hypothesized that 1) 30% throughfall reduction (drought) would decrease stem volume production and LAI. We targeted a 30% reduction as it represents the driest climate change predictions for the south-central USA (Easterling et al., 2018); 2) mid-rotation (year 5, 10) fertilization would help compensate for drought conditions and increase stem volume production and LAI such that growth of stands receiving fertilization and throughfall reduction would be similar to stands receiving ambient precipitation; 3) without thinning, fertilization would have little effect in ten-year-old stands 4) throughfall reduction would have less negative effects in thinned stands than non-thinned stands.

2. Methods

2.1. Site conditions

The study site was a loblolly pine plantation located within the Upper Gulf region near Broken Bow, OK (34.02972, −94.82306) that was a legacy of the PINEMAP Tier III study (Will et al. 2015), which focused on understanding the effects of drought and fertilization on carbon dynamics. The Tier III study included four sites spanning loblolly pine's commercial range: Virginia, Georgia, Florida, and Oklahoma. For the Oklahoma site, we report nine years of stand-level data collected from stand age 5 to 13, corresponding to the 2012 through 2020 growing seasons. Previously, stand and tree-level data from the Oklahoma site were reported in Maggard et al. (2016); (2017;) for the 2012 to 2014 growing seasons.

Thirty-year averages from Broken Bow, OK are 1300 mm for annual precipitation and 16.6° C for annual temperature (Mesonet, 2020). May receives the most precipitation, 162 mm, and August receives the least amount of precipitation, 69 mm (Mesonet, 2020). August also has the highest average daily maximum temperatures, 34.2 °C (Mesonet, 2020), which is higher than most locations within the loblolly pine commercial range (Will et al., 2015). Soils were the Ruston series (Fine-loamy, siliceous, semiactive, thermic Typic Paleudults) that have well-drained fine sandy loam surface texture and clay loam subsoil texture consisting of 3 to 8% slopes (USDA, 2020).

The site was prepared in August 2007 with a chemical treatment of Chopper® (27.6% imazapyr) at 680 g ha^{-1} and glyphosate at 2.8 l ha^{-1} (53.8% active ingredient). In October 2007, the site was burned and then subsoiled down to 51 to 61 cm with a shank attached to a bulldozer (Maggard et al., 2017). In January 2008, the site was planted with 1–0 bare-root seedlings that were a mix of improved half-sib families from the Western Gulf Tree Improvement Cooperative. Planting density was approximately 1650 trees ha^{-1} at an approximate 2 × 3 m spacing. In March 2008, Arsenal® (27.6% imazapyr) at 420 g ha^{-1} and Oust Extra® (56.25% sulfometuron, 15.0% metsulfuron methyl) at 175 g ha^{-1} were respectively applied for woody and herbaceous vegetation control.

2.2. Experimental design

From year five to nine (2012–2016) treatment structure was a 2 × 2 factorial testing the effects of throughfall reduction and fertilization with four randomized, complete blocks (16 plots total). Each plot was at least 0.1 ha in total size with 0.03 to 0.04 ha internal measurement areas. The different treatments were fertilization (no fertilization, fertilization) and throughfall reduction (no throughfall reduction, 30% throughfall reduction) with the following combinations: Control (C), non-fertilized and no throughfall reduction; Drought (D), non-fertilized with throughfall reduction; Fertilized (F), fertilization with no throughfall reduction; Fertilized with Drought (FD), fertilization with throughfall reduction. Throughfall reduction will hereafter be referred to as 'drought'.

Fertilizer was hand-applied in April 2012, before the fifth growing season, through a combination of urea (432 kg ha^{-1}), diammonium phosphate (140 kg ha^{-1}), and potassium chloride. Elemental rates were 224 kg N ha^{-1}, 28 kg P ha^{-1}, and 56 kg K ha^{-1}. Micronutrients were also hand-applied at a rate of 22.4 kg ha^{-1}, containing 6% sulfur, 5% boron, 2% copper, 6% manganese, and 5% zinc (Maggard et al., 2016). Throughfall reduction treatment targeted a 30% reduction in precipitation via throughfall-capture troughs. Throughfall reduction treatment was initiated in early summer 2012. Approximately 30% of plot surface area was covered by troughs and intercepted throughfall was diverted at least 3 m off-plot. Throughfall excluders were installed adjacent to each row of trees and comprised two 50 cm wide troughs separated by 50 cm, and ranged in height from 1.5 m to 0.5 m. Repairs were made as needed to continue throughfall capture. Additional construction details as well as map of location can be found in Will et al. (2015).

At the start of the tenth growing season (March 2017), a split-plot treatment of thinning was added, and previously fertilized plots were re-fertilized. All sixteen plots received the split-plot treatment, creating 32 subplots. The following combinations represent treatments from that point onward: C (control, non-thinned), C-T (control, thinned), D (drought, non-thinned), D-T (drought, thinned), F (fertilized, non-thinned), F-T (fertilized, thinned), FD (fertilized, drought, non-thinned), and FD-T (fertilized, drought, thinned). Thinning reduced trees per ha (TPH) by approximately 41% and basal area by approximately 28%. We thinned from below with constraints due to spacing among leave trees. Harvesting the trees among the throughfall excluders was not feasible. Rather, trees were killed by a combination of girdling and application of glyphosate above the girdle using the ‘hack-and-squirt’ method. Treated trees died during 2017 such that the 2017 growing season was transitional between a before and after thinning state. At time of herbicide treatment, the DBH of killed trees averaged 14.9 cm and residual trees averaged 16.3 cm. Re-fertilization of N and P was applied at the same rate as in 2012, a mixture of urea at 432 kg ha^{-1} and diammonium phosphate at 140 kg ha^{-1}, with no additional K or micronutrients added.

2.3. Weather data

Average monthly weather data for Broken Bow, OK were calculated from daily values provided by the local Mesonet weather station (34.04306, −94.62417, 18.4 km from site, Mesonet, 2020). Daily total rainfall, average temperature, maximum temperature, and minimum temperature, were used to calculate monthly averages and monthly standardized precipitation-evapotranspiration index (SPEI). Standardized precipitation-evapotranspiration index is a meteorological measurement of drought that accounts for temporal variation in moisture availability. For our purposes, monthly SPEI values were calculated based on the preceding 12-month period to account for water available for woody vegetation. Twelve-month SPEI has a strong correlation with Palmer Drought Severity Index, but better represents the climatic water balance (Zhao et al., 2017). The R package ‘SPEI’ was used to perform all calculations (Beguería and Vicente-Serrano, 2017).

2.4. Soil moisture

Soil volumetric water content (VWC) was recorded at 4 to 6 week intervals throughout the 2019 growing season (age 12). Moisture was measured from 0 to 12 cm using the HydroSense Soil Water Measurement System (Campbell Scientific, Inc., Logan, UT, USA). Four subsamples were taken from each subplot (n = 32) for a total for 128 samples for each measurement period. The location for each sample was randomly chosen within each plot.

2.5. Foliar nutrients

Foliar nitrogen (N) and phosphorous (P) concentrations were measured prior to the start of each respective growing season from 2012 to 2019. All samples were taken from dominant or co-dominant trees within each plot and sampled from the south side of the upper third of canopy. Before thinning (2012–2017), five subsamples were taken from each plot and combined for one plot-level sample. For 2018 and 2019, the thinning treatment was included and separate samples were taken for non-thinned and thinned subplots. Three subsamples were taken from each subplot and combined. Samples were dried at 60° C for at least 48 h. Dried samples were analyzed by the Soil, Water, and Forage Analytical Laboratory at Oklahoma State University. Foliar N was analyzed with a CHNS analyzer (TruSpec® Micro, LECO Corp.,Saint Joseph, Michigan). Foliar P was analyzed using an inductively coupled plasma spectrometer (Spectro Arcos, AMETEX, Berwyn, Pennsylvania).

2.6. Stand growth

Annual tree diameter breast height (DBH, 1.37 m) and height were recorded at the end of each growing season, starting before the 2012 growing season and ending in November 2020. This accounts for nine growing season. Diameter was recorded using two perpendicular caliper measurements from stand age 4 to 6 years (2012 to 2014); height was measured using height poles during this time period. Due to increased tree size, from 7 to 13 years (2015 to 2020), DBH was measured using diameter tapes and height was measured using a laser hypsometer (Laser Technology, Inc., Centennial, CO, USA). From DBH and height measurements, volume was calculated using the range-wide volume outside-bark equation from Van Deusen et al. (1981). Annual increment was calculated as the difference between the current growing season volume and the previous growing season volume. Experiment-wide mortality totaled 44 trees (out of 1,007) from 2012 to 2020, averaging 1.38 trees plot^{-1}. To calculate gross current annual volume increment, trees that were removed during thinning or that died were included in calculations, i.e., volume at time of death was kept constant and not subtracted from the total. Site index (base age 25, SI_{25}, using the equation from Diéguez-Aranda *et al.*, 2006) was calculated at age 13 for each plot using the ten tallest trees per plot.

2.7. Leaf area index

During the 2019 growing season, single-sided leaf area index (LAI) was measured using the LAI-2200C plant canopy analyzer (LiCor, Inc., Lincoln, NE, USA) at approximately 4 to 5 week intervals. All measurements were taken under diffuse light conditions, with clear or uniformly overcast skies, either in the morning before the sun had risen above the horizon or in the evening after the sun had gone below the horizon. A 90° viewing cap was placed on the light sensor, 180° away from the user, to limit edge effects. During the 2019 growing season, samples were taken at the four corners of each measurement subplot, with the user’s back to the plot corner and the sensor faced towards the plot center. Each LAI reading was taken at a ~1 to 1.5 m height and above throughfall exclusion troughs. A second sensor was placed within 1 km of the plots in an open field to record above-canopy light conditions. Annual LAI values presented are mean growing season values, not maximum values, and offer a conservative estimate of growing season LAI.

2.8. Drought intensity and growth

The relative effect of drought treatment was determined for annual basal area (BA) increment. The relative effects of drought on BA growth were calculated by dividing the annual increment of drought-treated plots (D and FD plots) by non-drought-treated plots (C and F plots) for the pre-thin period. To eliminate confounding competition effects in the analysis, thinned and non-thinned data were separated after thinning (2017–2020). Linear regression was used to determine the correlation between annual SPEI and the effects of drought on relative BA increment.

2.9. Statistical analysis

Treatment effects were analyzed using generalized linear mixed models (i.e., PROC GLIMMIX) and significance was assumed at $p \leq 0.05$, unless otherwise specified. Analyses were divided between pre-thinning (2012 to 2016) and post-thinning (2017 to 2020). Prior to split-plot treatment, main treatments and interactions were analyzed using an effects model with 'block' as a random effect. After split-plot treatment in spring 2017, the thinning effect was added to the model, and 'block*fertilization*drought' was also considered a random effect. If significant interactions were present, simple effect comparisons of least square means and their standard errors were made. When appropriate, data were analyzed with repeated measures to determine time effect and associated interactions. Soil moisture, foliar nutrients, and stand density were examined with autoregressive covariance structure, i.e., variance and correlations decrease with time. DBH increment, height increment, and gross current annual volume increment were examined by grouping covariance structure by year, i.e., variance and correlations were assumed dependent on annual weather conditions. Kenwood-Rodgers methods were also used to calculate unbiased denominator degrees of freedom. To control Type I error and increase statistical power, negative estimates of variance were calculated when warranted. Analysis was performed using SAS/STAT® software, Version 9.4 for Windows.

3. Results

3.1. Weather

The period 2011 to 2013 had below the normal precipitation of 1300 mm per year and experienced drought conditions (annual SPEI < -1.0, Fig. 1). Precipitation in 2014 was close to the annual average and SPEI approached 0. Annual precipitation was above average in 2015–2016 and 2018–2020 and corresponding SPEI values were greater than 1.0 for 2015–2016 and 2019–2020. Precipitation in 2017 (1150 mm) was below average which caused a mild drought (SPEI $= -0.5$). Similar to annual values, monthly SPEI values indicated drought conditions 2011–2013, an increase in SPEI during 2014, wet conditions 2015–2016 and 2018–2020, and a mild drought in 2017 (Fig. 1). For 2011, which was the year before treatment initiation, drought conditions were driven by both low precipitation and above average temperatures. Alternatively, drought conditions during the 2012 and 2013 growing seasons were mainly due to low precipitation (Fig. 1). Maximum temperatures in 2014 were lower than 2011–2013 which helped recovery of SPEI even though precipitation was near average.

3.2. Soil moisture

Soil VWC (0–12 cm) measured in 2019 represents a typical year with above average rainfall (1803 mm, Fig. 2). The effects of drought treatment varied with sampling date (significant drought*Julian date interaction, Table 1). During much of 2019, non-drought and drought plots had similar VWC. Drought plots (15.8%) were drier than non-drought plots (17.8%) in July ($p = 0.06$). Differences were again significant in October and December. For those two measurement dates, the VWC averaged 13.8% for drought plots and 16.8% for non-drought plots.

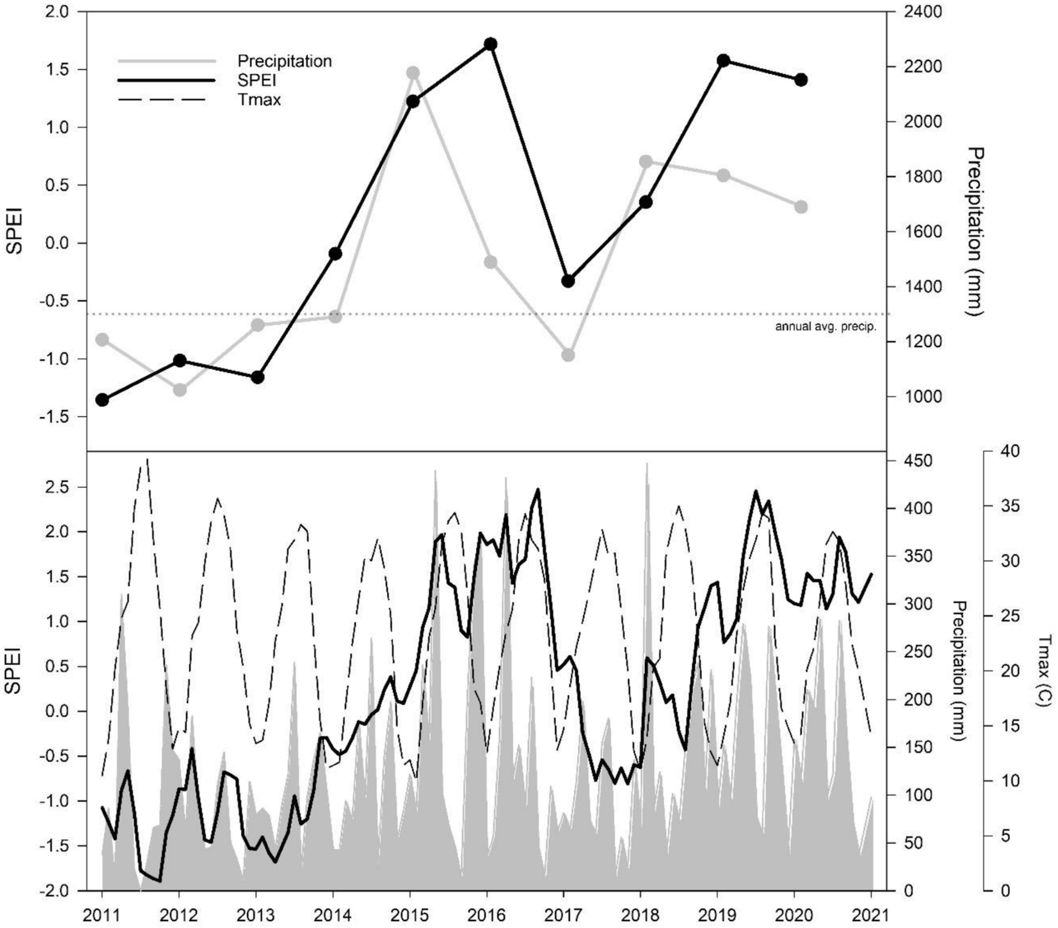

Fig. 1. Top: Annual precipitation and mean standardized precipitation-evapotranspiration index (SPEI). Dotted line shows 30-year average precipitation. Bottom: Monthly SPEI, precipitation, and mean daily maximum temperature (Tmax). Data are from 2011 to 2020 Broken Bow, OK Mesonet Station (34.04306, −94.62417). SPEI values below zero indicate dry periods and values above zero indicate wet periods; mild drought −1.0 to −0.5, moderate drought −1.5 to −1.0; severe drought −2.0 to −1.5; extreme drought ≤ -2.0 (Zhao et al., 2017).

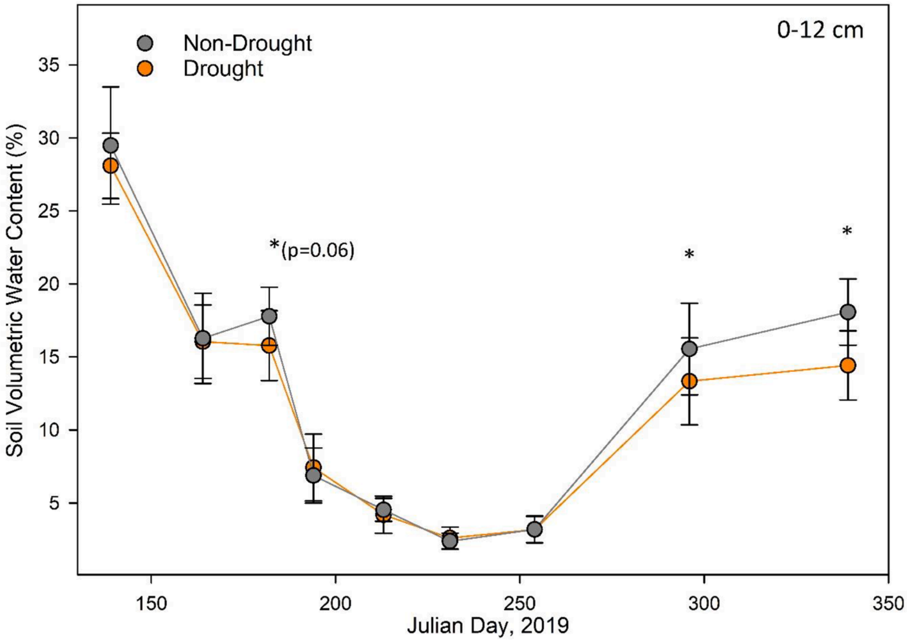

Fig. 2. Soil volumetric water content from 0 to 12 cm during the 2019 growing season. Drought main effects are presented, non-drought (C, C-T, F, F-T) vs. drought (D, D-T, FD, FD-T). Vertical bars indicate standard errors. There was a significant Julian day*treatment interaction ($p < 0.05$). Therefore '*' are used to indicate where non-drought is significantly greater than drought treatments.

Table 1
P-values from 2011 to 2020 growing seasons for fertilization (fert), throughfall exclusion (drought), year, and thinning (thin) effects on soil volumetric water content (VWC), foliar phosphorous (P) and nitrogen concentration (N), leaf area index (LAI), standing volume (Stand. Vol.), basal area (BA), trees per hectare (TPH), diameter breast height increment (DBH Inc.), height increment (HT Inc.), and gross volume current annual increment (Gross CAI). As appropriate, analyses are divided between pre-thin (2011 to 2016) and post-thin (2017 to 2020) or based on individual years. For soil VWC, 'year'= 'Julian day' circa 2019.

	Soil VWC	Foliar P	Foliar P	Foliar N	Foliar N	LAI	Stand. Vol.	Stand. Vol.	BA	BA
	2019	pre-thin	post-thin	pre-thin	post-thin	2019	2016	2020	2016	2020
fert	0.56	**0.0002**	**0.005**	**0.009**	**<0.0001**	**0.0002**	0.21	**0.05**	0.06	**0.03**
drought	0.26	0.36	0.33	0.54	0.41	0.11	**0.002**	**0.03**	0.25	0.23
fert*drought	0.73	0.09	0.83	0.08	0.60	0.75	0.30	0.86	0.27	0.78
year	**<0.0001**	**<0.0001**	**0.02**	**<0.0001**	0.23	–	–	–	–	–
fert*year	0.18	**0.03**	0.80	**<0.0001**	**0.03**	–	–	–	–	–
drought*year	**<0.0001**	0.32	0.83	0.47	0.39	–	–	–	–	–
fert*drought*year	0.38	0.75	0.95	0.06	**0.004**	–	–	–	–	–
thin	0.51	–	0.67	–	0.31	**<0.0001**	–	**<0.0001**	–	**<0.0001**
fert*thin	0.83	–	0.98	–	0.96	0.59	–	0.20	–	0.17
drought*thin	0.69	–	0.36	–	0.73	0.57	–	0.75	–	0.51
fert*drought*thin	0.57	–	0.73	–	0.28	0.52	–	0.40	–	0.49
year*thin	0.98	–	0.18	–	0.30	–	–	–	–	–
fert*year*thin	0.94	–	0.32	–	0.51	–	–	–	–	–
drought*year*thin	0.97	–	0.54	–	0.91	–	–	–	–	–
fert*drought*year*thin	0.39	–	0.38	–	0.78	–	–	–	–	–

	TPH pre-thin	TPH post-thin	DBH Inc. pre-thin	DBH Inc. post-thin	HT Inc. pre-thin	HT Inc. post-thin	Gross CAI pre-thin	Gross CAI Post-thin
fert	0.44	0.87	**0.04**	**0.01**	0.92	0.88	**0.04**	**0.01**
drought	0.53	0.82	0.28	0.95	**0.0001**	0.36	**<0.0001**	0.33
fert*drought	0.25	0.89	0.34	0.72	0.79	0.64	0.20	0.98
year	**0.0005**	**0.0007**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
fert*year	0.97	0.37	**0.0004**	0.45	0.18	0.26	0.13	0.36
drought*year	0.99	0.59	**0.006**	0.13	**<0.0001**	**0.004**	**0.0002**	**0.03**
fert*drought*year	0.96	0.89	0.17	0.43	0.93	0.95	0.10	0.93
thin	–	**<0.0001**	–	**<0.0001**	–	0.92	–	**<0.0001**
fert*thin	–	0.23	–	0.98	–	0.75	–	0.07
drought*thin	–	0.07	–	0.71	–	0.91	–	0.51
fert*drought*thin	–	0.35	–	0.77	–	0.77	–	0.20
year*thin	–	**0.03**	–	**0.04**	–	0.35	–	0.86
fert*year*thin	–	0.37	–	0.81	–	0.45	–	0.42
drought*year*thin	–	0.59	–	0.78	–	0.87	–	0.43
fert*drought*year*thin	–	0.15	–	0.65	–	0.53	–	0.94

3.3. Foliar nutrients

Foliar nutrient concentrations increased after fertilization in 2012 and 2017 (Fig. 3). Foliar P concentration increased with initial fertilization but statistical significance depended on year (significant fertilization*year interaction, Table 1). Fertilization increased foliar P concentration following the 2012, 2013, and 2016 growing seasons and again in 2017 after re-fertilization. Samples for 2017 were not separated by thinning treatment. After re-fertilization (post-thin, 2018–2019), the main effect of fertilization was significant (Table 1). On average, fertilization increased foliar P concentration by 6% in the pre-thin period and by 13% in the post-thin period. Pre-thin, the effects of fertilization on foliar N concentration varied by year, i.e., significant fertilization*year interaction (Fig. 3, Table 1), with differences significantly greater with fertilization following the 2012 and 2013 growing seasons. Likewise, fertilization significantly increased foliar N concentration when measured after the 2017 growing season (re-fertilized spring 2017). Foliar N concentration remained significantly greater post-thin (2018–2019). However, a significant fertilization*drought*-year interaction occurred because in 2018 the fertilized-drought (FD, FD-T) treatments had 8% greater foliar N concentration than fertilized (F, F-T) treatments, but both were similar in 2019. Neither drought or thinning main effects had any significant impact on foliar P or N concentrations (Table 1).

3.4. LAI

Both thinning and fertilization significantly affected LAI when measured in 2019 (Table 1, Fig. 4). Thinning decreased LAI by 20% (4.8 thin vs 3.9 non-thin), while fertilization increased LAI by 14% (4.6 fertilized vs 4.0 non-fertilized). Drought treatment non-significantly reduced LAI by 5% ($p = 0.11$).

3.5. Plot-level density, volume, and growth

During the pre-thin period, stand density (TPH) decreased by 2% from 2011 (age 4) to 2016 (age 9) but treatments did not influence mortality (Table 1). Thinning decreased TPH by an average of 41% (Fig. 5), from 1,570 TPH to 923 TPH, and basal area from 32 m^2 ha^{-1} to 23 m^2 ha^{-1} (Fig. 6). During the post-thinning period, mortality decreased TPH in non-thinned plots by 3% (1,570 TPH at age 10 to 1,524 TPH at age 13) but decreased TPH by only 1% (924 to 912 TPH) for the thinned plots, and resulted in a significant thinning*year interaction (Table 1).

During the pre-thin period, DBH increment exhibited significant fertilization*year and drought*year interactions (Table 1). Fertilization increased DBH increment in 2012 and 2014 by 9% on average (0.25 cm y^{-1}) . Drought decreased DBH increment in 2013, a reduction of 11% (0.31 cm), and increased increment in 2015 by 9% (0.17 cm, Fig. 7). Post-thin, fertilization, thinning, year, and year*thin were all significant (Table 1). During the post-thin period, fertilization increased DBH increment by 11% on average (0.12 cm y^{-1}). Thinning increased DBH

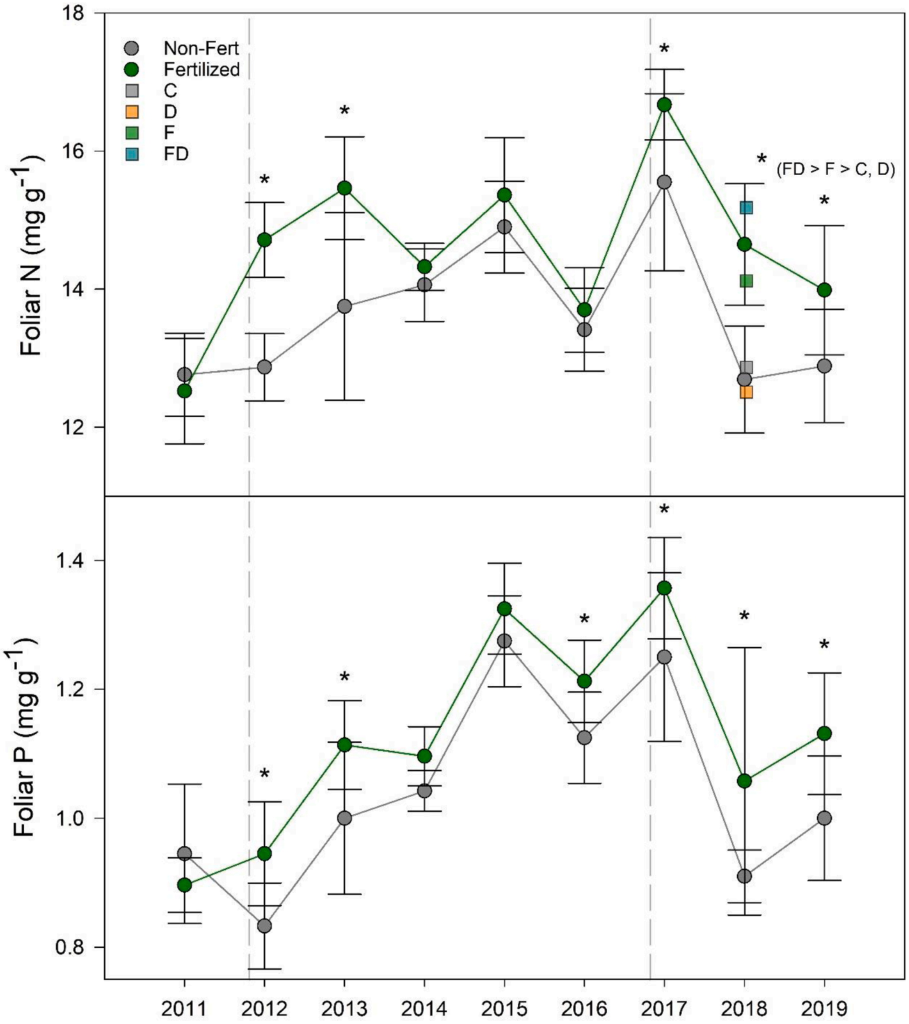

Fig. 3. Foliar phosphorous (P) and nitrogen (N) concentrations after specified growing seasons. An '*' is used to indicate years where the difference between fertilization treatments was significantly different. The exception is N concentration for 2018 which had a significant fert*drought interaction such that each of the whole-plot factors is portrayed. Analyses were conducted separately for the pre- and post-thin periods. Data from 2017 were grouped with 'pre-thin' data. Dashed lines indicate date fertilized. C = Control, F = Fertilized, D = drought. Vertical bars represent standard error.

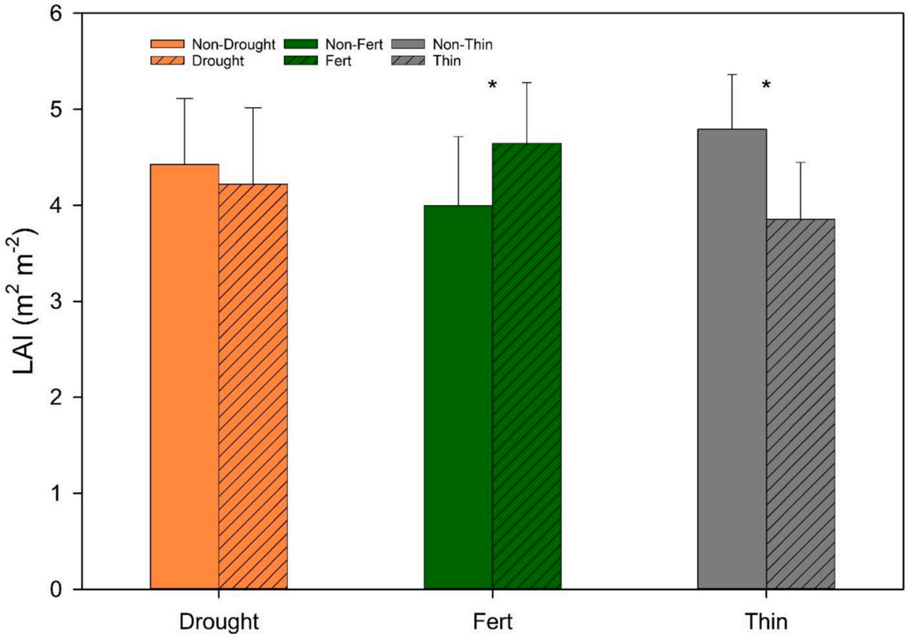

Fig. 4. Average single-sided leaf area index (LAI) during the 2019 growing season (twelfth growing season). Main effects (interactions n.s.) from drought and fertilization, and split-plot thinning effects are presented. Significance indicated by '*'. Vertical bars represent standard error.

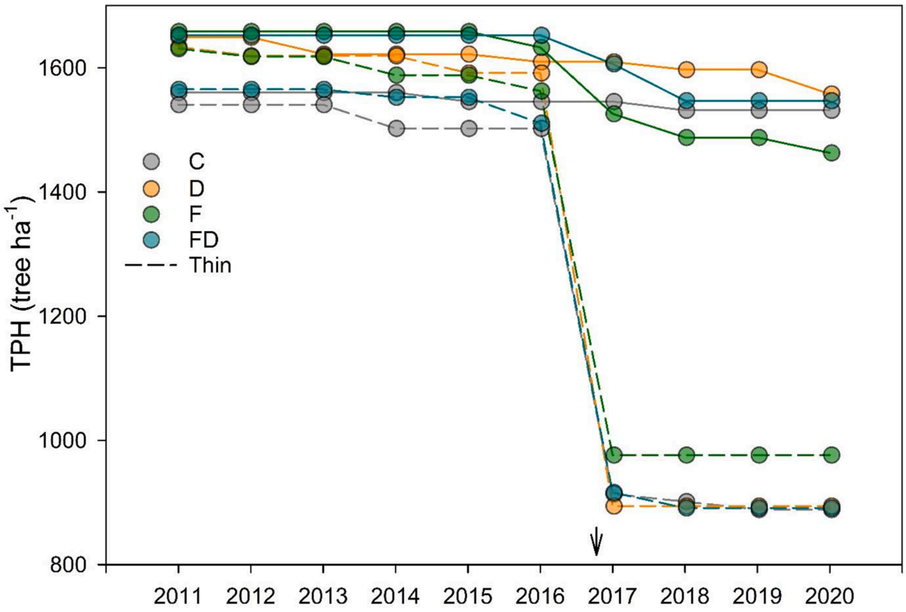

Fig. 5. Trees per hectare (TPH) after specified growing seasons. Analyses were separated between pre-thin (2011–2016; ages 4–9) and post-thin (2017–2020; ages 10–13). Arrow indicates date thinned. C = Control, F = Fertilized, D = drought.

increment in 2017, 2019, and 2020 but not in 2018 (thinning*year interaction). The increase of DBH increment for 2017 in thinned stands was likely an artefact of thinning-from-below. In the thinned subplots, the average DBH of killed trees was 14.9 cm and the average DBH of residual trees was 16.3 cm. Thinning effects in 2019 and 2020 on DBH increment (0.42 cm y^{-1}, 38%) reflect true increased growth rates. The net effect was that after nine years of treatment (stand age 13), DBH was 4% greater with fertilization ($p = 0.004$) and 7% greater with thinning ($p < 0.0001$). Fertilization increased basal area at the end of the pre-thin period (2016) by 5% and at the end of the experiment (2020) by 7% (Fig. 6). At age 13, basal area of the non-thinned stands averaged 50.3 m^2 $ha^{-1}$and for the thinned stands averaged 34.2 m^2 ha^{-1}.

Height increment was affected by drought treatment but the response varied on an annual basis (Fig. 8). During the pre-thin period, drought, year, and drought*year effects were all significant (Table 1); drought decreased height increment by an average of 18% (0.22 m y^{-1}) for the 2013, 2014, and 2016 growing seasons. During the post-thin period, year and drought*year effects were significant. In 2017, drought treatment produced a positive effect and increased increment 14% (0.13 m) while in 2020, drought treatment had a negative effect and decreased increment by 16% (0.15 m). Fertilization, thinning, nor any higher order interaction affected height increment (Table 1). The net result was that by stand age 13, only the drought treatment produced a discernable effect on height ($p = 0.01$), a decrease of 4% (0.39 m).

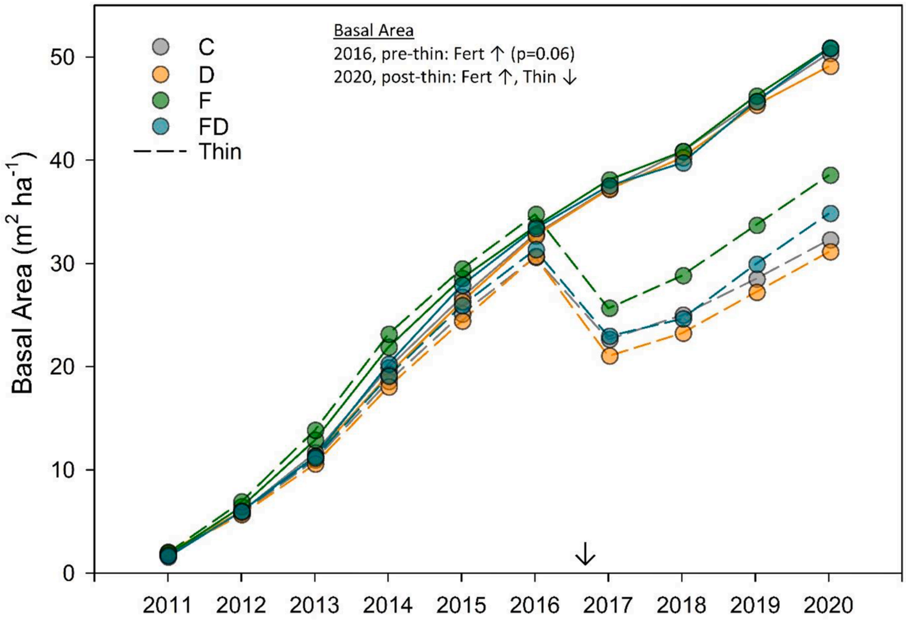

Fig. 6. Standing basal area at the end of specified growing season. Arrow indicates date thinned. Analyses were conducted at the end of the pre-thin period (2016; age 9) and end of the experimental period (2020; age 13). Significant effects are listed. C = Control, F = Fertilized, D = drought.

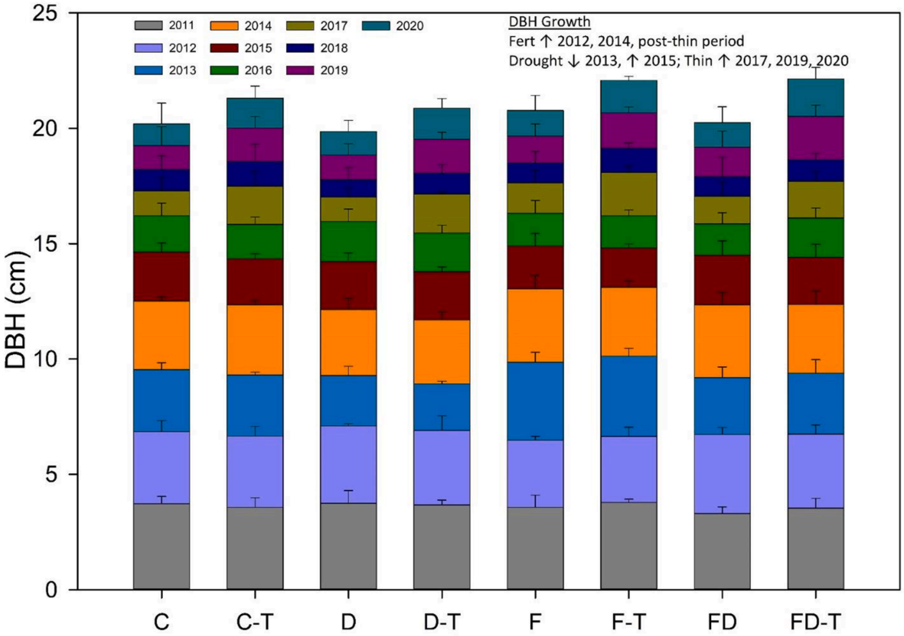

Fig. 7. Diameter breast height (DBH) at the end of specified growing season (ages 4–13). Beginning with 2012, the increments between successive years represent annual DBH growth associated with that growing season. 2011 represents growth from 2008 (planting) through 2011 (age 4). Analyses of DBH growth increments were separated between pre-thinning (2012–2016; age 5 to 9) and post-thinning (2017–2020; age 10 to 13). Listed effects indicate years when specific treatments were significant. C = Control, F = Fertilized, D = drought, T = thin. Vertical bars indicate standard errors.

Heights of the ten tallest trees per plot averaged 12.1 m for drought-treatment trees and 12.6 m for non-drought treatment trees, which translated into decreased ($p = 0.05$) SI$_{25}$ in droughted plots (20.4 m) compared to non-droughted plots (20.9 m).

At stand age 9 (end of pre-thin), drought decreased standing volume by 10% (13.5 m^3 ha^{-1}, Table 1, Fig. 9). When analyzed post-thin following the 2020 growing season (stand age 13), drought and fertilization effects were similar in magnitude, but opposite in direction. Drought treatment decreased standing volume by 8% (18.5 m^3 ha^{-1}) and fertilization increased standing volume by 7% (16.1 m^3 ha^{-}1, Table 1, Fig. 9). As expected, thinning decreased standing volume measured in 2020, a 33% decrease (90.8 m^3 ha^{-1}). In 2020, the differences due to fertilization and drought for individual tree-level volume mirrored those for stand volume. The overall mean tree volume was 0.19 m^3 ha^{-1}. Drought decreased individual stem volume by 7% ($p = 0.02$, 0.015 m^3 ha^{-1}) and fertilization increased individual tree volume by 7% ($p = 0.04$, 0.013 m^3 tree^{-1}). Thinning increased individual tree volume, on average, by 12% ($p = 0.0003$, 0.022 m^3 tree^{-1}).

Gross stem volume current annual increment (CAI), calculated without subtracting volume of dead or thinned trees, had significant fertilization, thinning, and drought*year effects (Table 1, Fig. 10). Before thinning, fertilization increased gross CAI by 5% (1.14 m^3 ha^{-1} y^{-1}). In 2013, 2014, and 2016, drought decreased gross CAI by 15% (4.32 m^3 ha^{-1} y^{-1}). For the post-thin period, fertilization, thin, year, and drought*year effects were significant. Fertilization increased gross CAI by 12% (3.58 m^3 ha^{-1} y^{-1}) and thinning decreased gross CAI by 31%

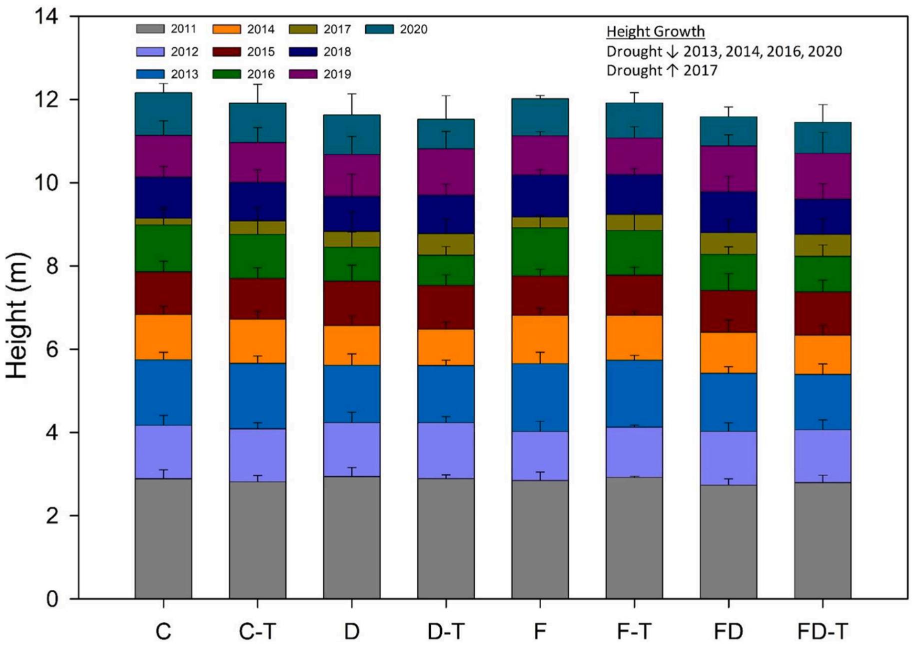

Fig. 8. Height at the end of specified growing season (ages 4–13). Beginning with 2012, the increments between successive years represent annual height growth associated with that growing season. 2011 represents growth from 2008 (planting) through 2011 (age 4). Analyses of height growth increments were separated between pre-thinning (2012–2016; age 5 to 9) and post-thinning (2017–2020; age 10 to 13). Listed effects indicate years when specific treatments were significant. C = Control, F = Fertilized, D = drought, T = thin. Vertical bars indicate standard errors.

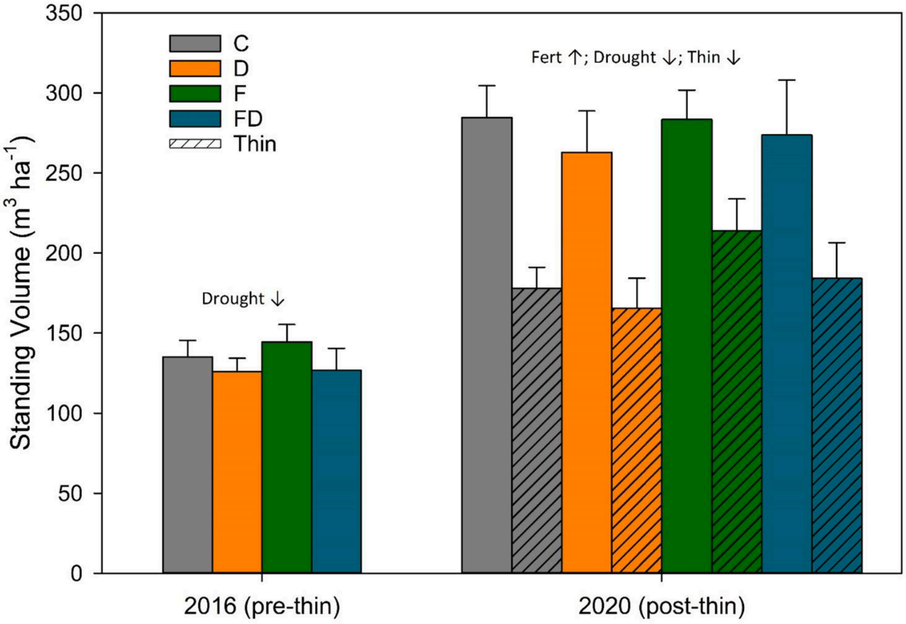

Fig. 9. Standing volume at the end of 2016 and 2020. 2016 represents pre-thin standing volume at age 9. 2020 represents post-thin standing volume at age 13. Significant effects are listed above bars. C = Control, F = Fertilized, D = drought. Vertical bars indicate standard errors.

(10.26 m^3 ha^{-1} y^{-1}). The interaction between thinning and fertilization was marginally significant ($p = 0.07$) and occurred because the positive effects of fertilization were greater in thinned (23% increase) vs non-thinned plots (6% increase). In 2018, drought decreased gross CAI by 16% (3.90 m^3 ha^{-1}). The net effect was that following the 2020 growing season and nine years of treatment, drought decreased total gross volume increment by 7% ($p = 0.03$), fertilization increased total gross volume increment by 8% ($p = 0.02$), and thinning decreased gross volume increment by 17% ($p < 0.0001$).

3.6. Drought intensity and growth

The relative basal area increment in response to drought treatment was linearly correlated with growing season SPEI and had a significant non-zero slope, $m = 0.058$, per change in SPEI ($r^2 = 0.61$, Fig. 11). During periods of meteorological drought, SPEI < 0, drought (D and FD) plots had greater reduction in basal area increment than non-drought (C and F) plots. As growing conditions became more favorable, SPEI greater than 0, drought treatment basal area increment was often greater than the respective non-drought treatments. Thus, drought treatments showed greater relative basal area increment post-drought than during-drought (i.e., recovery growth), irrespective of stand density (Fig. 11).

4. Discussion

Our first two hypotheses were that drought would decrease

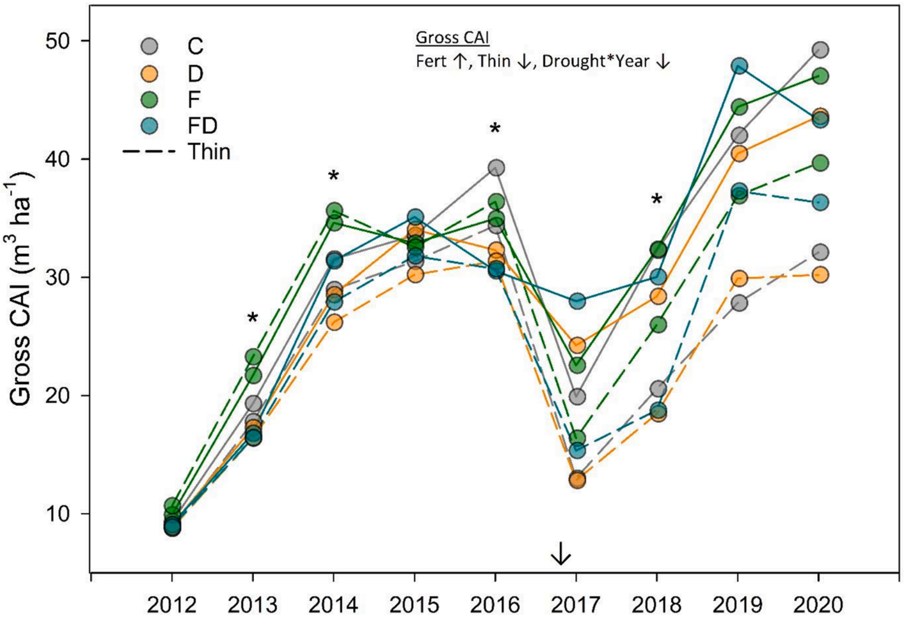

Fig. 10. Gross volume current annual increment (CAI) for specified growing seasons. Gross CAI is the annual increase in stem volume without subtracting losses due to mortality or removal. Arrow indicates date thinned. Analyses were split between pre-thinning (2012–2016; age 5 to 9) and post-thinning (2017–2020; age 10 to 13). Significant effects are listed. An '*' indicates years where drought caused a significant decrease in gross CAI. C = Control, F = Fertilized, D = drought, T = thin.

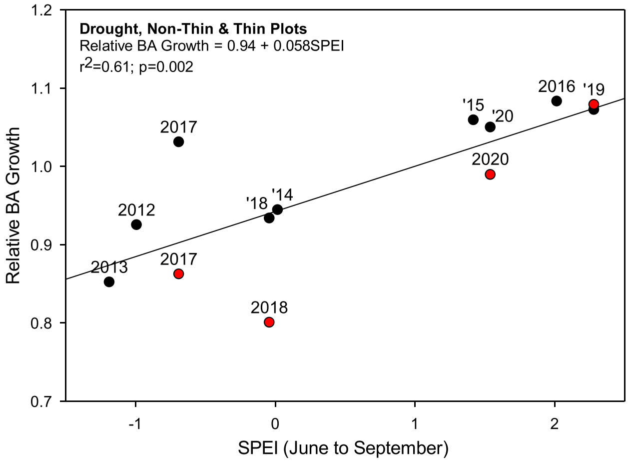

Fig. 11. Relationship between SPEI and relative gross basal area growth of drought compared to non-drought treatments. Thinned (black circles) and non-thinned (red circles) treatments are plotted separately. Relative basal area growth is gross basal area growth of the D and FD treatment divided by gross basal area growth of the corresponding C and F treatment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

productivity and that fertilization would increase productivity such that fertilization could compensate for the negative effects of 30% throughfall reduction. We did find this in regards to standing volume and total gross volume growth and these results were similar to an earlier report by Maggard et al. (2017). However, there were important differences in the timing of treatment response and whether treatments mainly affected diameter or height development. Our findings, though tied to site-specific conditions, are vital as site-intensive research augments understanding of large-scale ecological processes (Fahey et al., 2015). In regards to loblolly pine plantations, our location on the western edge of the commercial range likely represents responses to climatic variability for more xeric sites as well as future conditions for more mesic areas further east.

The effects of 30% throughfall reduction were greater in dry years and negligible in wet years and more important to height than diameter development. It is well established that drought reduces loblolly pine growth, but current-season precipitation was correlated with diameter growth rather than height growth in a previous studies (Amateis et al., 2013). In that region-wide analysis, authors speculated that because the majority of height growth is completed before drought conditions manifest in late summer the response of height growth was small. However, diameter growth continues until autumn (Cregg et al., 1988), such that current-year droughts reduce diameter development later in the growing season. Our 30% reduction in throughfall treatment had chronic impacts on soil moisture, including effects in the dormant season (Fig. 2), which may have been exacerbated by our location near the western edge of loblolly pine's commercial range. These chronic impacts likely carry-over into the early growing season of the next year. Recent analyses on the effects of higher summer temperature, and presumably greater VPD and water stress, indicated a reduction in the height-diameter relationship in a broad range of tree species (Fortin et al., 2018). In addition, loblolly pine planted beyond its native range in Oklahoma tended to be shorter for a given DBH (Harges, 2017). At our site, the net effect of reduced height growth due to nine years of 30% throughfall exclusion was a decrease in SI_{25} of 0.5 m and a 7% decrease in net volume. This may increase rotation length, which may lower profits for landowners (Shephard et al., 2021).

The impacts of reduced precipitation on plantation growth will likely be region- (precipitation regime) and site- (edaphic attributes) specific. In sister studies done on more mesic locations in Virginia and Florida, drought treatment had little to no effect on aboveground net primary production (NPP_A, Bracho et al., 2018) and stem increment (Will et al., 2015). Our current study supports sustained effects of drought on growth similar to those documented at our site during the first several years of treatment whereby drought decreased NPP_A (Bracho et al., 2018) and stem increment (Will et al., 2015). The companion study in Georgia also showed some reductions in stem growth and NPP_A due to throughfall reduction treatment, but this occurred during a severe regional drought (Will et al., 2015).

Drought-treatment effects varied by year. For instance, during the relatively wet 2019 growing season, drought and non-drought treatment plots had similar surface soil moisture (0–12 cm) except for late in the year when SPEI decreased to approximately 1. Not surprisingly, drought effects on CAI were not significant for 2019 as rainfall was likely great enough to saturate the soil even with the 30% throughfall reduction treatment. As reported in Maggard et al. (2016); (2017;), reduced soil moisture conditions due to drought treatment were larger during dry years than wet years (age six and seven), with similar results at the Georgia site (age seven, Samuelson et al., 2014). We did not measure soil moisture deeper than 12 cm during 2019. Soil matric potential from 0 to 90 cm was reduced by drought treatment previously at our site (Bracho et al., 2018). Likewise, deep soil water availability, 90–300 cm, can buffer against dry conditions (Qi et al., 2018). At drought-induced plots in Georgia, soil 90 cm and deeper accounted for the majority of plant available water, but on ambient precipitation plots, deep soil accounted for less water uptake (18% to 86%, Qi et al., 2019).

Fertilization increased standing volume by 7% and total gross volume growth by 8%, mainly due to increased DBH growth within the first three years after fertilizer application. Our fertilization results mirror those reported earlier in the stand development (Maggard et al., 2016) and at a well-drained site on the Georgia Piedmont (Samuelson et al., 2018). Fertilization generally increases DBH more than height (Allen et al., 2005). Although poorly-drained sites generally show greater height growth response to fertilization (Amateis et al., 2000), this result likely depends on stage of stand development and is not consistent as fertilization increased tree height at a moderately drained site in Louisiana (Sayer et al., 2004) and had no effect at a poorly drained site in Florida (Wightman et al., 2016).

Both foliar N and P increased after fertilization and indicates potential stand demand for nutrients was likely greater than soil supply, a common occurrence within mid-rotation stands (e.g., Allen et al., 1990). The benefits of fertilization on foliar N concentration only lasted a few years indicating high tree N demand and possible dilution among the larger trees in the fertilized plots. The fertilizer response on CAI at our site (1.8 m^3 ha^{-1} y^{-1}) was in the lower range (0.7 to 7.0 m^3 ha^{-1} y^{-1}) reported by Fox et al., (2007b) for one-time loblolly pine stand fertilization at mid-rotation. The somewhat muted response at our site could be related to relatively high native soil nutrient capacity as indicated by foliar N concentrations of the non-fertilized plots well above critical concentration thresholds of 12.0 mg N g^{-1} (Wells and Allen, 1985).

Measured during the 2019 growing season, LAI was greater due to fertilization and likely contributed to increased growth rates in that treatment (e.g., Borders et al., 2004; Allen et al., 2005). Precipitation during 2019 was well above average, which likely reduced the impact of throughfall reduction on leaf area development resulting in a non-significant decrease in LAI. During dry periods at our site (2012–2014), drought treatment decreased LAI and stem volume production (Maggard et al., 2017). At the Georgia site during wet and dry years, drought treatment decreased both LAI and volume production (Samuelson et al., 2018). Thus, the response may be site dependent.

Our third hypotheses was that that benefits of fertilization at mid-rotation would be greater in thinned than non-thinned stands because we expected that the high levels of competition in the non-thinned stands would mute the positive effects of fertilization. We did find a 24% increase in gross CAI due to fertilization among the thinned plots during the post-thinning period as compared to a 6% increase due to fertilization in the non-thinned plots, but this interaction was marginally significant ($p = 0.07$). The moderate level of thinning, 28% basal area reduction, may have reduced the differences to fertilization among thinned and non-thinned plots. Overall, thinning reduced gross CAI even though thinning increased DBH because of ∼ 40% fewer trees contributing to stand-level growth. As expected, thinning did not affect height growth (e.g., Bose et al., 2018).

Our fourth hypothesis, that thinning would mitigate negative drought effects, was not supported as the thinning*drought interaction was not significant. Generally, thinned stands are more resistant and resilient to drought (Sohn et al., 2016). Positive thinning effects under drought conditions can depend on time since thinning (Elkin et al., 2015), stand structure and age (i.e., large trees, D'Amato et al., 2013), or thinning intensity (i.e., heavy reduction, Bose et al., 2018). Wet conditions from 2018 to 2020 likely contributed to the lack of a drought*-thinning interaction in our study. For example, in ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws), thinning only increased net photosynthesis and leaf gas exchange during severe drought (Skov et al., 2004). Benefits of thinning on radial growth during drought in young stands were tied to increased soil moisture availability. In older thinned stands with greater water-use, thinning benefits shift to greater leaf area to leverage post-drought conditions (McDowell et al., 2006; Sohn et al., 2013).

The effect of drought treatment on growth increment was stronger in dry than wet years and it appeared that drought treatment plots recovered during wetter years by exhibiting increased basal area increment in years with above average precipitation (June-September SPEI). Related to this was significantly greater DBH increment in drought-treatment plots in 2015, which was the year with the highest annual SPEI. This finding is important because it indicates that negative responses to severe drought might be somewhat countered by compensatory growth in the long-term. Importantly, there were no negative drought legacy effects once wetter conditions returned. If anything, legacy effects may have been positive for drought treatment plots. In a similar study, trees showed compensatory growth, or 'overgrowth', up to nine years after drought (Ovenden et al., 2021). Along with this recent result, our findings document the potential for forest overgrowth and imply forest-level adaptability to periodic drought conditions. Therefore, impacts of a future drier climate might be partially mitigated by periodic 'wet' years assuming they continue to occur.

Reasons for recovery of drought stress treatment plots upon return of wetter conditions could be due to greater post-drought gas exchange, which has been reported in Norway spruce (*Picea abies* L., Sohn et al., 2013). Greater post-drought growth may also be driven by carbohydrate storage in roots during drought. Since growth slows before photosynthesis during the early stages of drought (e.g., Körner, 2003), trees experiencing moderate drought can have increased carbon storage (Hartmann et al., 2015). Previous research at our site showed that during 2013 and 2014 leaf-level net photosynthesis of trees in drought-treated plots declined by approximately 9% (Maggard et al., 2016), while stand volume growth declined 16% (Maggard et al., 2017). Loblolly pine under soil moisture limitation shows little change in fine root mortality and western-sourced trees can have increased belowground carbohydrate reserve with moisture limitation (Hallgren et al., 1991), a trend found within other species as well (Regier et al., 2009).

In our study, the fertilization and drought effects were additive, but the negative effects of drought could become worse if future droughts are stronger than predicted or occur in combination with higher temperatures (Adams et al., 2009). In addition, rising atmospheric CO_2 complicates prediction of drought effects through its influence on leaf-level gas exchange, water use efficiency, and storage of nonstructural carbohydrates (e.g., Will and Ceulemans, 1997; Will and Teskey, 1997; Li et al., 2018). Another uncertainty is the effects of drought on disturbance. We found fairly marginal impacts on stand productivity. Drought could increase the incidence of insect and pathogen outbreaks or increase the risk of wildfire, which could have catastrophic effects.

We focused on loblolly pine due to its commercial importance. Response to drought scenarios may be species-specific. Loblolly pine is typically planted in more mesic locations and has a recurrent flushing growth pattern, perhaps aiding 'catch-up' growth under favorable periods. Whereas slower-growing southern pine from more xeric environments, like longleaf pine (*Pinus palustris* Mill.), have shown no recovery growth post-drought (Samuelson et al., 2019). Fast-growing trees are more susceptible to drought than slow-growing trees (McDowell et al., 2006). However, intensive management practices, like site preparation, competition control, and density management, can reduce the possible negative consequences and can be modified to adapt plantation management to future conditions.

5. Conclusion

Loblolly pine is a critical component to timber production in the southeastern USA. Since our study site was near the western-extent of the tree's commercial range, results inform how future plantations might respond to climate change. Nine-years' worth of stand data showed a modest 7% decrease in volume production in response to a 30% throughfall reduction, that drought effects could be mitigated through nutrient management, and that growth of drought-treated plots had some ability to recover when conditions become wetter. As droughts likely become more frequent and more intense with climate change, our results give optimism for continued productivity of loblolly pine plantations in a future, drier climate.

CRediT authorship contribution statement

Noah T. Shephard: Conceptualization, Methodology, Data curation, Investigation, Resources, Formal analysis, Software, Visualization, Writing - original draft. **Omkar Joshi:** Funding acquisition, Conceptualization, Validation, Writing - review & editing, Supervision, Project administration. **Cassandra R. Meek:** Resources, Validation, Writing - review & editing. **Rodney E. Will:** Funding acquisition, Conceptualization, Validation, Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The author declare that there is no conflict of interest.

Acknowledgements

This work was supported by the USDA McIntire Stennis projects (OKLO3042, OKL0 3151), the Oklahoma Agricultural Experiment Station, and the Department of Natural Resource Ecology and Management at Oklahoma State University. Special thanks to gracious support of Mr. Ed Hurliman for the use of his property to support the Broken Bow, OK PINEMAP Tier III site. Funding for installation and measurement of the study site (2012-2017) was provided by Pine Integrated Network: Education, Mitigation, and Adaptation Project (PINEMAP), a Coordinated Agriculture Project funded by the USDA National Institute of Food and Agriculture, Award no. 2011-68002-30185. Thanks to Bob Heinman, Keith Anderson, Randy Holeman, Dennis Wilson and Caleb McKinney for installation, measurement, and upkeep of the study site.

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