LONG-TERM ABOVEGROUND GROWTH, CANOPY DYNAMICS, AND ECONOMIC IMPLICATIONS FROM THROUGHFALL EXCLUSION, FERTILIZATION, AND THINNING IN SOUTHEASTERN OKLAHOMA, USA

By

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Abstract: Loblolly pine (*Pinus tadea* L.) is the most commercially important timber species in the southern USA. Climate change induced drought, due to longer periods without rainfall, will alter forest growth in the region. Loblolly pine occurs on 21 million ha in the southeast and represents 87% of the regions timber production. The species productivity is likely to face new tests as climate change makes growing conditions more adverse. How climate change might affect common silvicultural practices, like fertilization and thinning, that typically increase stand productivity, is not known. This study, located in the more xeric southeastern Oklahoma, aimed to understand if a plantation regime shift could occur under drier conditions from a growth and efficiency standpoint. A 30% throughfall reduction (drought) treatment from age 5 to 12, fertilization at age 5 and 10, and thinning at age 10 were examined. From stand age 5 to 12, drought treatment decreased standing volume by 7% and fertilization increased standing volume by 8%, offsetting one another, and thus fertilization compensated for potential drought conditions. Additionally, drought-induced plots had +10% basal area growth after meteorological drought conditions subsided. Under current management strategies and potential compensatory growth, loblolly pine plantations appear to be sustainable under a drier climate. Further, efficiency analysis was leveraged to examine all treatment's ability to turn volume growth and stand density into timber products, i.e., pulpwood, chip-n-saw, and sawtimber, at 21, 26, and 31 rotation ages. At all rotation ages, fertilized-thinned stands were perfectly efficient, yet overall fertilization had no effect, and showed negative synergistic interactions with drought (-24% efficient). Thinning had the greatest ability to maintain effective production; non-thinned stands demonstrated a 32% decrease in efficiency. Drought treatment decreased efficiency by 11% after 26 years. Efficiency scores support thinning as a regime staple and fertilization to be ineffective in the long-term. Together, growth analysis supports fertilization to biologically compensate for drought, but efficiency analysis suggests fertilization unable to compensate on a resource-use basis.

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CHAPTER I

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) represents a critical component of forested land in the United States and has a large distribution across the southern U.S. landscape. The southern U.S. contains 40% of the nation's timberland, with plantation loblolly pine accounting for 34 million acres, making it the most abundant commercial species (Cooper *et al.*, 2000). Its dominance as a commercial timber species is attributed to fast juvenile growth and ability to successfully grow in a variety of physiographic regions with a diversity of soil types and moisture and temperature gradients (Allen *et al.*, 1990). Climate change is likely to affect the species in terms of timber production, as increased temperature and drought duration will occur throughout the range of loblolly pine plantations (Cooper *et al.*, 2000; Fox *et al.*, 2007), slowing stand growth (Collins *et al.*, 2013). In mitigating the negative effects of climate change, it is essential to assess economic criteria representing different management techniques.

The study site examined was located at the Pine Integrated Network: Education, Mitigation, and Adaption Project (PINEMAP) Tier III site in Broken Bow, OK established in 2012. Previous research at the site investigated the effects of throughfall reduction and fertilization. The site underwent mid-rotation thinning and re-fertilization in 2017 to further elucidate the chronic effects of water limitation, nutrient availability, and stand density on mid-rotation growth, in an effort to better guide management decisions.

The overall study comprises two parts. The first part of the research, Chapter III, involved mid-rotation growth and canopy assessment. To this effort, treatment effects, stand growth, and canopy production were quantified through Spring 2020. Results and analyses encompassed the critical point in plantation development where intraspecific competition intensifies and informed management decisions are critical. In the second part, Chapter IV, harvest (rotation) age, thinning, and fertilization under drought conditions were optimized through Data Envelopment Analysis (DEA). The DEA analytically quantified how different silvicultural strategies result in maximizing different objectives timber class, carbon storage, and profit. Results better inform Oklahoma timberland owners and other parties within the Upper Gulf region on consequences of different management regimes.

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CHAPTER II

LITERATURE REVIEW

1. CHARACTERISTICS

Loblolly pine occurs in areas with humid, warm temperatures and long hot summers, and mild winters (Baker and Langdon, 1990). The average frost-free period ranges from 180 days along the species' northern range in Delaware to 300 days in central Florida (Schultz, 1997). Low winter temperatures and associated ice and snow damage limit the species' northern dispersal. The threshold of 180-day frost free days occurs just north of the -23.3°C minimum temperature isotherm, indicating the minimum temperature limit (USDA, 2012). Lack of precipitation limits westward occurrence when annual precipitation decreases below 1000 mm (Schultz, 1997).

Establishing with long-range, wind dispersed seeds, and rapid juvenile growth, the species often comes to dominate anthropogenic and naturally disturbed sites. Shade-tolerant hardwoods persist in the understory of loblolly, increasing in numbers and size as stand dynamics progress, becoming co-dominant with loblolly over time (Baker and Langdon, 1990). Loblolly pine are intolerant of shade and result in climax forests classified as southern mixed hardwood-pine forest (Baker and Langdon, 1990). Plantation silviculture prevents this natural progression through practices such as hardwood and herbaceous weed competition control, typically accomplished by herbicide application, and harvesting between ages of 25-30 (Fox *et al.*, 2007a).

2. *INDUSTRIAL OVERVIEW*

The southern United States contains over 245 million acres of forested land, equal to 32% of total forested land in the U.S (Oswalt *et al.*, 2018). Of these 245 million acres, loblolly pine represents over 25% forested acres in the South, with plantations accounting for half of the tree's abundance (Oswalt *et al.*, 2018). Loblolly pine's increase in abundance throughout the 20th century can be attributed to federal programs like the Conservation Reserve Program (CRP) and Environmental Quality Incentives Program (EQUIP). Signed into law under the 1985 Farm Bill, CRP offers rental payments in exchange for landowners removing environmentally sensitive land from agricultural production, and planting trees to restore water quality and reduce erosion (2018). EQIP offers financial assistance to timberland owners that implement tree establishment and/or forest stand improvement to improve forest health and productivity and increase carbon storage (Stubbs, 2010).

The two main southeastern softwood timber species are *Pinus taeda* and *Pinus elliottii*, loblolly and slash pine, accounting for 34 and 7 million plantation acres, respectively (Oswalt *et al.*, 2018). In 2016, total softwood timberland removals in the U.S. South were 5.6 billion ft^3, which represent over 60% of total softwood removals in the country (Oswalt *et al.*, 2018). Often colloquially referred to as the 'wood basket' of the nation, southern timber-related sectors are estimated to contribute more than 1 million jobs and at least $51 billion annually in employee pay to the region, and produce more timber than any other country (Wear and Greis, 2013).

3. *CONCERNS OF TIMBERLAND OWNERS*

The vast majority (~83%) of softwood timberlands in the southeastern U.S. are owned by private entities. In 2017, southern private loblolly pine plantations were estimated to be owned 58% by corporate and 39% by non-corporate landowners (Oswalt *et al.*, 2018). Since a substantial proportion of owners are non-corporate, management objectives and concerns are more diverse, reflecting decisions that are not solely based on the profitability.

In 2016, southern pine timber-owners across the Southeast were surveyed to assess concern of stand health. In the study, drought was a leading factor believed to be a causal agent of declining stand health (Coyle *et al.*, 2016). Respondents indicated that they heavily relied on information from universities and outreach programs to address concerns (Coyle *et al.*, 2016). Therefore, university-based research is essential to develop effective drought management strategies and distribute results to landowners.

4. LOBLOLLY PINE SILVICULTURE

4.1 FERTILIZATION

Much of loblolly pine's dominance as a commercial species is attributed to increased production; mean annual increment (MAI) has more than doubled since 1940, and rotation lengths are 50% shorter (Fox *et al.*, 2007a). Fertilization is a key tool in enhancing loblolly pine stand growth. Fertilizer increases loblolly pine growth by increasing leaf area index (LAI) and leaf biomass (e.g. Albaugh et al. 1998, 2004; Jokela and Martin 2000; Will et al. 2002). From an increase in leaf production, an increase in carbon gain and stem production can be expected as well (e.g. Albaugh et al. 2004; Jokela and Martin 2000). Nutrients that benefit growth are often in short-supply. Nitrogen (N) and phosphorous (P) primarily limit southern loblolly pine growth; at the time of canopy closure, 5-8 years since stand initiation (Fox *et al.*, 2007b), the potential use of soil nutrients of plantations out-paces soil availability (Allen, 1987). During canopy closure intraspecific competition for light increases rapidly. To outcompete neighboring trees for light, loblolly pine grow rapidly in height at the cost of consuming available soil nutrients, in-turn making nitrogen and phosphorous limiting.

Applying fertilizer at an intermediate stand age is a common silvicultural technique (Fox *et al.*, 2007b) that is most effective when combined with other techniques such as vegetation control or thinning (Allen, 1987). Fertilization rates are ideally site dependent, but intermediate-aged loblolly stands typically receive an application of 220-170 $kg \cdot ha^{-1}$ N and 30 $kg \cdot ha^{-1}$ P, with an approximate growth response averaging 4 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ for 8-10 years (Fox *et al.*, 2007b). Intermediate-aged stand fertilization often occurs around stand age 12 or 13 in Upland Coastal Plain sites that are well-drained and can induce a volume response of 6-8 $m^3 \cdot ha^{-1} \cdot yr^{-1}$ for 5 to 6 years (Jokela, 2004). Compared to Fox *et al.* (2007b) which reported a slightly lower and generalized volume return of 4 $m^3 \cdot ha^{-1} \cdot yr^{-1}$, the Jokela (2004) estimation is more representative of good site quality and intensive management, since it incorporates well-drained soils and previous fertilizer applications.

4.2 MID-ROTATION THINNING

Thinning is widely utilized as a forest management tool around the time of crown closure that reduces interspecific and intraspecific competition and increases growth of residual trees (e.g. Smith, 1986). Remaining trees achieve greater leaf production and diameter growth (e.g. Burkes *et al.*, 2003; Hennessey *et al.*, 2004), increasing in timber value (Baker and Langdon, 1990). To maximize the additive effects of mid-rotation thinning, fertilization is often implemented with thinning in loblolly pine plantations, resulting in greater increases in current annual increment (CAI; yearly stem growth) and LAI when compared to thinning alone (Sayer *et al.*, 2004).

Stand health is improved through thinning. Reducing stems$\cdot$ha^{-1} increases stand vigor, decreasing susceptibility to damaging agents such as insect outbreaks (Waring and Pitman, 1985). It can also limit wind damage during natural disasters and increase salvageable product (Stanturf *et al.*, 2007). As fertilizer effects decrease with stand age, thinning can reinstall desired stem production. Fertilization becomes financially unattractive as stand age increases, stand nutrient demands dramatically increase and likewise large amounts of nitrogen and phosphorous are needed to meet demands (Fox *et al.*, 2007b).

5. DROUGHT CONTEXT AND SIGNIFICANCE OF CLIMATE CHANGE

5.1 CLIMATE CHANGE IN THE SOUTHCENTRAL U.S.A

It is inevitable that climate change will alter tree growth in the Southcentral, U.S.A, though it is difficult to determine what future condition will affect stand production the most. Multiple climate change scenarios predict higher runoff with more severe precipitation, higher evapotranspiration, and lower near-surface soil moisture coincident with more extreme temperatures (Collins *et al.*, 2013). Expected changes likely will be more significant where loblolly encounters temperature and precipitation limitations along its western distribution in Oklahoma and Texas.

Increased variation in precipitation is predicted for the southern U.S., caused by increasing atmospheric CO_2 and global temperatures, resulting in more extreme rain events and drought severity (Li *et al.*, 2011). Namely, the number of days exceeding 100°F is projected to increase from 20 up to 70 by 2070 in parts of Oklahoma, over a two-fold increase (Kloesel *et al.*, 2018). Overall precipitation is predicted to increase in the southcentral U.S. Wetter winters and drier summers are predicted for the region with emphasis on fewer soaking rain events during the growing season (Easterling *et al.*, 2018). Increased drought severity is expected by the end-of-century as well, with conditions not seen within the past millennia (Cook *et al.*, 2015); though Dust Bowl era extreme temperatures and drought duration remain the benchmark for historical records, global change induced soil moisture deficits are expected to increase throughout the century, due to greater evapotranspiration and vapor pressure deficit (VPD) (Breshears *et al.*, 2013; Wehner *et al.*, 2017; Easterling *et al.*, 2018).

The severity of disturbances such as hurricanes, fire, and pathogens are predicted to increase as well, impacting forest productivity (Stanturf *et al.*, 2007; Wear and Greis, 2013) . Overall, loblolly pine production will be most affected due to mortality. High winds from hurricanes can uproot and break stems, resulting in downed biomass, and in-turn, the threat of wildfires increase as dead fuels accumulate (Susaeta *et al.*, 2014). On top of increased tree mortality and fire risk, the chance and severity of pest outbreaks will increase as well, since stand vigor decreases after disturbance events occur (Stanturf *et al.*, 2007).

5.2 CLIMATE CHANGE INTERACTIONS WITH LOBLOLLY PINE

5.2.1 REDUCED WATER AVAILABILITY

Along loblolly pine's western edge, it is expected for consecutive dry days to increase and heavy downpours to increase in intensity throughout the current century (Shafer *et al.*, 2014). Additionally, a thirty-percent reduction in growing season precipitation, June to November, has been predicted for the Southern Plains thru 2035 (Kirtman *et al.*, 2014). As such, loblolly pine stands in southeastern Oklahoma will face increased water stress with increased temperatures and drought, leading to decreases in stem production (Maggard *et al.*, 2016, 2017). Such conditions will negatively affect tree growth. For example, net canopy assimilation ($Mg\ C \cdot ha^{-1} \cdot y^{-1}$) is positively correlated to growing season precipitation in simulations. Atlantic and Gulf Coast areas with growing season precipitation ~600 mm (Schultz, 1997) have high productivity, while areas inland (eastern Texas and southeastern Oklahoma) that average 300-350 mm from June to September (Schultz, 1997) have lower productivity (Sampson and Allen, 1999).

Winter months in the Southcentral U.S. are expected to become slightly wetter (Collins *et al.*, 2013). Despite higher overall precipitation, higher annual mean temperature (Collins *et al.*, 2013) may have a larger effect on loblolly plantations; higher temperatures will negatively affect trees by increasing vapor pressure deficit (VPD). Vapor pressure deficit increases both soil evaporation and plant transpiration, leading to lower photosynthetic rates and ultimately reduced net primary production (NPP; $MgC \cdot ha^{-1} \cdot yr^{-1}$) (Breshears *et al.*, 2013).

Irrigation studies have shown both positive (e.g. Allen *et al.*, 2005) and no effect (e.g. Samuelson *et al.*, 2004) on loblolly pine stand growth, leading to questions about the efficacy of irrigation as a viable management tool and the importance of supplemental water on productivity. Negative implications from drought are of more interest, since amplified future drought conditions are highly probable. Chapter III looks to further understanding of loblolly pine's interactions with drought.

5.2.2 DROUGHT, FERTILIZATION, AND THINNING INTERACTIONS

Fertilization and thinning are staples of loblolly pine plantation silviculture to increase productivity and yield. In regards to drought, there might be an important interaction. If fertilization increases LAI and increases stand evapotranspiration, thinning can offer solutions to alleviate moderate LAI and water-stress.

Maggard et al., (2016, 2017) reported that fertilization did not increase leaf-level or stand-level water use. Rather, it increased water use efficiency (stem production/water use). Water use efficiency increased in fertilized loblolly pine stands (Maggard *et al.*, 2017), driven by greater stomatal control, when compared to stands receiving no additional nutrients (Maggard *et al.*, 2016). With fertilization, trees subsequently reduced stomatal conductance and achieved a less negative mid-day leaf water potential (Maggard *et al.*, 2016). Increased nitrogen and phosphorus availability allows water-limited trees to maintain photosynthetic rates, aided by larger immediate carbon pools being available.

Whereas nitrogen limitation can lead to greater amounts of carbon being stored for subsequent use (Green *et al.*, 1994).

Thinning increases stand water availability to residual trees by decreasing stand evapotranspiration (Teskey *et al.*, 1987), increasing precipitation throughfall (Stogsdill Jr *et al.*, 1989, 1992), and enhancing stand resistance and resilience to drought conditions (McDowell *et al.*, 2006; D'Amato *et al.*, 2013). These benefits are significant to loblolly pine plantations since fast growing species have been found to have greater sensitivity to drought (McDowell *et al.*, 2006).

5.2.3 DROUGHT AND NEEDLE FALL

Trees in Oklahoma have demonstrated earlier peak needlefall with drought (Hennessey *et al.*, 1992). Decreased leaf lifespan allows trees to maintain a positive carbon budget during unfavorable conditions. (Chabot and Hicks, 1982). This is beneficial when the carbon cost of foliage maintenance in is greater than potential carbon gain from foliage (Chabot and Hicks, 1982). For example, premature needlefall can help loblolly pine avoid consequences of high vapor pressure deficit when moisture is limiting (Breshears *et al.*, 2013). Drought and fertilization have been shown to change needlefall patterns and loblolly pine has plasticity in leaf variation that leads to “fine tuning of leaf distributions along environments” (Schoettle and Fahey, 1994), aiding its ability to maintain consistently high stem production.

Drought negatively effects loblolly pine needle longevity, but fertilization has been shown to both increase (Schoettle and Fahey, 1994) and decrease (Vose and Allen, 1991) leaf longevity in pines. Increased foliage longevity is supported by the retention of nutrients in older leaves and increased net photosynthesis (Schoettle and Fahey, 1994). Alternatively, decreased foliage longevity have been attributed to increased foliage production and shading of older leaves, leading to negative carbon balances in older foliage and abscission (Balster and Marshall, 2000).

Stand density does not directly affect needle retention (Dougherty *et al.*, 1995). Indirect benefits from greater resource availability, like increased throughfall, aid loblolly pine stands during drought (Stogsdill Jr *et al.*, 1989). Hennessey *et al.* (1992) showed premature abscission when precipitation was less than 500 mm from May-October in southeastern Oklahoma. No evidence exists to support increased needle retention with thinning during drought.

5.2.4 DROUGHT STRATEGY

In forested areas, analysis of disturbance interactions have focused on drought and growth dynamics, and how thinning can mitigate adverse effects (e.g. Sohn *et al.*, 2016). Understanding how forest stands react to drought is key for management decisions. More informed decisions can be made by landowners to accommodate drought strategies specific to certain species. Ecosystem disturbance response is largely classified into three categories: resistance, resilience, and recovery. *Resistance* in forested ecosystems can be characterized by the ability to avoid reductions in growth during drought and can be understood as the ratio of during-drought to pre-drought growth (Kaufman, 1982; Lloret *et al.*, 2011). *Resilience* is the ability to reach pre-drought growth performance after the disturbance or the ‘speed of recovery’ and is the ratio of post-drought to pre-drought growth (Tilman and Downing, 1994; Lloret *et al.*, 2011). *Recovery* is the ability to recuperate growth lost during drought and is the ratio of post-drought to during-drought growth (Lloret *et al.*, 2011; Sohn *et al.*, 2016).

Drought response in terms of resiliency, resistance, and recovery has yet to be formally quantified in loblolly pine stands. Many studies have determined drought's impact on loblolly pine stand-level characteristics such as NPP (e.g. Bracho *et al.*, 2018), photosynthesis and water-use (Maggard *et al.*, 2016), and intercepted photosynthetically active radiation (IPAR) (Samuelson *et al.*, 2014), but not on drought strategy.

In understanding loblolly pine's response to drought, it is critical to determine whether the tree is sourced from eastern or western states. Western-source loblolly pine stands have demonstrated drought resilience; historically, western seed sources have been selected for greater drought resistance, or the ability for continued growth during drought, compared to eastern sources (Bongarten and Teskey, 1986). Western trees growing under xeric conditions have been shown to decrease stomatal conductance and transpiration loss under drought conditions, a physiological trait characterized as an avoidance and resilience strategy (Bilan *et al.*, 1977; Teskey *et al.*, 1987). Compared to eastern seed sources from more mesic conditions that have higher growth rates, western seed sources under xeric conditions have lower photosynthetic rates (Teskey *et al.*, 1987), where sustained and repeated drought conditions further decreases net photosynthesis and leaf conductance (Bongarten and Teskey, 1986; Maggard *et al.*, 2016).

This trend gives way to eastern seed sources having greater height and volume gains over a rotation age (Will *et al.*, 2010), leading to most western commercial plantations using eastern seed sources. Despite the logic that trees from xeric sites will outperform trees from mesic sites under moisture limitation due to greater drought adaption (e.g. Eilmann *et al.*, 2013), conditions need to be excessively dry in order to observe resilience strategy out performing resistance strategy (Teskey *et al.*, 1987). In a future climate with repeated moisture stress during the growing season, trees from xeric locations can be expected to have greater tolerance to severe conditions.

6. ECONOMIC CONTEXT AND FORESTRY OPTIMIZATION

6.1 FINANCIAL IMPACT

U.S. loblolly pine timber production has been expected to increase with climate change due to higher atmospheric CO_2 concentrations, which are expected to increase net photosynthesis (Murthy *et al.*, 1996; Gonzalez-Benecke *et al.*, 2017). Production will likely increase the most in areas with low site index, and greater growth can be expected in cooler areas from modeled increases in air temperature and CO_2 concentrations (Gonzalez-Benecke *et al.*, 2017). Despite an increase in production, predictions have shown both positive and negative implications on the timber market. Kirilenko and Sedjo (2007) found that U.S. timber production would increase by 2045, and that increased timber supply would lead to lower log prices and increased consumption. In this scenario, consumers would benefit from lower prices while producers may ultimately lose out. Alternatively, Perez-Garcia *et al.* (2002) stated that increased harvests in the southern U.S. would lead to increased mill production, allowing a higher demand to be met. As a result, sawmills create higher demand for large harvests (due to low prices) and proportionally large consumer gain from increased production will end in overall economic gain for the region (Perez-Garcia *et al.*, 2002).

Contrary to ambiguous financial predictions, amplified environmental disturbances with greater occurrence (Stanturf *et al.*, 2007) will have a negative impact on loblolly pine production. For example, in 2005 Hurricane Katrina damaged 2 million hectares (ha) of timberland in Mississippi, Louisiana, and Alabama (Stanturf *et al.*, 2007). More recently, Hurricane Michael severely impacted Florida and southern Georgia timberland in 2018. An estimated 958 thousand ha of timberland were damaged, with an extensive loss of $466 million to southern pine timber (McClure *et al.*, 2018). Annual damages from hurricanes are expected to increase by 8% of total US gross domestic product and if no adaption is implemented, hurricanes may cost the U.S. $19 billion per year (Nordhaus, 2010).

Determining if future changes in the timber market or increased natural disturbances will have a larger effect on Southeastern U.S. timber economics is difficult; it is also difficult to predict the future price of loblolly pine sawlogs and pulpwood for the mid-21st-century. However, future long-term market dynamics do not dictate current management regimes. Potential market dynamics do not have any effect on present day outcomes and it would be irrational to base timber management on what *could* happen. Rather, it would be shrewd to focus timber management on mitigating climate change implications.

6.2 FOREST OPTIMIZATION METHODS

Linear programming is a mathematical tool used in forestry to take into account management constraints, prevent natural resource use beyond certain thresholds, and lead to an objective optimization (Bettinger *et al.*, 2016). Forest-level optimization typically involves selecting the best timing and placement of management activities to maximize or minimize an objectives such as NPV, harvest volume, or other forest commodities (Borges *et al.*, 2013; Başkent *et al.*, 2014; Kaya *et al.*, 2016).

Data envelopment analysis (DEA) is a nonparametric method based on linear programming that measures the relative efficiency of similar units, typically known as decision making units (DMU's) (Marinescu *et al.*, 2005). First introduced by Charnes *et al.* (1978), DEA involves each DMU having the same inputs and outputs, determining on what DMU is the most efficient and the least inefficient based on a relative efficiency score. Used as an optimization technique, DEA creates a composite production possibility frontier to compare each DMU, where each efficiency represents the distance to the frontier: scores of 1 are efficient and scores less than 1 are inefficient (e.g. Marinescu *et al.*, 2005). DMU's that lie on the frontier are considered efficient and those do not are inefficient.

A major strength of DEA is that it does not require any specific statistical distributions or mathematical production function (Viitala and Hänninen, 1998; Susaeta *et al.*, 2016). Additionally, DEA can be easily used to minimize an input (e.g., cost) with respect to multiple outputs (e.g. timber production, carbon sequestration) (Marinescu *et al.*, 2005). Major limitations to DEA stem from the relativeness of the efficiency scores, values are only comparable to peer DMU's within the analysis but not comparable to a theoretical maximum-results are not comparable across studies (e.g. Viitala and Hänninen, 1998). Since DEA is a non-parametric approach sensitivity to error is a common critique, where measurement error and sample size can strongly effect efficiency scores (Avkiran, 2013; Susaeta *et al.*, 2016).

6.3 DEA IN FORESTRY

DEA has been used globally to optimize the forestry sector. Often, it has been used to assess big-picture operational activities and harvest logistics relative to industrial management, but not small-scale silvicultural techniques. For instance, Viitala and Hänninen (1998) analyzed the efficiency of public forestry organizations in Finland across 19-state programs and determined organizational efficiency based on factors like road construction and forest planning. Likewise, Marinescu *et al.* (2005) examined different forest product companies in Canada to determine the most effective allocation of forest stands in regards to lumber production, timber transportation, and stumpage cost. Also, Salehirad and Sowlati (2005) examined regional differences in efficiencies within British Columbia, Canada with common forestry variables like labor, log consumption, timber production, and timber class.

DEA has been applied to improve certain large-scale criteria within the forestry sector. However, landscape management is primarily only important to stakeholders, i.e., corporations, that are involved in large operations or if there is prerogative to comprehensively analyze timber management. Using DEA to optimize silvicultural techniques within a rotation age remains limited. Accordingly, Chapter IV is aimed to fill the knowledge gap.

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CHAPTER III

LONG-TERM GROWTH EFFECTS OF SIMULATED-DROUGHT WITH MID-ROTATION FERTILIZATION AND THINNING ON A LOBLOLLY PINE PLANTATION IN SOUTHEAST OKLAHOMA, USA

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ABSTRACT

Loblolly pine (*Pinus taeda* L.) is the most productive commercial softwood species in the continental USA. Plantation silviculture will face novel productivity challenges due to climate change-induced drought. We examined the effects of 30% throughfall reduction (drought), fertilization, and thinning on a loblolly pine plantation in southeastern Oklahoma, USA to understand how nutrient availability and stand density interact with drier conditions to affect productivity and canopy dynamics. Our treatments were applied at mid-rotation: throughfall reduction age 5 to 12, fertilizer age 5 and 10, and thinning age 10. During dry periods, drought treatment decreased tree height by 18%, after fertilizer application, tree diameter increased by 9%, and after thinning increased tree diameter by 5%. This resulted in fertilization (+8% standing volume) and simulated-drought (-7% standing volume) counter balancing each other at age 12. Positive fertilization effects were supported by increased foliar nitrogen (N) and phosphorus (P) following fertilization, along with increased leaf area index (LAI; +14%) in fertilized plots and intercepted radiation (+5%) in fertilized-thinned plots at age 12. Drought-induced plots demonstrated 11% greater growth efficiency at age 12. Trees under drought treatment had 10% greater basal area growth during wet growing seasons, suggesting droughted trees may exhibit compensatory (recovery) growth after meteorological drought subsides. We show that management and possible post-drought recovery indicates continued plantation viability even with more numerous future droughts.

Keywords: loblolly pine, drought, fertilization, thinning

1. INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is the most prevalent and commercially important evergreen species in the southeastern USA. Within the region it is the largest single-species biomass contributor, composing 20% 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). In addition to its wide-scale planting, its role in regional biomass production is due to rapid growth attributed to extraordinary juvenile volume production, which is aided by intensive plantation silviculture (Fox *et al.*, 2007a). However, loblolly pine timber productivity may be challenged by climate change-induced drought (Vose *et al.*, 2018).

Within the South, 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). Conditions like higher temperatures and subsequently higher vapor pressure deficits (VPD) are predicted consequences 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). Drought causes adverse effects for timber-producing forests (Easterling *et al.*, 2018; Vose *et al.*, 2018). Proximate problems include, increased mortality (e.g. Vose *et al.*, 2018), reduced stand-level growth (e.g. Maggard *et al.*, 2017), altered biomass partitioning (Green *et al.*, 1994), and decreased 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 large part by increased foliar nutrients, leaf area index (LAI), intercepted photosynthetically active radiation (IPAR), and growth efficiency (GE) (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). In contrast, fertilization at mid rotation is a common treatment with between 200,000 to 400,000 ha of southern timberlands annually fertilized (Albaugh *et al.*, 2019).

While thinning reduces overall stand growth, it increases growth of residual trees and economic returns. Mid-rotation 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 resistance and resilience to drought. Thinning increases precipitation throughfall (Stogsdill Jr *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 has proven useful under drought conditions. 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 looming, there is incentive to examine what effects soil moisture limitation will have on plantation growth. Reduced soil moisture, fertilization, and thinning effects appear to be dependent on site-specific moisture availability. In mesic locations like Georgia and Virginia, USA, variation in soil moisture availability had variable effects on net photosynthesis, volume production, LAI, and IPAR (Samuelson *et al.*, 2014; Ward *et al.*, 2015). In contrast, stands in Oklahoma, where it is drier, showed reductions in net photosynthesis, volume production, and LAI under simulated drought (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). In contrast, 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 that depend on region and water status.

To address the interaction between nutrient availability, reduced water availability, and stand density, we quantified eight-years of fertilization, drought, and thinning treatments on growth and canopy dynamics 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 Tier III site installed as part of Pine Integrated Network: Education, Mitigation, and Adaption Project (PINEMAP). 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 study thus far has examined the three-way interaction between fertilization, thinning, and throughfall reduction. To the best of our knowledge the study presents the longest soil moisture reduction experiment for loblolly pine, and perhaps North American forestry research, though 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, LAI, GE, and IPAR; 2) mid-rotation (year 5, 10) fertilization would help compensate for drought conditions and increase stem volume production, LAI, GE, and IPAR such that fertilization combined with throughfall reduction would be similar to stands receiving ambient precipitation; 3) without thinning, fertilization will have little effect in a ten-year-old stand 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. The Tier III study included four sites spanning loblolly pine’s commercial range, Virginia, Georgia, Florida, and Oklahoma. The objectives of Tier III were to understand the effects of drought and fertilization on carbon dynamics. For the Oklahoma site, we report 8 years of stand-level data collected from stand age 5 to 12, corresponding to the 2012 to 2019 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.

Specific site characteristics and climate averages can be found in Will *et al.* (2015). Thirty-year averages from Broken Bow, OK are 1,300 mm for annual precipitation and 16.6ºC 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 temperatures, 34.2 ºC (Mesonet, 2020), which is higher than most locations within the loblolly pine commercial range (Will *et al.*, 2015). Soils on site were the Ruston series that have well-drained fine, sandy loam surface texture and clay loam subsoil texture (Fine-loamy, siliceous, semiactive, thermic Typic Paleudults) consisting of 3 to 8% slopes (http://soilseries.sc.egov.usda.gov, accessed August 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 then subsoiled down to 51 to 61 cm with subsoiling shanks 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 a 2 x 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 x 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. A 30% reduction in growing season precipitation mimics the driest climate change predictions for the south-central USA (Easterling *et al.*, 2018). 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 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, doubling plot total to thirty-two. 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 basal area by approximately 40%. Harvesting the trees among the throughfall excluders was impossible. 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 growing season is transitional between a before and after thinning state. Re-fertilization of nitrogen and phosphorous was applied at 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) (https://www.mesonet.org/index.php/weather/daily_data_retrieval, accessed

April 11, 2020). Daily total rainfall, average temperature, average maximum temperature, and average 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 different temporal variations in moisture availability. For our purposes, monthly SPEI values were calculated based on the preceding 12-month period to account for water available to 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 (https://cran.r-project.org/web/packages/SPEI/index.html).

2.4 SOIL MOISTURE

Volumetric soil water content was recorded at 4 to 6 week intervals throughout 2019. 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 plot (n=32) for a total for 128 samples for each measurement period. The location for each sample was randomly chosen within the specified plot.

2.5 FOLIAR NUTRIENTS

Foliar nitrogen (N) and phosphorous (P) 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. From 2012 to 2017, the thinning treatment was not tested. During this time period, 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 plots. Three subsamples were taken from each plot and combined. Samples were dried at 60º for at least 48 hours. 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 in spring 2012 and ending in December 2019. This accounts for eight-years of growing season data. 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 12 years (2015 to 2019), 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 growth was measured as the difference between the current growing season volume and the previous growing season volume. Experiment-wide mortality totaled 41 trees (out of 1,007) from 2012 to 2019, averaging 1.28 trees plot^{-1}. To find gross stand volume growth, trees that were removed during thinning or died were included in calculations, i.e., volume at time of death was kept constant and not subtracted from the total.

2.7 LEAF AREA INDEX, GROWTH EFFICIENCY, AND FIPAR

Leaf area index (LAI) was measured using the LAI-2200C plant canopy analyzer (LiCor, Inc., Lincoln, NE, USA). During the 2019 growing season, LAI was measured 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 90º viewing cap was placed on the light senor, 180º away from the user, its purpose being to limit edge effects. During the 2019 growing season, samples were taken at the four corners located within each measurement plot, 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 from plots in an open field to record above-canopy light conditions.

Loblolly pine in the southeastern USA keep foliage for 1.5 years, and foliage on trees during the growing season represents both the previous year's foliage and the developing current year's foliage (Will *et al.*, 2002). The previous year's foliage typically begins to abscise in early August to late September, therefore peak LAI also occurs during this time period. Annual LAI values presented in this paper are mean growing season values, not maximum values, and offer a more conservative estimate of growing season LAI.

Growth efficiency (GE) was calculated by the following relationship: annual stem volume production (m^3 ha^{-1} yr^{-1}) / average annual LAI. For example, stem volume production in growing season 2019 was divided by foliage on trees during the 2019 growing season. This relationship shows the combined effect of cohorts on the tree during stem growth.

Growing season photosynthetically active radiation above (PAR_{above}) and below (PAR_{below}) the canopy were measured via hemispherical photographs under diffuse light conditions concurrent with LAI measurements, except the first measurement was June 2019. To limit edge effects, the center of each plot was sampled by one photograph per plot, with a digital camera (Model E8400, Nikon, Tokyo Japan) and a fisheye lens. Each photo was taken approximately 1.78 m above the ground. Photos were analyzed with the Gap Light Analyzer (GLA) 2.0 software (Frazer *et al.*, 1999) to calculate to PAR_{below}, the total amount of diffuse and direct PAR transmitted through the canopy to the understory. PAR_{above} was calculated by GLA, dependent on latitude and longitude, daily total radiation, and spectral fraction. Daily radiation was taken from observed measurements at the local weather station (see *Weather Data*) and spectral fraction was the amount of total radiation received as direct and diffuse PAR (ranging from 0.44 to 0.46). Spectral fraction was multiplied by daily total radiation to obtain PAR_{above}. Fraction of intercepted photosynthetically active radiation, fIPAR, was defined by the following and represents the hypothetical maximum portion of PAR intercepted by the forest canopy:

$$fIPAR = (PAR_{above} - PAR_{below}) / PAR_{above} \tag{1}$$

2.8 DROUGHT INTENSITY AND GROWTH

Drought effects were determined for basal area (BA) to determine the long-term effects of throughfall reduction. The relative effects of drought on BA growth were calculated by dividing growth of drought-treated plots (D plots) (n=8) by control growth

(C plots) (n=8) for pre-thin. To eliminate confounding competition effects, thinned and non-thinned comparisons were examined and analyzed separately from 2017-2019. Linear regression was used to determine the correlation between annual SPEI and the effects of drought on relative BA growth. Furthermore, the resiliency of non-thinned drought plots to natural drought in 2017,was examined and calculated per the following (e.g. Sohn *et al.*, 2016):

$$RESIL_{BA} = \frac{POST_{REL.\ BA\,GROW}}{PRE_{REL.\ BA\,GROW}} \tag{2}$$

Post-thinning growth, $POST_{REL.\ BA\,GROW}$, was calculated as average relative basal growth in 2018 and 2019. Pre-thinning, $PRE_{REL.\ BA\,GROW}$, was average relative basal area growth in 2015 and 2016. To make values relative, non-thinned treatments (D, F, FD) were divided by the average C response. Because thinning occurred mid drought, thinned plots could not be included in the analysis.

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. Analysis was divided between pre-thinning (2012 to 2016) and post-thinning (2017-2019). 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, 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. Data were analyzed with repeated measures to determine time (year) effect and associated interactions. As such, for each dependent variable examined an exclusive covariance structure was identified using Akaike information criterion (AIC), AICc, CAIC, and Bayesian information criterion (BIC). 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

Over the course of the experiment, weather conditions 2011-2013 were hot and dry. From 2014-onward, conditions generally became wetter and milder (Figure 1a). Average monthly maximum temperature (T_{max}) and total precipitation (2011 to 2020) were similar to historic growing season averages (Mesonet, 2020), and indicated moderate to severe growing season drought from 2011 to 2013 (Figure 1b). Within growing seasons, March to October, April had lowest average maximum temperatures (23.3ºC) and August the highest average (33.7ºC). The 2011 (year before the initiation of the experiment) and 2012 growing seasons had the least rainfall. Drought conditions (SPEI) were driven by both high temperatures and low rainfall (Figure 1b). July and August 2011 recorded the two highest average T_{max}, 38.6ºC and 39.3ºC, respectfully, and July 2012 was close at 35.7ºC (Figure 1b). Late-2011 growing season (Aug., Sept.) had the lowest SPEI values (-1.9) due to low precipitation and high T_{max}. Alternatively, early 2012 and 2013 growing seasons showed low SPEI, approximately -1.5, due to low precipitation (Figure 1b). The lowest growing season average T_{max}, 28.5ºC, was in 2014.

2015 was by-far the wettest year, 2177 mm. Likewise, wetter growing conditions occurred in 2015 and 2016 (>1.5 SPEI) followed by a mild drought (~ -0.5 SPEI) in 2017. From 2018 to 2019, conditions were favorable and rainfall was above (Figure 1a) the historic 1300 mm average (Mesonet, 2020) and showed a wide range in SPEI from -0.4 to 2.5 (Figure 1b)

3.2 SOIL MOISTURE

The 2019 growing season serves as a representative estimate of soil moisture availability (0-12 cm) for an average-to-wet year (Figure 2). During the 2019 growing season, non-drought and drought plots had similar soil moisture, with one measurement period in July trending towards significance ($p=0.08$) and drought plots drier by 11% ± 6% (mean ± SE). Soil moisture was affected by drought treatment after the growing season was completed (significant drought*Julian date interaction) (Table 1). In October and December, drought plots were 16% ± 7% and 20% ± 6% drier than the ambient throughfall plots.

3.3 FOLIAR NUTRIENTS

Foliar nutrients increased after fertilizations in 2012 and 2017. Foliar P significantly increased under initial fertilization (pre-thin; 2012-2017, n=8) and there was also a significant fertilization*year interaction (Table 1). The effect of fertilization was significantly greater following the 2012, 2013, and 2016 growing seasons and again in 2017 after refertilization. 2017 was considered pre-thin since samples were not divided between non-thin and thin for that year. After re-fertilization (post-thin, 2018-2019, n=16), the main effect of fertilization was significant. (Figure 3, Table 1). Phosphorous concentrations rose steadily until 2017, then decreased slightly from 2018 to 2019. On average, fertilization increased P by 6% in pre-thin period and by 13% in post-thin period. Pre-thin, the effects of fertilization on foliar N varied by year (Figure 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). Post-thin, fertilization main effect was significant, but a significant fertilization*drought*year interaction occurred since fertilized-drought (FD, FD-T) treatments were 8% greater than fertilized (F, F-T) treatments in 2018, but both were similar in 2019. Neither drought or thinning main effects had any significant effect on foliar P or N concentrations (Table 1).

3.4 PLOT-LEVEL DENSITY, VOLUME, AND GROWTH

Thinning decreased stand density (trees per hectare, TPH) by an average of 41% (Figure 4, Table 1). During the pre-thinning, TPH decreased by 2% from 2011 (age 4) to 2016 (age 9). Drought and fertilization did not affect stand density (Table 1).

DBH growth exhibited significant treatment*year interactions (Table 1). DBH was most affected by fertilization and thinning, and less frequently by drought (Figure 5). During the pre-thin period, fertilization increased DBH growth in 2012 and 2014 on average by 9% per year (0.25 cm). Drought only decreased DBH growth in 2013, a reduction of 11% (0.31 cm) (Figure 6). Post-thin, fertilization, thinning, and year main effects were all significant. Fertilization increased DBH growth by 10% (0.11 cm). Thinning increased DBH growth in 2017 and 2019, on average by 43% (0.50 cm), but not in 2018 (thinning*year interaction). The increase in average DBH of the thinned stands in

2017 was in part an artefact due to removal of smaller trees during thinning. In the thinned subplots, the average DBH of killed trees was 15.91 cm and the average DBH of residual trees was 16.19 cm. The difference in 2019 reflects true differences in DBH growth. The net effect was that after eight years of treatment (stand age 12), DBH was 3% greater with fertilization ($p = 0.012$), 2% smaller with drought ($p = 0.07$), and 5% greater with thinning ($p = 0.0002$).

Height growth was affected by drought treatment but the response varied on an annual basis (Figure 7). During the pre-thin period, drought, year, and drought*year effects were all significant (Table 1); drought decreased height growth by an average of 18% (0.22 m) within each of the 2013, 2014, and 2016 growing seasons. During the post-thin period, drought, year, and drought*year effects were all significant, whereby the drought treatment produced a positive effect, and increased height growth in 2019 by 14% (0.13 m). Fertilization, thinning, nor any higher order interaction affected height growth (Table 1). The net result was that by stand year twelve, only drought produced a discernable effect on height ($p=0.08$), a decrease of 3% (0.31 m).

Drought and fertilization affected standing volume pre-thinning and post-thinning. At stand age 9 (end of pre-thin) in 2016, drought decreased standing volume by 10% ($p<0.0001$; -13.52 m^3 ha^{-1}) and fertilization increased standing volume by 4% ($p=0.06$ 5.08 m^3 ha^{-1}) (Figure 7, Table 1). When analyzed again in 2019 (stand age 12), drought and fertilization effects were similar in magnitude, drought decreased standing volume by 7% ($p=0.04$; -13.95 m^3 ha^{-1}) and fertilization increased standing volume by 7% ($p=0.05$;13.21 m^3 ha^{-1}). As expected, thinning decreased standing volume measured in 2019, a 35% decrease (80.55 m^3 ha^{-1}). In 2019, the differences due to fertilization and drought for stand-level volume mirrored those for individual tree volume. The overall mean tree volume was 0.16 m^3 ha^{-1}. Drought decreased stem volume by 7% ($p=0.02$; 0.012 m^3 ha^{-1}) and fertilization increased tree volume by 7% ($p=0.03$;0.011 m^3 $tree^{-1}$). Thinning increased individual tree volume by 10% ($p=0.001$; 0.015 m^3 $tree^{-1}$).

Gross stem volume growth, calculated including mortality and removals, had a significant fertilization*drought*year interaction during the pre-thin period (Table 1). The interaction was primarily driven by F plots having greater annual gross volume growth than the other treatments and the drought treatments the lowest (Figure 8). Specifically, F > D with C and FD intermediate in 2012, F > C > D, FD in 2013 and 2014, and C > FD with F and D intermediate in 2016. For the post-thin period, fertilization, thin, year, and drought*year effects were significant. Fertilization increased gross volume by 15% (3.89 m^3 ha^{-1}) and thinning decreased by 31% (-9.99 m^3 ha^{-1}). In 2018, drought decreased gross volume growth by 16% (-3.10 m^3 ha^{-1}). The net effect was that after eight years of treatment, fertilization increased gross volume growth by 9% ($p=0.013$), drought decreased gross volume growth by 7% ($p=0.034$), and thinning decreased gross volume growth by 16% ($p<0.0001$).

3.5 CANOPY DYNAMICS

Both thinning and fertilization significantly affected LAI when measured in 2019 (Table 2). 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) (Figure 9). Drought non-significantly reduced LAI by 5% ($p=0.11$). For GE, only drought had an effect. Droughted plots had GE of 9.2 m^3 ha^{-1} LAI^{-1} which was 11% greater than for ambient precipitation plots (8.5 m^3 ha^{-1} LAI^{-1}). (Figure 9). This difference was likely due to the 5% lower LAI (denominator) more so than an increase in stem volume growth (3% difference in 2019 between drought and non-drought plots). There was a significant thinning and thinning*fertilization effect on mean fIPAR measured in 2019 (Table 2). Overall, thinning reduced fIPAR. The interaction occurred predominantly because the fertilization treatments caused a large increase in fIPAR relative to the non-fertilized treatments for the thinned plots, while there was little difference among fertilized and non-fertilized treatments for the non-thinned treatments (Figure 10).

3.6 DROUGHT INTENSITY AND GROWTH

The relative basal area growth in response to drought was linearly correlated with growing season SPEI and had a significant non-zero slope, m=14.5 per change in SPEI (Figure 11). During periods of drought, SPEI < 0, drought (D) plots had greater reduction in growth than control (C) plots. As growing conditions became more favorable, SPEI > 0, drought basal area growth was greater than the respective control basal area growth. Thus, drought-only treatment showed greater basal area growth post-drought than during-drought (i.e., recovery growth), irrespective of stand density (Figure 11).

$RESIL_{BA}$ was analyzed by differences of least squares means, D, F, and FD, pairwise comparisons to C, or 1. Fertilization had a positive effect on $RESIL_{BA}$ (1.12; $p=0.029$). The D and FD treatments were not significantly different than C ($p>0.31$;Figure 11). Still, D decreased $RESIL_{BA}$, 0.94, in response to the meteorological drought the site experienced in 2017.

4. DISCUSSION

Under a drier climate scenario, eight years of sustained ~30% reduction in throughfall decreased stem volume production by approximately 7%. Fertilization counteracted the decrease in drought-induced stem production by increasing growth. While thinning did not significantly interact with either fertilization or drought treatments, the thinned plots that were fertilized had greater fIPAR which may indicate greater future growth in fertilized-thinned stands relative to other treatments. Drought effects are likely tied to region-specific soil moisture. 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), stem increment (Will *et al.*, 2015), and volume growth (Ward *et al.*, 2015). However, 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), stem increment (Will *et al.*, 2015), and volume growth (Maggard *et al.*, 2017). 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).

Our first hypothesis, that drought would negatively affect productivity, was supported as throughfall reduction decreased height growth, diameter growth, and volume growth. However, the effects were greater in dry years and negligible in wet years. In fact, there was some evidence of compensatory basal area growth in the drought treatments during years with above average rainfall. Soil moisture limitation has previously been shown to reduce diameter (Cregg *et al.*, 1988; Maggard *et al.*, 2016), height (Samuelson *et al.*, 2018), and volume growth (Maggard *et al.*, 2017; Samuelson *et al.*, 2018) in loblolly pine stands in Oklahoma and Georgia. Drought significantly decreased height growth more frequently (2013, 2014, 2016) than DBH growth (2013), perhaps indicating stem elongation to be secondary when water is limiting (Samuelson *et al.*, 2018). For loblolly pine, the majority of height growth occurs earlier during the growing season than diameter growth and height growth acts as a larger carbon sink (Dougherty *et al.*, 1994). Under drought conditions, diameter growth may be favored over height growth since it is a smaller carbon sink (Cregg *et al.*, 1993). Annual height growth also stops with the transition from earlywood to latewood (Jayawickrama *et al.*, 1997). During dry growing seasons in southeastern Oklahoma, latewood transition can occur in late-June, causing height growth to stop while diameter growth continues through late October (Cregg *et al.*, 1988). Usually, tree growth is more sensitive to drought than photosynthesis (Körner, 2003; McDowell, 2011). Previous research on these stands did not find a decrease in leaf-level photosynthesis with the drought treatments (Maggard *et al.*, 2016).

During the 2019 growing season, a year characterized by wet conditions, 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 stem growth were not significant for 2019 as rainfall was likely great enough to saturate the soil even with the 30% reduction treatment. As reported in Maggard *et al.* (2016, 2017), reduced soil moisture conditions due to drought treatment were more numerous during dry years than wet years (age six and seven), with similar results at the Georgia companion site (age seven) (Samuelson *et al.*, 2014). Tree rooting can influence soil moisture. Little separation in soil moisture between drought treatments could be attributed to drought decreasing soil moisture deeper than 12 cm (Domec *et al.*, 2010; Phillips *et al.*, 2016), as shallow soil can resaturate after large rainfall events. For example, soil matric potential from 0-90 cm was reduced by drought treatment previously at our site (Bracho *et al.*, 2018). Deep soil water availability, 90-300 cm, can buffer against dry conditions (Qi *et al.*, 2018). At drought-induced sites in Georgia, soil 90 cm and deeper accounted for the majority of plant available water, but on ambient precipitation plots, deep soil often accounted for less uptake of available water (18% to 86%) (Qi *et al.*, 2019).

Fertilization increased standing volume by 8% and volume growth by 9% and this was mainly due to increased DBH growth as there was little effect on height growth. Our fertilization results mirrored 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). As noted by Maggard *et al.* (2017) effects could be linked to site drainage, as poorly-drained sites show greater height growth response to fertilization (Amateis *et al.*, 2000), though this remains uncertain as fertilization increased 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). Discrepancies indicate that fertilization effects on height may be less tied to site drainage and more related to nutrient status, and that nutrient poor sites, especially P, show greater height growth response to fertilization (Allen *et al.*, 1990)

Both foliar N and P increased after fertilization (2012, 2017) and signified potential stand demand for nutrients was 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. While foliar N concentration demonstrated greater flux than P (Figure 3), both N and P concentrations were above critical concentration thresholds of 12.0 mg N g^{-1} and 1.0 mg P g^{-1} (Wells and Allen, 1985). Greater N-depletion can be explained by N being less soil stable than P. Plantations cannot capture all applied N as it rapidly mobilizes and leeches as NO_3^- (Vitousek and Matson, 1985; Vitousek *et al.*, 1992) or volatilizes as NH_3 (Kiser and Fox, 2012; Raymond *et al.*, 2016). In contrast, well-drained upland sites like ours have greater P-supply due to greater retention than poorly drained coastal sites (Pritchett and Comerford, 1982; Fox *et al.*, 2011), a relationship governed by soil properties like clay-content and soil chemistry (Kiser and Fox, 2012).

We hypothesized that benefits of fertilization at mid-rotation would be greater in thinned than non-thinned stands. We did not find any interactions between thinning and fertilization or thinning and drought treatment to support this hypothesis. However, we did find a thinning*fertilization interaction for fIPAR which may indicate greater relative growth in the fertilized-thinned plots during the next several growing seasons. Thinning reduced gross volume growth even though thinning increased DBH because there were approximately 40% fewer trees contributing to stand-level growth. Overall, fertilization and thinning are both beneficial for diameter growth (e.g. Will *et al.*, 2002; Albaugh *et al.*, 2004; Sayer *et al.*, 2004). Thinning did not affect height growth which was expected (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, thinning and drought interactions are positive (Sohn *et al.*, 2016) whereby thinned stands are more resistant and resilient to drought. Perhaps we would have found an interaction if 2018 and 2019 had been drier years. Thinning increases growth of residual trees and allows for a greater proportion to attain sawtimber status (Amateis and Burkhart, 2005) and remain defect free (Green *et al.*, 2018). Additionally, positive thinning growth effects can be limited to 20 years (Elkin *et al.*, 2015), dependent on stand structure (i.e., large trees) (D'Amato *et al.*, 2013), or restricted by thinning intensity (Bose *et al.*, 2018)..

Under simulated drought, fertilization compensated for drier conditions, in that FD and FD-T were respectively similar to C and C-T treatments when evaluating volume production. Drought (-7% net volume) and fertilization (+8% net volume) were additive effects that counter acted one-another. This was shown in 2017 under mild drought, as fertilization increased basal area growth resiliency and resulted in FD being similar to C plots. Fertilization and drought effects are dependent on physiographic region and moisture regime. Fertilization (+25%) heavily negated drought (-9%) in terms of production in a Georgia stand over the course of five-years during dry and wet periods (Samuelson *et al.*, 2018). However, in more mesic Virginia stands, fertilization increased production and drought treatment had no effect on production, for instance F, FD > C, D (Ward *et al.*, 2015).

The effect of drought treatment on growth was stronger in dry than wet years and it appeared that drought plots showed resiliency during wetter years by exhibiting increased basal area growth in years with above average precipitation. Reasons for this recovery to the stress imposed by the drought treatment upon return of wetter conditions could be due to greater post-drought gas exchange during recovery 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), hypothetically allowing for remobilization and greater aboveground growth when favorable conditions return. 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, such as drought-tolerant black poplar (*Populus nigra* L.), as well (Regier *et al.*, 2009). Managed forests with high nutrient availability also need to invest less belowground carbon to root symbionts to acquire nutrients (Vicca *et al.*, 2012). With less belowground carbon demand, trees in drought-induced plots likely invest more carbon in stem production after drought using stored carbohydrates.

As climate change drought, i.e., drought conditions experienced with higher temperatures, becomes more common, fertilization may not compensate for drought conditions. For now, the fertilization and drought effects were additive, but could become complicated by rising atmospheric CO_2. Both severe drought and fertilization can decrease non-structural carbohydrate storage in roots and decrease carbon for future growth, but drought effects may be dependent on severity (Li *et al.*, 2018). Trends show that severe drought depletes belowground storage (carbon starvation) but moderate drought (carbon limitation, similar to our study), may show no change or increase storage by 10% (Li *et al.*, 2018). On the other hand, greater atmospheric CO_2 resulting in greater carbon gain can encourage belowground carbon storage and maybe lessen carbon limitation under climate change (Li *et al.*, 2018).

Other long-term drought studies focused on rainforest ecosystem respiration in Brazil (da Costa *et al.*, 2014) and forest fecundity in Spain (Bogdziewicz *et al.*, 2020). We focused on aboveground production due to loblolly pine's commercial status within the southeastern USA. Response to drought scenarios may be species-specific. Loblolly pine is typically planted in more mesic locations and has an indeterminate growth pattern, aiding 'catch-up' growth and increased GE under favorable periods. Whereas slower-growing southern pine from more xeric environments, like longleaf pine (*Pinus palustris* Mill.), have shown no recovery growth and lower GE post-drought (Samuelson *et al.*, 2019). Fast-growing trees (McDowell *et al.*, 2006), like loblolly pine, are more susceptible to drought than slow-growing trees like shortleaf pine (*Pinus echinata* Mill.) (Saud *et al.*, 2019). Despite this, loblolly pine has shown superior survival than shortleaf pine at mid-rotation, mainly due seedling mortality (Dipesh *et al.*, 2015), and under severe drought conditions (Klockow *et al.*, 2020), and supports loblolly pine's risky rapid-growth approach to be beneficial under current conditions. Intense management practices like site preparation and competition control aid increased survival and diminishes possible negative consequences from the rapid-growth strategy (Dipesh *et al.*, 2015; Klockow *et al.*, 2020). However, in terms of timber production, Shephard et al. (submitted) found dry conditions increased loblolly pine efficiency to produce pulpwood, since slower growth can lead to a greater proportion of a stand being relegated to pulpwood status. For now, with greater growth and survival than other species, loblolly pine plantations are an essential component to recent work that advocated tree planting to increase carbon storage in the continental USA by 20% (Domke *et al.*, 2020).

We measured canopy dynamics during the 2019 growing season and tried to link those to treatment effects on growth. Precipitation during 2019 was well above average which made it difficult to tease apart the drought effects. However, loblolly pine foliage remains on the tree for 1.5 years such that the 2019 measurements of LAI and fIPAR reflect conditions for both 2018 and 2019. In 2018, growing season precipitation was lower than previous years and SPEI slightly below zero. Positive fertilization effects on LAI and fIPAR supported the second hypothesis that fertilization would compensate for drought treatment (C, C-T~FD, FD-T). Non-fertilized, non-thinned stands had similar fIPAR as fertilized, non-thinned stands, yet fertilization increased fIPAR in thinned stands so fIPAR was similar to non-thinned stands with greater LAI. Even though fertilization increased LAI, fIPAR is a better predictor of productivity, as it relates to photosynthetic energy capture (Will *et al.*, 2005). Drought had no effect on fIPAR or LAI, yet increased GE. Greater GE was likely driven by slightly lower LAI ($p=0.11$), greater drought height growth in 2019, and marginal, non-significant +3% volume production. In dry periods on-site (2012-2014), drought treatment had no effect on GE, decreased LAI, and decreased volume production (Maggard *et al.*, 2017). Approximately equal reductions in LAI and volume resulted in no GE effect, unlike in 2019, where LAI and volume (height) acted in opposite directions. At the Georgia site during wet and dry years, drought treatment decreased both LAI and volume production, but did not affect GE (Samuelson *et al.*, 2018). The differences between Oklahoma and Georgia sites trends towards western droughted trees demonstrating increased production in wet periods.

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 are central in trying to understand how future plantations might respond to climate change. Eight-years' worth of stand data showed that the positive effects of fertilization were similar in magnitude to the negative effects of a 30% throughfall reduction. Drought-treatment plots showed greater basal area growth compared to non-droughted plots during wetter years which may indicate some resiliency of loblolly pine plantations to drought. Increased fIPAR in fertilized-thinned stands underlined the importance of thinning to capture synergistic treatment effects. Drought increased GE and cautiously supports compensatory growth of throughfall reduction treatments during wet periods, like the one we measured in 2019. As droughts likely become more frequent and more intense with climate change, our results give optimism to western-sourced loblolly pine continuing to be a suitable plantation species for a future, drier climate.

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LIST OF TABLES AND FIGURES

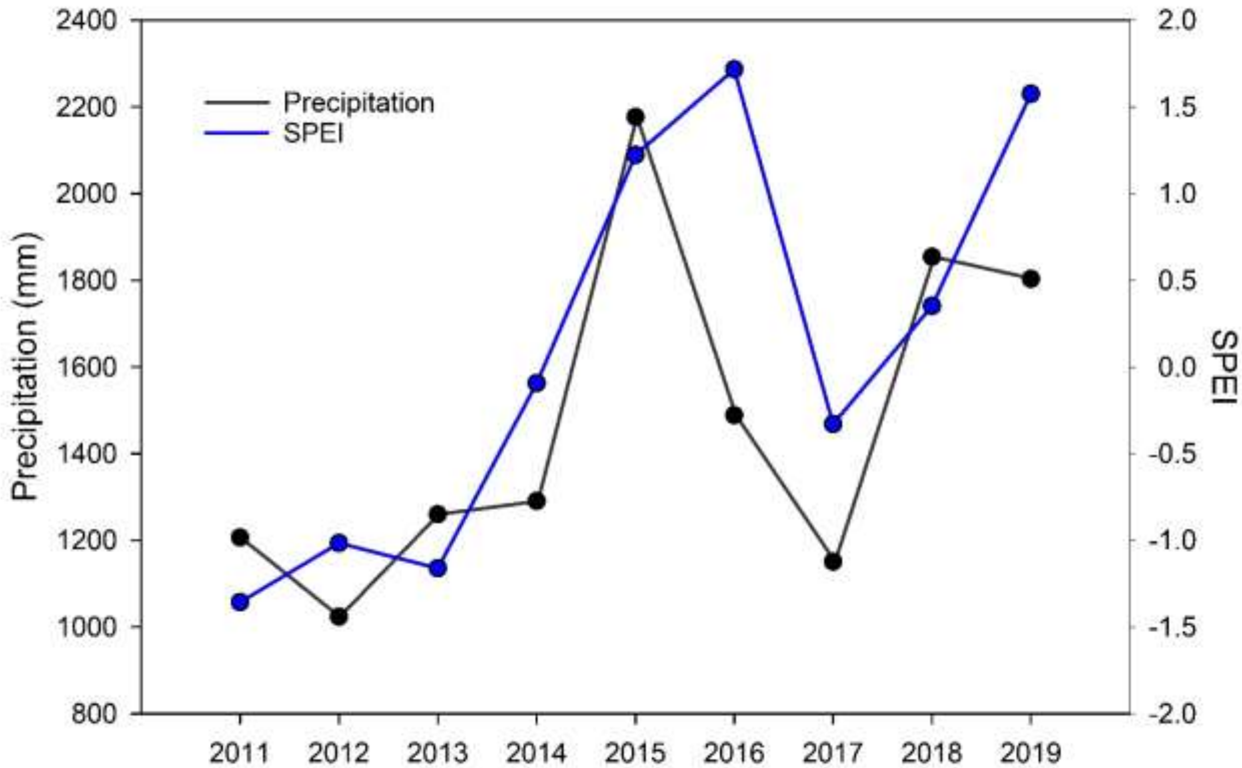

FIGURE 1A. Annual total precipitation and standardized precipitation-evaporation index (SPEI). Both values are averaged from monthly values (Figure 1a), January to December, for each respective year.

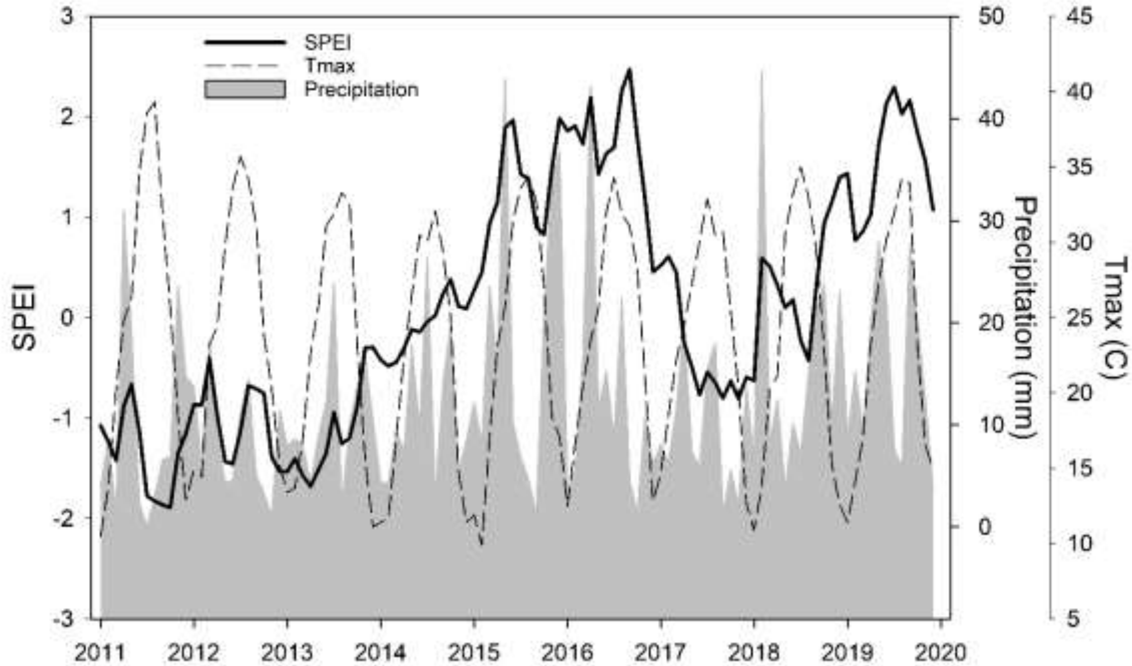

FIGURE 1B. Monthly standardized precipitation-evaporation index (SPEI), total precipitation, and average monthly maximum temperature (Tmax) from 2012 to 2019 for Broken Bow, OK. Data from Broken Bow, OK Mesonet Station (34.04306, -94.62417). SPEI values below zero indicate dry periods and values above 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).

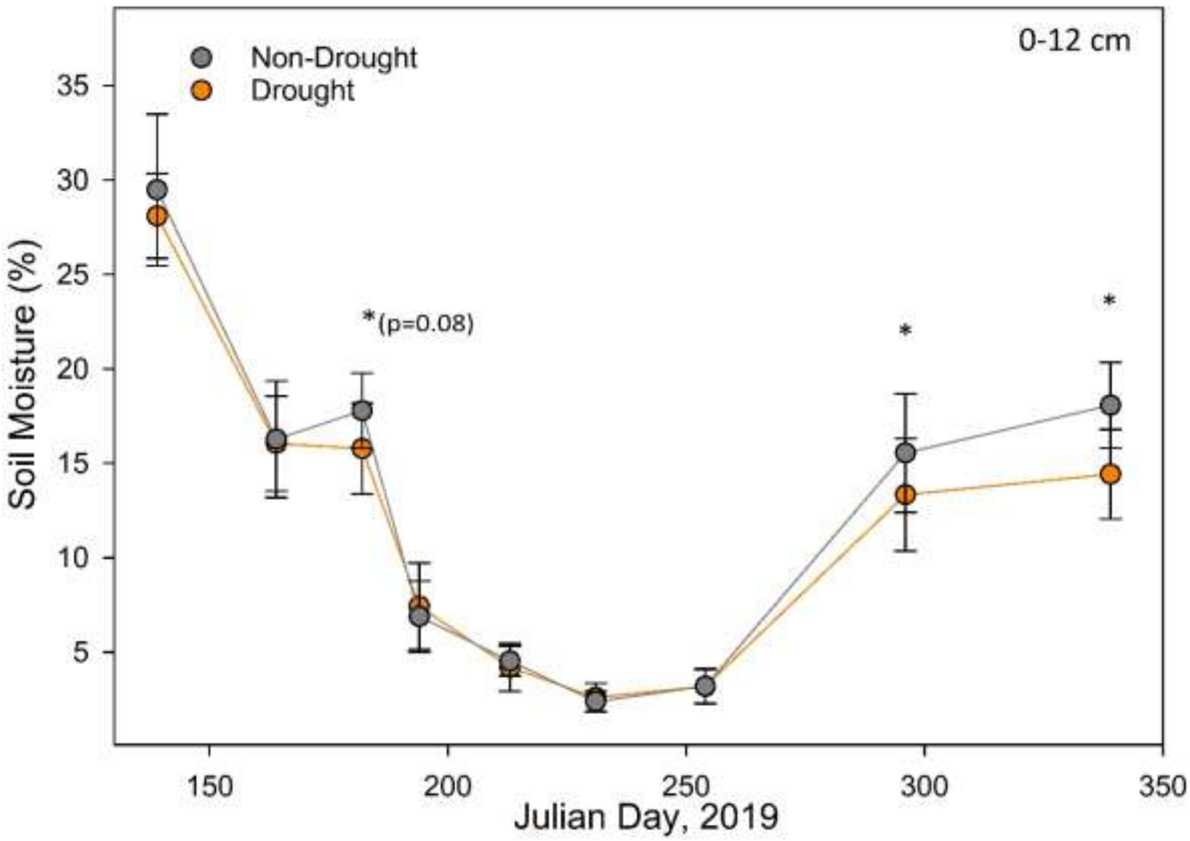

FIGURE 2. Volumetric soil moisture from 0 to 12 cm, during the 2019 growing season. Drought main effects were examined, non-drought (C, C-T, F, F-T) vs. drought (D, D-T, FD, FD-T) and vertical bars indicate standard errors. There was a significant Julian day*treatment interaction ($p < 0.05$). Therefore '*' are used to indicate where non-drought is significantly greater than drought treatments

TABLE 1. P-values from 2011 to 2019 growing seasons for fertilization (fert), throughfall exclusion (drought), year, and thinning (thin) effects on soil moisture, foliar phosphorous concentration (P) and nitrogen concentration (N), standing volume and growth (Stand. Vol.), trees per hectare (TPH), diameter breast height growth (DBH grow), height growth (HT grow), and gross volume growth (Gross Vol. Grow). Analysis is divided between pre (2011 to 2016) and post-thin (2017-on) analysis. * indicates 'year'= 'Julian day' circa 2019.

				2012 to 2019			
	Soil Moisture (2019*)	Foliar P (pre-thin)	Foliar P (post-thin)	Foliar N (pre-thin)	Foliar N (post-thin)	Stand. Vol 2016	Stand. Vol. 2019
fert	0.58	**0.02**	**0.01**	**0.01**	**0.01**	0.06	**0.05**
drought	0.28	0.52	0.34	0.54	0.67	**<0.0001**	**0.04**
fert*drought	0.74	0.25	0.84	0.08	0.59	0.11	0.62
year	**<0.0001**	**<0.0001**	**0.01**	**<0.0001**	0.24	NA	NA
fert*year	0.06	**0.01**	0.79	**<0.0001**	**0.03**	NA	NA
drought*year	0.0003	0.26	0.82	0.47	0.40	NA	NA
fert*drought*year	0.40	0.75	0.95	**0.06**	0.0041	NA	NA
thin	0.28	NA	0.69	NA	0.28	NA	**<0.0001**
fert*thin	0.72	NA	0.98	NA	0.96	NA	0.32
drought*thin	0.51	NA	0.39	NA	0.71	NA	0.63
fert*drought*thin	0.35	NA	0.75	NA	0.25	NA	0.46
year*thin	0.99	NA	0.16	NA	0.30	NA	NA
fert*year*thin	0.93	NA	0.29	NA	0.52	NA	NA
drought*year*thin	0.94	NA	0.52	NA	0.91	NA	NA
fert*droug*year*thin	0.42	NA	0.35	NA	0.78	NA	NA

	TPH (pre-thin)	TPH (post-thin)	DBH Grow (pre-thin)	DBH Grow (post-thin)	HT Grow (pre-thin)	HT Grow (post-thin)	Gross Vol. Grow (pre-thin)	Gross Vol. Grow (post-thin)
fert	0.44	0.96	**0.02**	**0.01**	0.88	0.46	0.17	**0.002**
drought	0.53	0.80	0.21	0.46	**0.0002**	**0.05**	**0.01**	0.86
fert*drought	0.25	0.71	0.27	0.65	0.70	0.66	0.40	0.96
year	**0.0005**	0.0033	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
fert*year	0.97	0.15	0.0002	0.43	0.23	0.78	**0.00**	0.14
drought*year	0.99	0.52	0.0016	0.19	**0.0024**	**0.01**	**<0.0001**	**0.04**
fert*drought*year	0.96	0.24	0.19	0.33	0.89	0.81	**0.01**	0.82
thin	NA	**<0.0001**	NA	**<0.0001**	NA	0.65	NA	**<0.0001**
fert*thin	NA	0.18	NA	0.82	NA	0.39	NA	0.39
drought*thin	NA	0.06	NA	0.99	NA	0.83	NA	0.30
fert*drought*thin	NA	0.51	NA	0.91	NA	0.46	NA	0.20
year*thin	NA	0.13	NA	**0.02**	NA	0.43	NA	0.82
fert*year*thin	NA	0.25	NA	0.73	NA	0.98	NA	0.74
drought*year*thin	NA	0.61	NA	0.84	NA	0.80	NA	0.48
fert*droug*year*thin	NA	0.58	NA	0.71	NA	0.92	NA	0.85

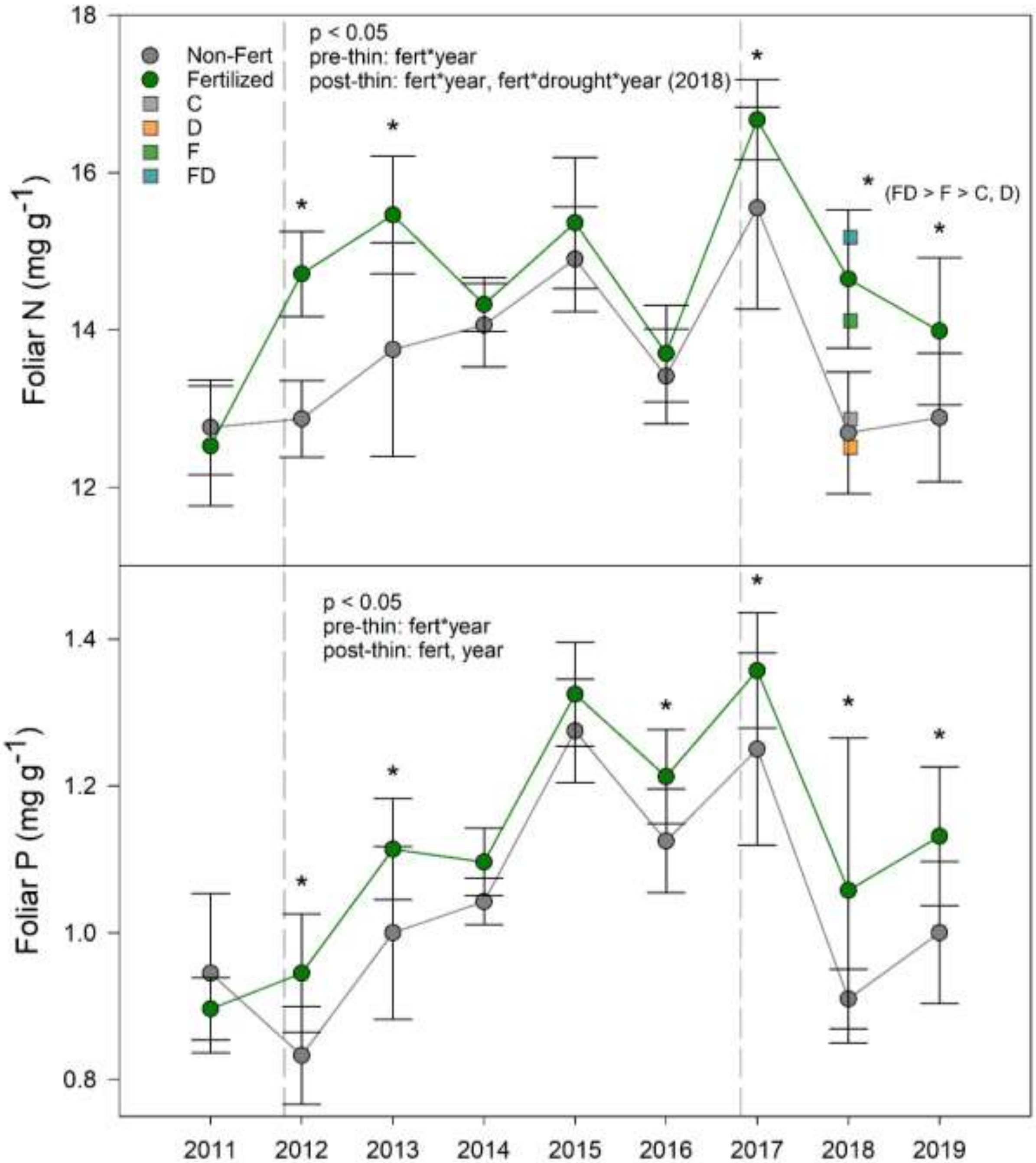

FIGURE 3. Foliar phosphorous (P) and nitrogen (N) concentrations after specified growing seasons. Foliar P and N includes fertilization main effects in pre-thin (2011-2017; ages 4- 10; n=8) and post-thin (2018-2019; ages 11-12; n=16), but nitrogen contains all main effect treatments in 2018 because of a fert*drought interaction. Analysis was conducted separately for the pre- and post-thin periods. Thinning was not accounted for in 2017, and is considered 'pre-thin'. Dashed lines indicate when fertilized. '*' denotes significant fert or fert*year effect. C = Control, F = Fertilized, D = drought (n=4). 'Fert' is fertilization. Vertical bars represent standard error.

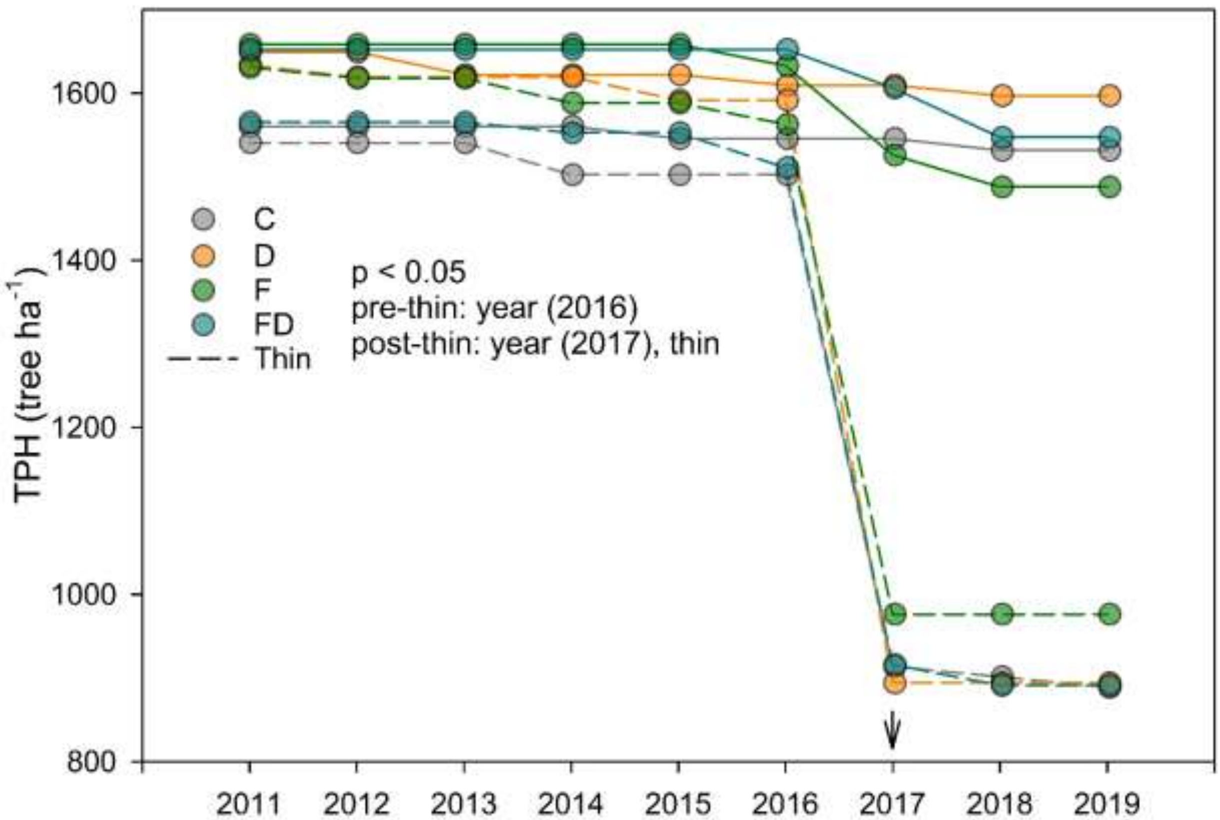

FIGURE 4: Trees per hectare (TPH) after specified growing seasons. Analysis was among years, listed when significant, and separated by arrow between pre-thin (2011-2016; ages 4- 9) and post-thin (2017-2019; ages 10-12). C = Control, F = Fertilized, D = drought (n=4)

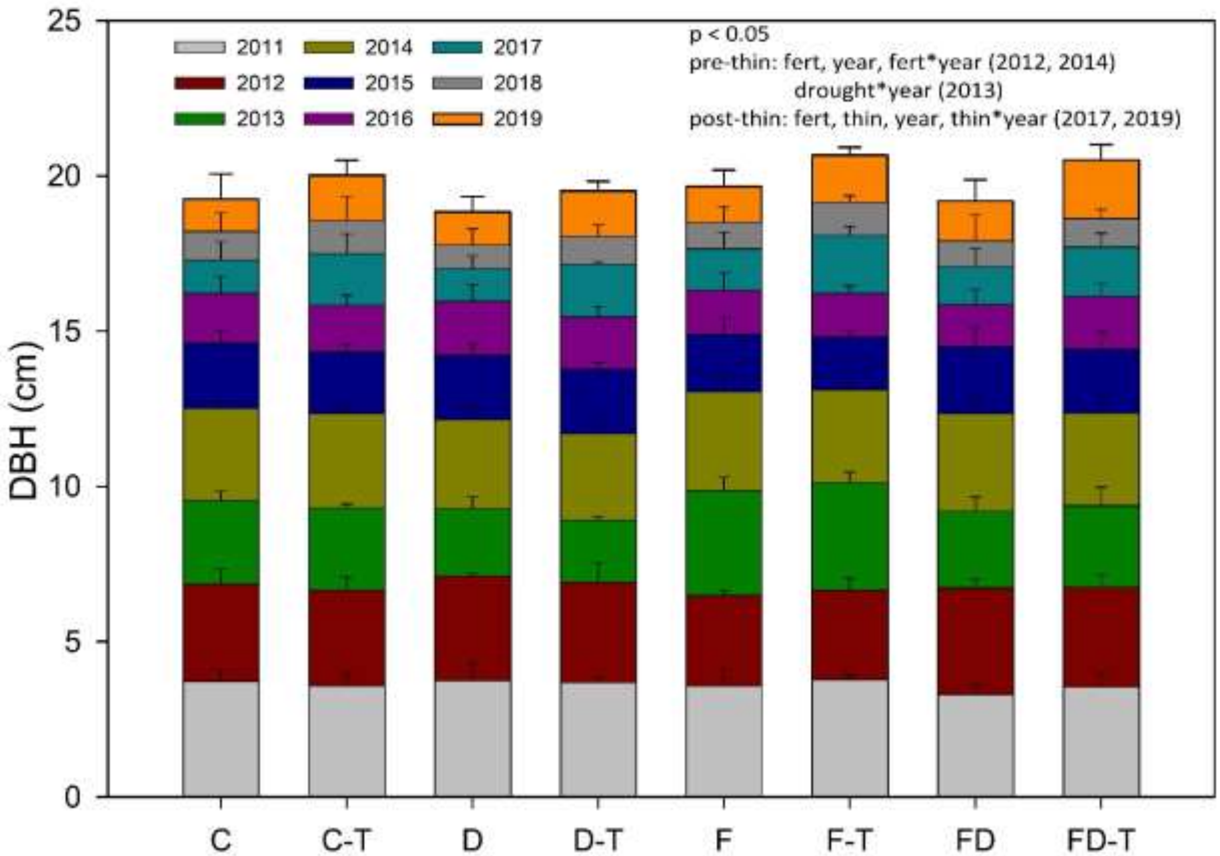

FIGURE 5. Diameter breast height (DBH) at the end of specified growing season (ages 4-12). Beginning with 2012, the increments associated with indicated years represent annual DBH growth. 2011 represents growth from 2008 (planting) through 2011 (age 4). Annual DBH growth analysis is listed when year*treatment is significant; analysis is separated between pre-thinning (2012-2016; age 5 to 9) and post-thinning (2017-on; age 10 to 12). C = Control, F = Fertilized, D = drought, T = thin (n=4). Vertical bars indicate standard errors.

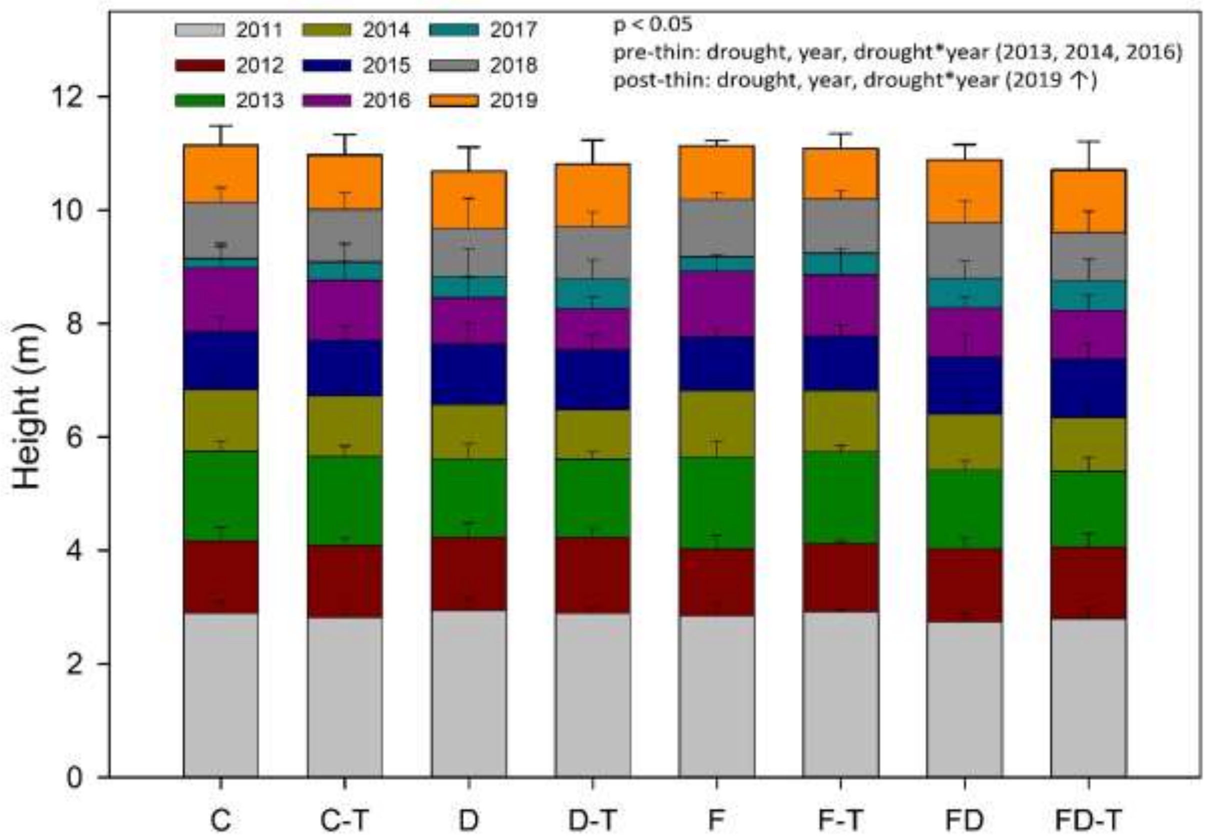

FIGURE 6. Height at the end of specified growing season. Beginning with 2012, the increments associated with indicated years represent annual height growth. 2011 represents growth from 2008 (planting) through 2011 (age 4). Annual height growth analysis is listed when year*treatment is significant under repeated measures analysis; analysis is split between pre (2012-2016; age 5 to 9) and post-thinning (2017-on; age 10 to 12). In 2019, drought increased height growth. C = Control, F = Fertilized, D = drought, T = thin (n=4). Vertical bars indicate standard errors.

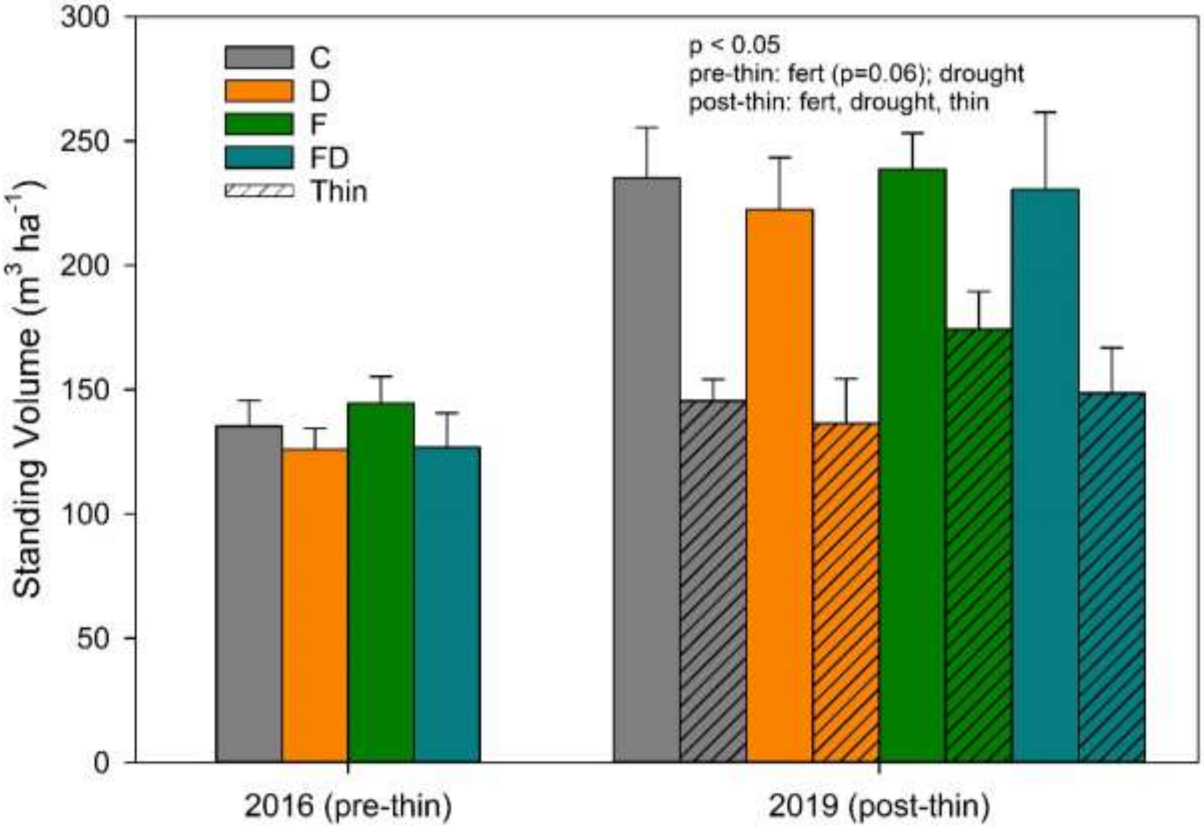

FIGURE 7. Annual standing volume at the end of specified growing season (stand ages 4-12). Standing volume does not include mortality or removals. 2016 represents pre-thin net volume from at age 9. 2019 represents post-thin net volume at age 12. Analysis was without annual effect. C = Control, F = Fertilized, D = drought (n=4), 'fert' is fertilization.

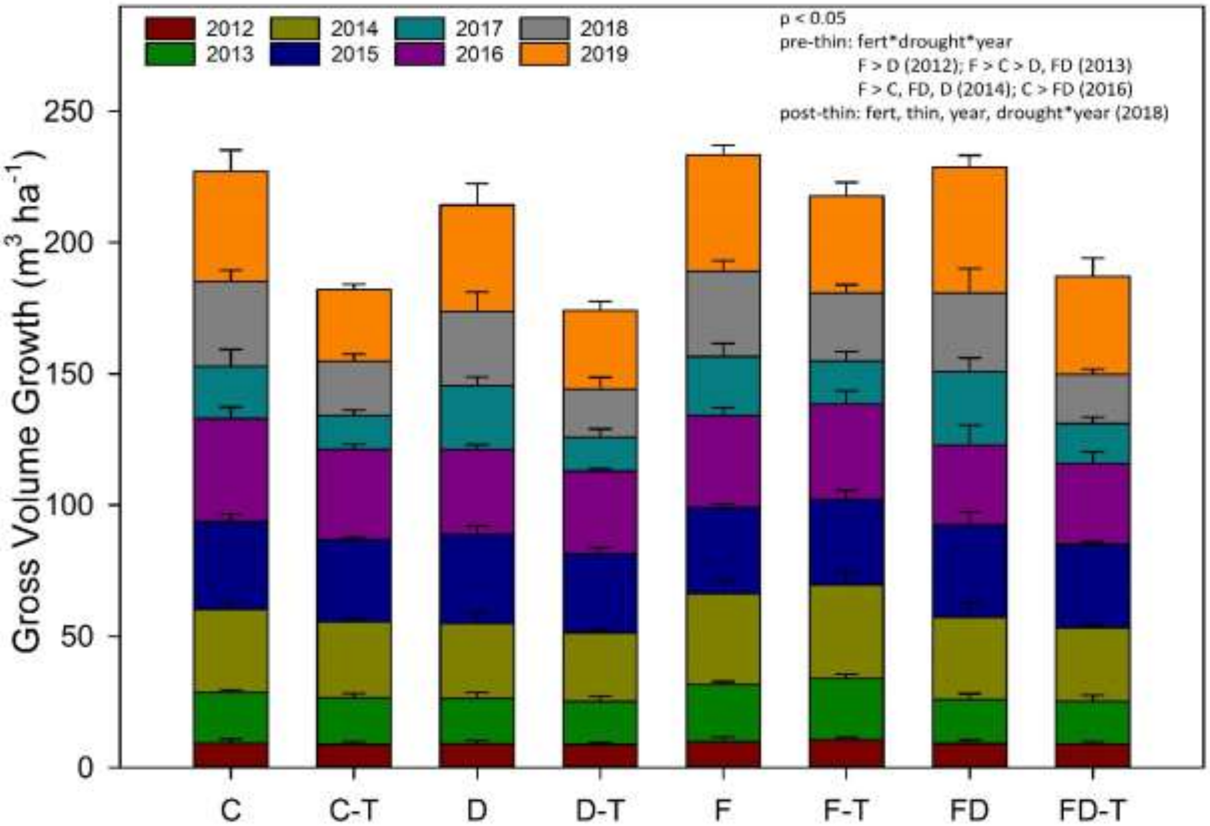

FIGURE 8. Annual gross volume growth for specified growing season. Gross volume is standing volume plus mortality and removals. Annual gross volume growth analysis is listed when treatment*year was significant. When only two treatments are listed as different on the figure, i.e., F>D, those are the two extremes and the other two treatments are intermediate and not different from other treatments. C = Control, F = Fertilized, D = drought, T = thin (n=4), 'fert' is fertilization. Vertical bars indicate standard errors.

TABLE 2: P-values from 2019 growing season for the effects of fertilization (fert), throughfall exclusion (drought), thinning (thin), and Julian day (jd) on leaf area index (LAI), growth efficiency (GE), and fraction of intercepted photosynthetically active radiation (fIPAR).

	2019		
	LAI	GE	fIPAR
fert	**0.0002**	0.56	0.29
drought	0.11	**0.04**	0.68
fert*drought	0.75	0.89	0.66
thin	**<0.0001**	0.21	**0.0013**
fert*thin	0.59	0.28	**0.05**
drought*thin	0.57	0.34	0.43
fert*drought*thin	0.52	0.13	0.13

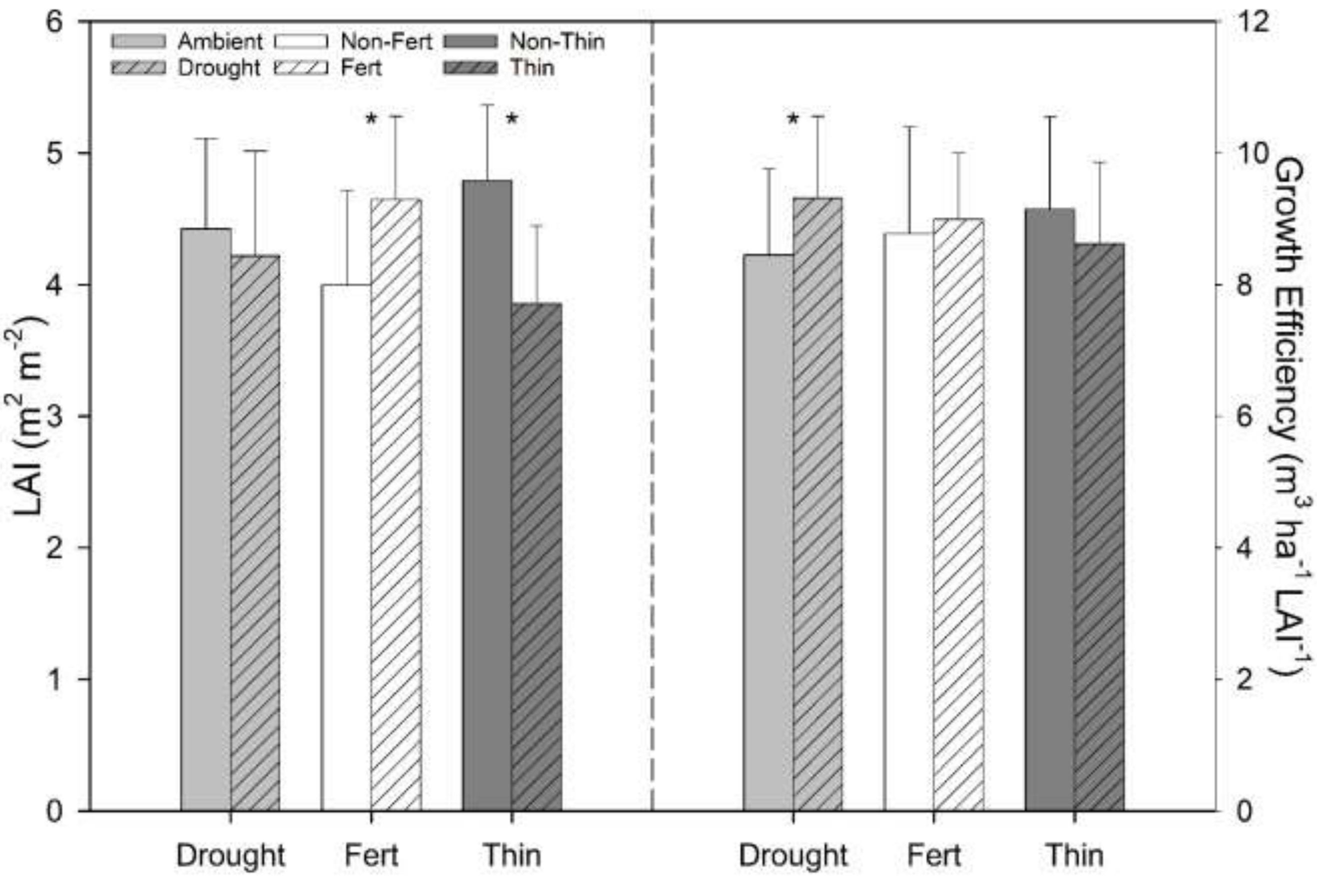

FIGURE 9. Average growing season leaf area index (LAI) and growth efficiency (GE) during the 2019 growing season (twelfth growing season). Significance at α=0.05 and indicated by '*'. Main effects from drought and fertilization, and split-plot thinning effect are presented (n=16).

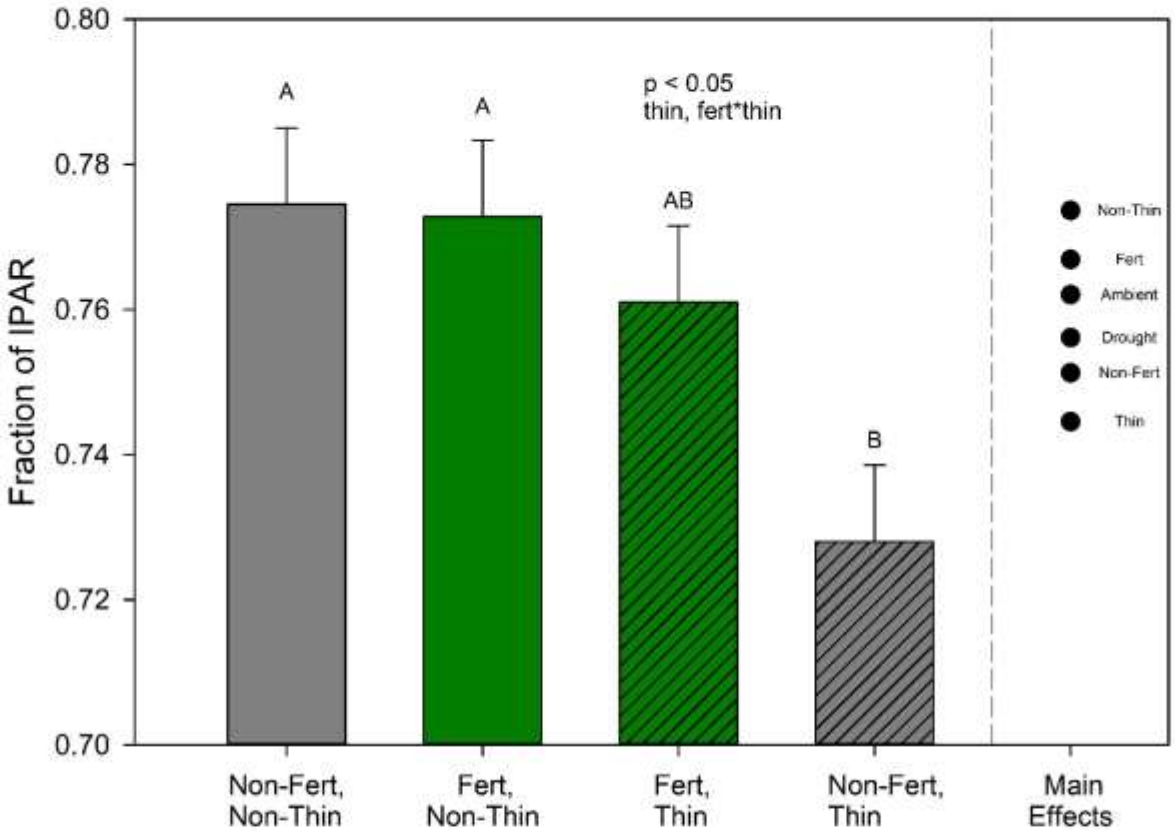

FIGURE 10. Fraction of intercepted photosynthetically active radiation (IPAR) during the 2019 growing season (twelfth growing season). Vertical bars indicate standard errors. Significance at α=0.05. Different letters show significance within fert*thin effect (n=8). Main effects from drought and fertilization, and split-plot thinning effect are also presented (n=16). '2019, Fert*Thin' indicates fertilization and thinning interaction (n=8), with different letters showing significant differences.

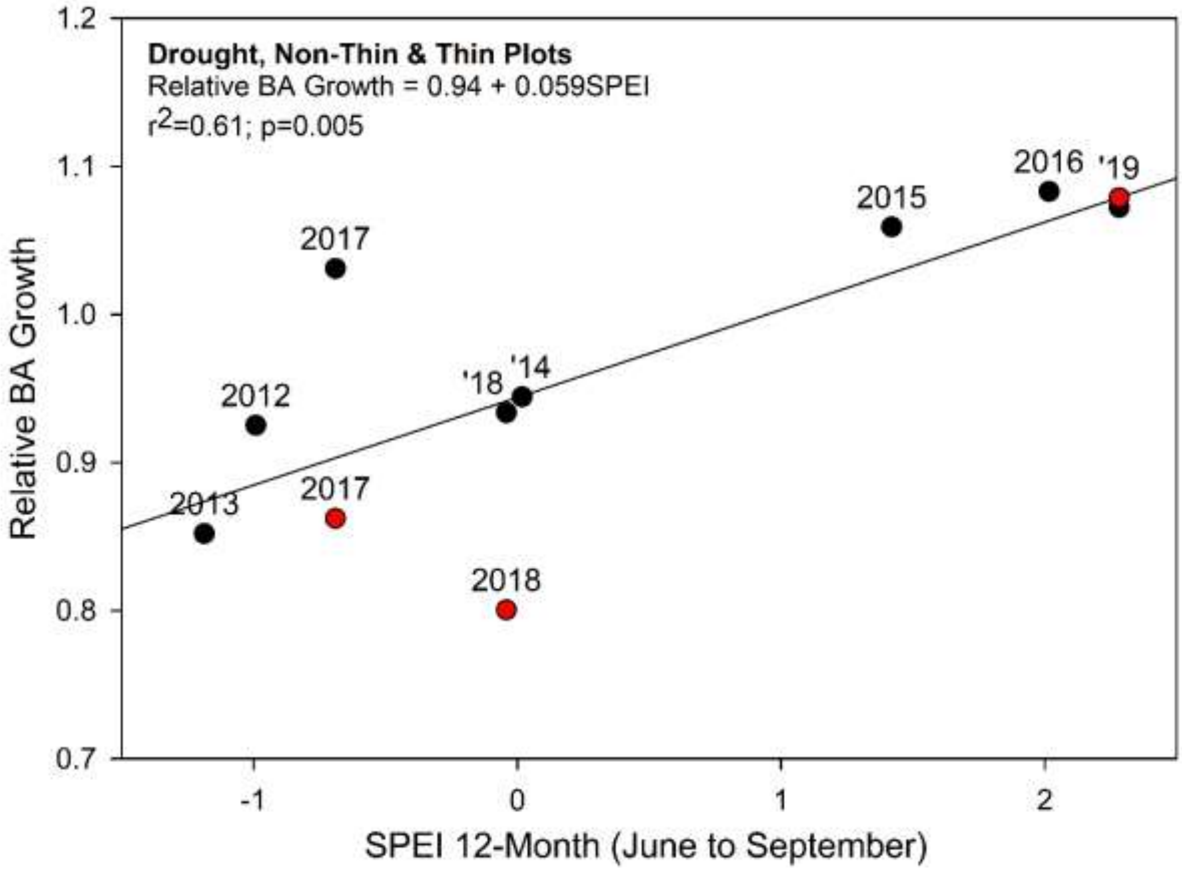

FIGURE 11. Relationship between SPEI and relative gross basal growth in respect to drought and thinning. Thinned and non-thinned treatments are plotted separately. Red circles represent effect comparisons involving thinned stands (2017-on). Relative basal area growth is gross basal area growth of the D and FD treatment divided by gross basal area growth of the corresponding C and F treatment (n=8).

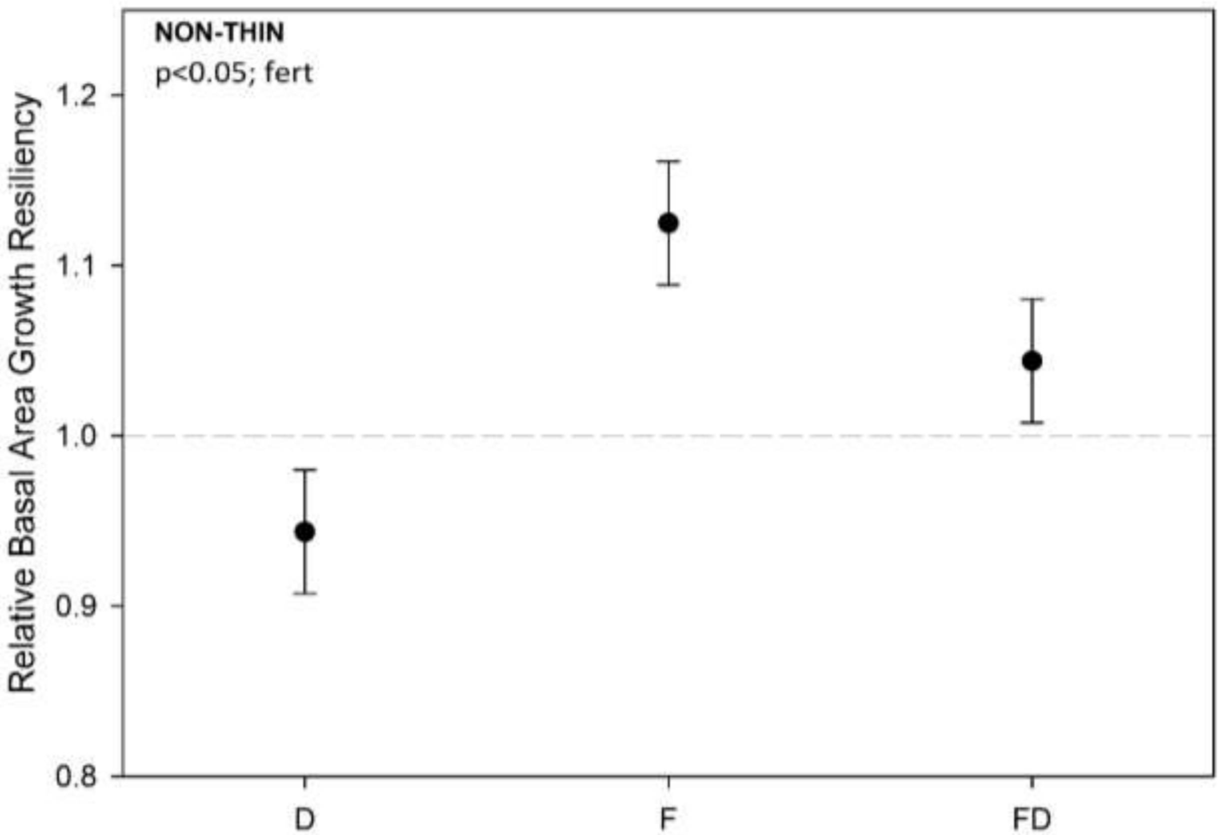

FIGURE 12: Resiliency of non-thinned treatments to 2017 drought conditions. Resiliency is defined as average 2019 and 2018 basal area growth divided by average 2015 and 2016 basal area growth. Values were made relative by dividing basal area resiliency in non-thinned (D, F, FD) plots by the non-thinned control (C) response. D = drought, F = Fertilized, T = thinning.

CHAPTER IV

A STAND LEVEL APPLICATION OF EFFICIENCY ANALYSIS TO UNDERSTAND EFFICACY OF FERTILIZATION AND THINNING WITH DROUGHT IN A LOBLOLLY PINE PLANTATION

ABSTRACT

Loblolly pine **(***Pinus taeda* L.) is the most important and productive commercial timber species in the southern USA. Common plantation management practices such as fertilization and thinning could become inefficient and economically disadvantageous given anticipated climate change effects, such as increased drought severity, especially in the drier Upper Gulf region of the south-central USA. To calculate technical and economic efficiency, we used data envelopment analysis (DEA) to assess the ability of fertilized, thinned, and drought-induced loblolly pine plots in southeastern Oklahoma (n=32) to turn volume growth and stand density (inputs) into timber products- pulpwood, chip-n-saw, sawtimber- and stored carbon (outputs) across 21, 26, and 31-year rotations. The highest efficiencies were for the fertilized-thinned treatments. We found that thinned stands remain technically, economically, and overall efficient as rotation age increased. Non-thinned stands had lower efficiencies than thinned stands and exhibited a 28% decrease in overall efficiency between ages 21 and 31. Drought decreased overall efficiency by at least 11% when rotation age was 26 years or longer. Fertilization with drought decreased overall efficiency on average by 24%. The results reiterate the importance of thinning to efficiently mediate drought conditions and should remain a staple of plantation silviculture. Results also indicate that fertilization is not likely to help ameliorate drought impacts, from an efficiency standpoint. Study results will benefit practitioners in gauging active forest management decisions and their likely outcomes from a resource efficiency perspective.

Keywords: data envelopment analysis, loblolly pine, drought, optimization, rotation age

1. INTRODUCTION

Loblolly pine (*Pinus taeda* L.) represents a critical component of forested land in the USA and has a large distribution across the southern landscape. It is the most intensively managed and productive conifer species in the nation- and perhaps the northern hemisphere (Fox *et al.*, 2007a; Zhao *et al.*, 2016). The species is the largest live aboveground biomass contributor in the region at 2.1 billion tons which represents 20% of total aboveground live biomass (Oswalt *et al.*, 2019). Climate change will likely affect timber production of loblolly pine, as increased temperature and drought intensity and duration are predicted to occur throughout the commercial range (Collins *et al.*, 2013; Kloesel *et al.*, 2018) which has the potential to reduce stand growth (Will *et al.*, 2015; Maggard *et al.*, 2016, 2017; Bracho *et al.*, 2018). Plantations located on the western edge of the commercial range likely will realize the effects of climate change soonest due to drier and more variable conditions (e.g. Kloesel *et al.*, 2018) as well as higher summer temperatures which increase vapor pressure deficit and water stress (Breshears *et al.*, 2013; Will *et al.*, 2013). For instance, the plantation used for the current study, planted at the limit of its natural range, was more sensitive to experimental throughfall reduction than stands further east (Will *et al.*, 2015; Bracho *et al.*, 2018).

Research suggests that loblolly pine timber production may increase in the future in response to higher atmospheric CO_2 concentrations (Gonzalez-Benecke et al., 2017), which are expected to increase net photosynthesis and growth (Murthy *et al.*, 1996; McCarthy *et al.*, 2010; Gonzalez-Benecke *et al.*, 2017). Any potential increase related to increasing CO_2 concentrations likely will be site-specific and depend on availability of other limiting factors such as soil nutrients (McCarthy *et al.*, 2010).

Despite an increase in production, predictions have shown both positive and negative implications on the timber market. For example, Kirilenko and Sedjo (2007) determined that increased timber supply would lead to lower log prices and increased consumption, thus consumers would benefit from lower prices while producers may eventually lose revenue. On the other hand, increased tree mortality (Brecka *et al.*, 2018) and greater risk (e.g. Nordhaus, 2010) with longer rotation ages, from slower growing stands (Sohngen *et al.*, 2001), could negatively impact timber production with climate change. With this interplay, sustainability of forest management is of real concern.

The vast majority of softwood timberlands in the southeastern USA are owned by private entities and removals from these lands account for 58% of national removals (Oswalt *et al.*, 2019). Within southern pine management, changing species and decreased planting density can increase revenue and carbon storage (Susaeta *et al.*, 2014), including carbon pricing increases profitability and optimal rotation age (Nepal *et al.*, 2012), and there is an inherent need for forest management to maintain ecosystem services under variable climate, particularly to drought (Susaeta *et al.*, 2019).

The goal of this paper was to use a data-driven, analytical approach to assess how drought conditions affect the production and profitability of fertilization and thinning within a loblolly pine plantation located in southeastern Oklahoma, USA under different rotation ages. We examine efficiency of silvicultural options under the context of timber production and carbon storage. Pulpwood, chip-n-saw, and sawtimber products were quantified to determine how drought, thinning, and fertilization treatments might change the ability of plantation silviculture to produce the full range of different valued products. Carbon storage was calculated to assess total rotation biomass production, irrespective of product class, and to include modern silvicultural efforts to support non-consumptive ecosystem services (Susaeta *et al.*, 2014; D'Amato *et al.*, 2018). A non-parametric method, data envelopment analysis (DEA), was used to evaluate efficiency under technical (production) and price (economic) efficiency. DEA was originally designed to evaluate an organization's ability to turn multiple inputs into multiple outputs (Cooper *et al.*, 2011).

Due to ease of its calculation, DEA is widely used in the business sector, including the forest industry. For example, Viitala and Hänninen (1998) analyzed efficiency of forestry organizations in Finland to gauge efficiency of big-picture strategies like forest planning, administration, training, and extension work, suggesting inefficiencies lead to a large reduction in profit. Likewise Marinescu *et al.* (2005) examined Canadian forest product companies in regards to optimizing profit and employment. There are a few other applications of efficiency analysis (Grebner and Amacher, 2000; Siry and Newman, 2001) in forestry sector.

While efficiency analysis is more commonly used in forest industry and policy analysis, its application to understand production and price efficiencies associated with forestland management has been limited. To this end, Susaeta *et al.* (2016a) conducted a DEA analysis to explore the role of plot-level attributes (age, density) and climate change effects (precipitation, temperature) in providing ecosystem services in Florida, USA. Their results suggested that naturally regenerated pine forests in Florida were inefficient at producing timber and carbon and that climate change might have little effect on efficiency. In contrast, Susaeta *et al.* (2016b) observed that climate change increased efficiency associated with similar plot attributes within plantations. These differences between naturally regenerated forest and plantations indicate that loblolly pine plantations were largely efficient in producing future ecosystem services despite climatic variability. The dichotomy between the two studies suggests that more intense silviculture likely is important to increase efficiencies.

DEA results quantitatively differ from capital budgeting tools, like net present value (NPV), and can be characterized as operations-oriented rather than profit-oriented. The NPV, which is commonly used in forestry investment analysis, provides the financial trajectory of a timber management decision without taking the scale of investment into account (Bullard and Straka, 2011). The advantage is that DEA utilizes input-output relationships to estimate the level of efficiency, which can be used to minimize slack or the waste of unused resources (Siry and Newman, 2001). For decision makers and investors, DEA can be more informative than NPV results due to these benchmarking techniques as evaluations are followed with detailed information, i.e., slacks, on how to improve performance of examined entities (plots), thus aiding management by indicating where improvement is most needed (Tone, 2001).

Our research contributes to existing knowledge in four ways. First, no research to the best of our knowledge, has quantified technical and price profit efficiencies associated with silvicultural actions (thinning, fertilizer, herbicides etc.) that are commonly used to improve timber growth and productivity in the plantation forests in the southern USA. Second, building on previous research (Susaeta *et al.*, 2016b), we quantified the effectiveness of management actions, like thinning and fertilization by exploring relative efficiencies with and without drought conditions. Third, since future climate change likely will have more severe effects on loblolly pine growth in the western portion of the south-central USA than other regions, our findings provide important management implications for the landowners, field practitioners, and government agencies to better prepare climate change adaptation plans. Finally, unlike previous research that relied on secondary data sources for growth and yield estimates, our input attributes are primary data from a site in southeastern Oklahoma.

2. METHODS

2.1 MODEL SPECIFICATION

We use the slack-based DEA modeling to determine technical efficiency. Each Decision Making Unit (DMU), such as plots having a unique silvicultural practices in our case, needs inputs to produce outputs, and it is advantageous to limit inputs, but to maximize outputs (Cooper *et al.*, 2011). Generally, efficiency can be considered as the ratio between outputs and inputs. Technical efficiency is when a DMU's given set of inputs cannot be decreased or outputs cannot be increased, without decreasing other inputs or increasing other outputs (Cooper *et al.*, 2011). A DMU can be made more efficient by either a proportional reduction in inputs or output augmentation. Slack criteria were added to the primal technical DEA model, defined as surplus inputs or output shortages for DMU, and provides more restrictive efficiency estimates, i.e., slack-based models (SBMs). The plot-level inputs were volume growth, stand density, and outputs were pulpwood, chip-n-saw, and sawtimber products, as well as carbon storage. Finally, since forest landowner does not have any control over drought, it was categorized as non-discretionary input variable (Banker and Morey, 1986). In DEA analysis, three types of efficiencies, namely technical, economic, and overall efficiencies are obtained. The technical efficiency aims to minimize the inputs and maximize outputs, economic efficiencies focus on minimizing costs and maximizing revenue, and overall efficiencies balance out both inputs and costs (Cooper *et al.*, 2011).

2.2. DATA SPECIFICATION

2.2.1 INPUTS

Our aim was to quantify the technical, price, and overall efficiency of loblolly pine stands to produce timber and store carbon under different treatments and at different rotation ages, given mid-rotation volume production and stand density. Each input was derived from annual tree surveys conducted at the end of the respective growing seasons from 2012 to 2019 at a site near Broken Bow, Oklahoma (34.02972, -94.82306). This site was established as part of the Tier III network established by the Pine Integrated Network: Education, Mitigation, and Adaptation Project (PINEMAP) (Will *et al.*, 2015) and included a factorial combination of throughfall reduction and fertilization replicated four times in a 5-year-old plantation in 2012, for a total of 16 plots averaging 0.02 ha. In throughfall reduction plots, 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. Weather and environmental variables were monitored to gauge the effect of external factors into pine survival and growth. (Will *et al.*, 2015).

Throughfall reduction troughs were installed in early-summer 2012. We refer to the throughfall reduction treatment as ‘drought’, since it simulated potential effects of reduced precipitation. Fertilization in spring 2012 included an elemental application of nitrogen (224 kg ha^{-1}), phosphorous (28 kg ha^{-1}), potassium (56 kg ha^{-1}), plus micronutrients. In spring 2017, a thinning split-plot treatment was added, and plot number doubled to 32. Half of each plot was thinned to decrease basal area by ~40% and previously fertilized plots received re-application of nitrogen (224 kg ha^{-1}) and phosphorous (28 kg ha^{-1}). Eight-years of growth data were used to compute volume production, specifically, net plot-level stem volume growth (m^3 ha^{-1}) from year five to twelve (2012-2019) (Table 1), along with current plot-level density (trees per hectare; TPH), assessed at year twelve (2019) (Table 1). Likewise, management costs associated with these attributes were used to as inputs in the profit model. For the 16 drought treated plots, a categorical input variable, '1', was assigned to capture exogenous conditions of a 30% throughfall reduction (Table 1).

2.2.2 OUTPUTS

To obtain technical outputs, measured growth at the Broken Bow site also was used to model ensuing tree growth, and ultimately harvested timber yield and carbon storage for 21, 26, and 31-year rotation ages. Growth and yield modeling involved individual-tree models within the Forest Vegetation Simulator (FVS) to mimic treatment conditions (Crookston and Dixon, 2005). Outputs were pulpwood, chip-n-saw (CNS), and sawlog products (Mg ha^{-1}), and carbon storage (Mg ha^{-1}). Timber products were the summation of thinning and harvested tonnage per product class within each rotation age (Table 1). The FVS Carbon Report, which provides alive and dead, below and aboveground biomass, forest litter, herbaceous layer, and carbon stored in finished timber products, was obtained to account for carbon storage information.

2.2.3 DMUS

Thirty-two individual treatment plots from the Broken Bow site were treated as DMUs. Standard DEA protocol requires the total number of DMU's to be 3 times the total number of inputs and outputs (e.g. Cooper *et al.*, 2011). Plots represented eight unique silvicultural and soil moisture treatment combinations (n=4) of control (C), fertilization (F), drought (D), and thinning (T): C, C-T, D, D-T, F-T, FD, FD-T. The same DMUs were used for all technical, price, and overall efficiency models, keeping input values constant, while changing output (harvest) values with common operational rotation ages of 21, 26, and 31-years (e.g. Shrestha *et al.*, 2015).

2.3 GROWTH AND YIELD MODELING

Individual tree growth and yield models were used to predict stand-level removal totals (thinning plus harvest) and carbon storage under different nutrient availabilities, water availabilities, and stand densities, as mentioned in section 2.2.3. Removal timing was as follows: thinning year 9 and 15, clearcut harvest year 21, 26, and 31. Year nine thinning was not modeled, but was included in product total and carbon storage outputs. Modeled stand-level production of pulpwood (10.2 to 20.3 cm diameter breast height; dbh), chip-n-saw (20.3 to 25.4 cm dbh), sawlog (>25.4 com dbh), and total-stand carbon storage was quantified at each removal. Carbon storage was derived from growth and yield modeling by applying multipliers to biomass estimates (Hoover and Rebain, 2011). The conversion factor of 52.50 lbs ft^{-3} and 0.84 Mg m^{-3}, developed from equations in Harges (2017) was used in the analysis.

2.4 TECHNICAL MODEL

It was assumed that greater volume growth and stand density were associated with more intense and expensive silviculture, i.e., inputs sought to be minimized, while increased timber production and carbon stored led to greater profits and favorable carbon balance, i.e., outputs sought to be maximized. Therefore, the modeled harvest yield and carbon storage were analyzed using the SBM technical model using these assumptions. Or simply, the effectiveness of different regimes to convert stand growth to finished products and stored carbon.

DEA was performed independent of year. Three separate models were used for each harvest age, and therefore efficiency outcomes were not confounded with harvest age. *DEAFrontier*™ software was used to perform all analyses (Zhu, 2014). DEA acts as a decision support tool to aid management in selecting the 'best' silviculture treatments to achieve the highest output to input ratio.

2.5 PRICE MODEL AND SENSITIVITY ANALYSIS

Unit costs and prices (Table 1) were added to inputs and outputs, respectively, to develop a price model. Costs and prices were exclusive to each DMU. To obtain unit costs and prices, present values for each respective input and output were calculated then divided by the unit itself. To mathematically distinguish thinning treatments, thinning costs were realized and gatewood prices were used. Carbon storage and output carbon price were removed from the price model, but kept in technical and overall models, since there was no viable carbon tax scheme in the USA when this analysis was conducted.

In the price model, input costs were assessed using average silvicultural costs (Table 2) found in the Upper Gulf region (Maggard and Barlow, 2018) and verified with a local timberland owner (Ed Hurliman, pers. comm., October 19, 2019). Likewise, output gatewood prices were based on 10-year stumpage averages (2010-2019) from Texas A&M Forest Service (TFS, 2020) and added to average southern-wide values of cut-and-haul costs (Harris et al., 2018). Our accepted real interest rate was 5%. Unit costs and prices were reviewed under an interest sensitivity analysis at 26-years. Additional real interest rates of 3% and 7% were applied to present value calculations in order to understand how rates could manipulate unit prices. The estimated timber product values are functions of capital costs and prices, which cannot be predicted with certainty. Therefore, it is important to conduct sensitivity analysis to gauge how changes in assumed timber prices and interest rates can influence results (Bullard and Straka, 2011).

2.5 DEA MODEL APPLICATION

Through technical, price, and overall DEA models, optimal management regimens were found for different drought, fertilization, thinning, and rotation age treatments. As such, slacks were assessed at rotation ages of 21, 26, and 31-years. Profit analysis, conducted via assigning unit costs and prices to slack values, and provided a dollar value to inefficient management decisions.

2.6 EFFICIENCY

To parse the importance of treatments on efficiency, we distinguished the following classifications: robustly efficient and best practice $\theta=1$; marginally inefficient $0.9 < \theta < 1$; and distinctly inefficient $\theta < 0.9$ (Sowlati, 2005). Robustly efficient stands reflect optimal management decisions. Marginally inefficient stands reflect management decisions that could be altered but inefficiencies are nuanced, and management can be understood as operationally efficient. Distinctly inefficient treatment regimens are of concern because they indicate severely unproductive management decisions. If stands start inefficient, they are likely to have inefficient harvest yields.

2.7 PARAMETRIC STATISTICS

Overall efficiency scores were analyzed using generalized linear mixed models (GLMMIX) and significance was assumed at $p \leq 0.05$. Main (fertilization, drought) and split (thinning) plot effects were examined using block and block*fertilization*drought as random effects. Data were analyzed with repeated measures to determine rotation age effect using unstructured covariance. Kenwood-Rodgers method were 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. The parametric tests performed were intended to provide ancillary clarity to DEA results. Regardless of the results of the parametric tests, greater efficiency is assumed to be preferable, regardless of magnitude. Analysis was performed using SAS/STAT® software, Version 9.4 for Windows.

3. RESULTS

3.1 TREATMENT EFFECTS

Among the treatments and their interactions, the significant terms in regards to efficiency were thinning ($p=0.0007$), rotation age ($p<0.0001$), drought ($p=0.001$), fertilization*drought interaction ($p=0.02$), thin*rotation age interaction ($p<0.0001$), and drought*rotation age interaction ($p=0.009$). All other terms were not significant. Technical, price, and overall efficiency with rotation age declined for the non-thinned stands, but was higher and nearly constant with rotation age for thinned stands (Table 3, Figure 1). Fertilization and drought had a negative synergistic interaction. On average, fertilized-ambient (F, F-T) stands had the highest average scores (θ_O=0.86) and fertilized-drought (FD, FD-T) stands had one the lowest average scores (θ_O=0.66), with non-fertilized ambient and non-fertilized drought treatments intermediate. As such, FD-T was the only thinned treatment to be distinctly inefficient (Table 3). Regardless of stand age, F-T stands were perfectly efficient (θ_T = 1), followed by C-T and D-T stands (average θ_T =0.97). In contrast, D, and FD stands demonstrated the lowest scores among treatments which decreased with stand age (θ_T < 0.83) (Table 3).

The negative impacts of drought on efficiency increased with rotation age and resulted in a significant drought*rotation age interaction. Drought treatments (D, D-T, FD, FD-T) and non-drought, treatments (C, C-T, F, F-T) had similar overall efficiencies at age 21. In drought stressed treatments, decreased efficiency by 10% (drought θ_O=0.70; non-drought θ_O=0.78) at 26 years and 29% (drought θ_O=0.61; non-drought θ_O=0.86) at 31 years (Figure 2). Drought effect increased with time since non-drought stressed plots increased in overall efficiency between 26 and 31 years, +10% (Figure 2). Price efficiency, θ_P, generally mimics technical trends. Technical and price efficiency are not concurrent, but together describe overall efficiency (Susaeta *et al.*, 2016b). We will refer to overall efficiency for the remainder of the paper since it offers a succinct measure of input and output dynamics.

3.2 SLACKS

For a specified variable, non-zero slacks translate to inefficacy, while zero slacks translate to efficiency. Technical slacks concisely describe the management decisions (density, volume growth) that lead to production inadequacies (timber, carbon). Distinctly inefficient treatment regimens (Table 3) also had large non-zero slacks (Table

4). This relationship was principally caused by stand density, sawlog production, and carbon storage. Stand density slacks peaked at 26-years, while sawlog and carbon slacks gradually increased with age. All three attributes increased within non-thinned stands, while thinned stands had minimal slacks regardless of stand age. Sawtimber and carbon storage had the largest influence on slacks. In contrast, volume growth, pulpwood, and chip-n-saw products played minor roles in driving inefficiency due to zero or near-zero slacks, or slacks representing a small proportion of respective inputs or output criteria (Table 4, Table 1).

3.3 ECONOMIC ANALYSIS

Profit forgone represents the difference between actual profit and optimal profit found on the best-practice frontier (Figure 3). Thinning produced a positive effect and decreased lost profit. All thinned stands were below \$1,000 ha^{-1} lost, while all non-thinned stands eventually surpassed \$3,000 ha^{-1} lost. Fertilization was beneficial only when combined with thinning. F-T displayed complete optimization with time with ~\$0 ha^{-1} lost. The C-T, ~\$500 ha^{-1} lost, and D-T stands, ~\$400 ha^{-1} lost, were surprisingly similar in lost profit. Fertilized-only stands (F) reflected high consequences of not thinning, \$4,364 ha^{-1} lost by 26-years. In terms of drought interactions, thinning mitigated economic losses from drought, and fertilization exacerbated drought losses in non-thinned stands. In drought-only (D) stands, drought losses were minimized with a short rotation age of 21-years (\$443 ha^{-1}), similar to control-thinned (C-T) at 21-years (\$485 ha^{-1}). Negative drought and fertilization interactions in non-thinned stands resulted in losses in FD by 26 and 31 years.

Results from sensitivity analysis provide important insights. On average, 3% and 7% interest increased input volume costs by 12% and decreased volume costs by 10%, respectively. For output prices, 3% interest increased output price by an average of 64% and 7% interest decreased output price by 38%. Interest rates can alter NPV calculations, but we assume rates to be inconsequential in terms of DEA. It has also been shown that present value calculations are more sensitive to inventory errors and growth modeling than interest rates (Holopainen *et al.*, 2010).

4. DISCUSSION

Because fertilized-thinned stands were the most optimal and profitable treatment, efficiency and slack results from DEA reinforce the use of typical plantation silviculture. Thinning demonstrated the consistent ability to mitigate profit lost, even under adverse drought conditions. Drought decreased efficiency with rotation age. Importantly, there was a significant drought and fertilization interaction whereby fertilization decreased efficiencies and economic returns under drier conditions.

4.1 TREATMENTS

The decreases in efficiency that occurred with age in the non-thinned treatments were probably linked to increased intraspecific competition and decreased resource availability. Thinning and is used to increase resource availability, increase DBH growth, and increase profitability. To that end, efficiency was stable in our thinned plots with increasing stand age. Stand productivity and stem accretion depends on nutrient and soil water availability (Allen *et al.*, 1990; Ryan *et al.*, 1997; Hennessey *et al.*, 2004). However, our results proved stand efficiency to be independent of stand productivity.

Fertilization, which increased productivity in all fertilized stands (F, F-T, FD, FD-T), decreased efficiency when combined with drought (FD, FD-T) (Table 3).

Decreased stem growth has been associated with decreased mid-rotation nutrient availability as stand-level demand for nutrients surpasses soil supply capacity (Allen *et al.*, 1990; Fox *et al.*, 2007b). In our models, fertilization successfully mediated nutrient declines in ambient plots and maintained perfect efficiency in thinned stands (Table 3) and is supported by numerous studies that mainly support mid-rotation fertilization in tandem with thinning (e.g Jokela *et al.*, 2004). Fertilization significantly reduced efficiency in drought stressed plots (FD, FD-T). This indicates that nutrient management will not be helpful to compensate for reduced efficiency related to drought conditions. Profit-wise, Fernández *et al.* (2018) found similar results within eucalyptus plantations. Additional fertilization decreased profitability, but managing for greater soil moisture availability, via irrigation, increased profitability. However, their results were driven by reduced stand-level mortality and increased capture of lower class product.

Soil moisture limits stem growth for loblolly pine, especially in the western part of its range (Moehring and Ralston, 1967; Hennessey *et al.*, 1992; Hennessey *et al.*, 2004). The drought*rotation age interaction (Figure 2) supports negative drought affects increase with stand age. Thinning may help maintain efficiency by decreasing water stress. Thinning can be used to increase stand-level drought resiliency (Sohn *et al.*, 2016), decrease stand-level water use (Teskey *et al.*, 1987), and increase tree-level vigor to drought (Skov *et al.*, 2004). Despite detrimental drought effects, i.e., less sawlog production and carbon storage, D-T stands had similar efficiency to C-T stands. Brèteau-Amores *et al.* (2019) argue that thinning is an effective management tool to mitigate economic losses during drought within beech (*Fagus sylvatica* L.) and Douglas-fir (*Pseudotsuga menziesii* Mirb.) dominated forests. Stand density management has successfully limited lost profit by ~20% under the most extreme drought conditions (Brèteau-Amores *et al.*, 2019).

Maintenance of high efficiency values in thinned drought-only stands (D-T) could be driven by more efficient production of smaller class product. Drought-induced stands produced less gross biomass and sawtimber, and pulpwood was a greater proportion of timber product (Table 1). Greater overall efficiency, again calculated as output/input, could potentially be influenced by decreased plot-level growth (input) and increased low-value product (output) (section 4.2). We also noted that profit efficiencies were lower than technical efficiencies in general. It is because non-thinned stands generally produced larger quantities of lower value products than thinned stands. It is worth noting that lower value timber product prices (e.g., sawlog) are relatively less suppressed in past decade (TFS, 2020) than high value sawlog prices. Therefore, smaller profit efficiencies, compared to technical efficiencies, make intuitive sense.

Future, drier climate conditions may have less impact if thinning is aggressively applied. Thinning moderates drought-related diameter growth decline and increases sawtimber development (Livingston and Kenefic, 2018). Under current climate conditions and traditional silviculture (thinning, fertilization, 25 to 30 year rotation age), sawtimber production primarily defines landowner objectives and profitability (Henderson and Munn, 2003). However, increased drought could lead to a future shift of primary products away from sawtimber in a scenario of relatively low sawtimber and adequate pulpwood or biomass prices (Henderson and Munn, 2003; Kantavichai *et al.*, 2014). Recently, increased woody bioenergy feedstock production has been advocated to increase global net carbon capture, (Favero *et al.*, 2020).

4.2 SLACKS

The slack results agree with the fundamental objectives of southern pine plantation silviculture, which is to maximize high-value products while minimizing initial investment (Table 4). As such, sawlog production and TPH were among the most prevalent slacks. Minimal slacks of volume growth, pulpwood, and CNS show that stands had adequate stem production in early to mid-rotation and low-value timber products (pulpwood, CNS) were generally less important from an efficiency standpoint.

Thinned stands showed nominal TPH and sawtimber slacks, while non-thinned showed larger TPH and sawtimber slacks (Table 4) which in turn led to lower efficiency. Decreased stand density leads to a greater proportion of a stand being classified as sawtimber at the end of the rotation (Amateis and Burkhart, 2005). There is direct inverse relationship between stand density and diameter growth (Will *et al.*, 2001; Will *et al.*, 2005). Thinning reduces intraspecific competition and increases diameter growth which produces sawtimber sized trees sooner, while non-thinned stands suffer greater tree mortality and stagnation (e.g. Hennessey *et al.*, 2004) which produces more pulpwood due to smaller average tree size and by leaving trees with defects (Amateis and Burkhart, 2005; Green *et al.*, 2018).

Unlike fertilizer and thinning, slower volume growth associated with drought, which was used as an input for DEA, is not an outcome of a management action. We attempted to reconcile this problem by using a categorical variable for drought treated plots (section 2.2.1). Further, a DEA sensitivity analysis was performed to determine pulpwood's influence on technical efficiency and high scores were found in D-T treatment (Supplementary Figure 1). Drought-thinned stands produced more pulpwood than any other thinned treatment, but produced less sawtimber, and stored less carbon (Table 1)

Carbon storage, a measure of gross plot production, also drove inefficiency. Carbon cycling and subsequent storage are important non-commodity based processes that decrease under soil moisture limitation (Bracho *et al.*, 2018). Our results indicate stand density management was more tightly associated with increased water availability than the dry climate scenario, as thinned drought stressed plots had the same efficiency as thinned non-drought stressed plots (Figure 2, Table 3). Lower density stands store less biomass and carbon than higher density stands (Burkes *et al.*, 2003). But, DEA examines the *efficiency* of each treatment regime- such as carbon stored per tree- not absolute production. Carbon efficiency from thinning was likely driven by greater increases in storage per tree than reductions in total stand biomass related to decreased stand density. Similar to sawlog production relationships, thinning leads to more high-value and long-lived products (Amateis and Burkhart, 2005), and accordingly greater long-term carbon storage (Nepal *et al.*, 2012).

Carbon pricing was not included in the presented models. To anticipate a future carbon market and understand potential pricing effects on efficiency we included carbon-pricing in the DEA price model at \$18 Mg C^{-1}, a suggested price to achieve carbon reform (Klenert *et al.*, 2018). Under all treatments, price efficiency, and thus overall efficiency, insignificantly changed. Marginal changes in efficiency indicate that a carbon market may not influence price or overall efficiency and supports our decision to exclude carbon from the price model. It also indicates that the suggested carbon price is not high enough to increase efficiency in control, fertilized, drought stressed, or non-thinned plots.

4.3 ECONOMIC ANALYSIS

Profit foregone analysis gives dollar value to the inability of specific treatments to produce rotation-defining sawtimber product. Results suggest that thinning minimizes profit loss with age, as all thinning treatments showed lower losses than the reciprocal non-thinned treatments. Mid-rotation thinning enhances long-term revenue by capturing intermediate revenue for landowners. Lost profit in non-thinned treatments, like F and FD plots with severe intraspecific competition, emphasize the importance of sawtimber production. All non-thinned stands eclipsed \$3,000 ha^{-1} lost by 26-years. Consequences from not managing competition include increased tree mortality (Hennessey *et al.*, 2004), stem defects (Green *et al.*, 2018), and ultimately decreased sawtimber production (Amateis and Burkhart, 2005). Relative prices of pulpwood and sawtimber determine the primary product and optimal rotation age for the landowners having profit maximizing goals. Generally, when pulpwood prices are approximately less than half of sawtimber prices, sawtimber production controls rotation profitability (Henderson and Munn, 2003).

Profit foregone values are founded upon NPV calculations across respective rotation ages. Since gatewood timber prices were used in the analysis, present value calculations and profit foregone results are much higher than if stumpage price were used as in Nepal *et al.* (2012) or Shrestha *et al.* (2015). In this paper, profit foregone is a cumulative value realized across three different ownership groups: the landowner, logger, and mill. Fertilization is not an indiscriminate practice (Albaugh *et al.*, 2019) and is often only done when financially attractive. In this analysis, it is assumed that fertilization costs will be outweighed by increased harvest revenue. Also, gatewood price can violate stumpage price fundamentals, where it is normally assumed that thinning generates positive revenue for the landowner. Evaluating with gatewood prices can occasionally generate negative revenues due to high harvesting costs and low cash-flow (Baumgras and LeDoux, 1991).

4.4 MANAGEMENT IMPLICATIONS

Our study results have important management implications. First, the DEA strongly indicated that thinning is the best tool to manage loblolly pine under drought conditions. Adding fertilization, with or without thinning, did not increase efficiency of drought stands. Our analysis demonstrates that the effective use of thinning, that primarily harvests pulpwood in the process, is economically and technically more efficient than accumulating higher volume by applying fertilizer. The role of thinning, as an adaptation tool to mitigate drought effects (see Sohn *et al.*, 2016), confirms its importance as a commonly adopted silvicultural action. Secondly, shorter-rotation silviculture is beneficial as it relates to efficiency in drought-induced or non-thinned stands, and may indicate a future shift in plantation management. If future droughts substantially increase mortality (Brèteau-Amores *et al.*, 2019) or tree defects (Green *et al.*, 2018), non-thinned, short rotation stands could provide an alternative to capture the greatest amount of total product (Kantavichai *et al.*, 2014). Additionally, the majority of forest landowners in the United States manage timberland for non-commodity objectives such as wildlife management, aesthetics, and bequests. Thinning is a well suited management action to meet these goals as it reduces canopy density and increases growth of herbaceous and understory woody plants, which provides an important habitat benefits game animal such as wild turkey and whitetail deer (e.g. Peitz *et al.*, 2001)

For private stakeholders, our results further call for effective forest management outreach under climate change. As a primary steward of forestland, private forest landowners are in the forefront of making forest management decisions. Therefore, outreach involving thinning, fertilization, and drought, and the associated economic efficiency are likely be well received by the landowners. Finally, publicly owned forests in the Southeastern U.S. mostly have limited management and are naturally regenerated (Oswalt *et al.*, 2019). Our results indicate managing intraspecific competition can increase forest value under drought conditions and ensure future timber production.

4.5 FUTURE RESEARCH

Our DEA models provide clarity to consequences realized from silvicultural options used to mediate drought effects - altering rotation age, thinning, and/or fertilization. Other avenues can be explored. Additional modeling is needed to understand climate change adaptation strategies like species substitution with shortleaf pine (e.g Susaeta *et al.*, 2014). With largely sympatric ranges, shortleaf pine is slower growing (Dipesh *et al.*, 2015), more fire tolerant (Stewart *et al.*, 2015), and presumably drought tolerant (Burns, 1990) than loblolly pine, and has been suggested as a replacement for loblolly pine on xeric sites (Guldin, 2019). Next, uneven-aged silviculture can be considered as an alternative to even-aged management. Uneven-aged management maintains regular sawtimber production to a greater extent than even-aged (plantation) management (Guldin and Baker, 1988) and invokes greater resilience to extreme climatic events (Diaci *et al.*, 2017). Such management could go hand-in-hand with shortleaf pine substitution, due to the species adaptation to fire, and fire's ability to create multi-cohort and structurally diverse forests (Guldin, 2019). Lastly, our DEA models can be improved upon through use of stochastic attributes, which could account for random variables like error, biological growth, and weather phenomena (i.e., drought) (Susaeta *et al.*, 2019). All of these additional insights provide ample opportunity to further knowledge between silvicultural options, production, and profit within loblolly pine management in the context of climate change.

5. CONCLUSIONS

DEA is a management aid to help identify inefficiencies among different management criteria and is useful to improve management practices. In our analysis, fertilized and drought-induced loblolly pine plantations without thinning on the western commercial extent had reduced efficiency and profitability. Under status-quo conditions, fertilization with thinning remains a profitable regime. Moreover, thinning had the greatest ability to manipulate high-value products and remains an essential tool to increase profits, indifferent of drought conditions. Under chronic drought conditions, DEA indicates fertilization is a poor management decision when used without thinning and that thinning should be used to mitigate lost profit. While our conclusions are specific to southeastern Oklahoma using the 10-year average timber prices, we expect similar trends in the Southeast region of the U.S.

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TABLE 1. Mean input and output criteria for eight treatment combinations (n=4) at rotation ages of 21, 26, and 31 years. Input was based on measured stand-level density and volume data, from 2012 (yr. 5) to 2019 (yr. 12). Output was modeled stem tonnage (Mg ha^{-1}) and total carbon storage (Mg C ha^{-1}). Dollar values were input costs and output prices, i.e., stand density divided by planting cost (Section 2.5). Abbreviations: control (C), drought (D; 30% throughfall reduction), fertilized (F; fertilized age 5 and age 10), and thinning (T; 40% BA reduction at age 10). Standard errors are in parenthesis. Average values (Avg.) represent non-thinned (NT) and thinned (T) treatments.

INPUT		**Drought**		**Stand Density** (yr 12)		**Volume Growth** (yr 5 to 12)		
yrs 5 to 12	**Treatment**	NA		trees ha^{-1}	Price input	m^3 ha^{-1}	Price input	
	C	0		1532 (51.78)	0.15	226.73 (9.84)	2.03	
	C-T	0		889 (24.54)	0.26	137.14 (4.38)	9.76	
	D	1		1597 (72.02)	0.15	213.16 (9.97)	2.16	
	D-T	1		894 (85.38)	0.27	127.56 (8.77)	9.98	
	F	0		1488 (31.48)	0.16	230.12 (6.83)	2.5	
	F-T	0		976 (34.23)	0.24	165.30 (7.19)	8.91	
	FD	1		1547 (87.17)	0.15	222.19 (15.18)	7.72	
	FD-T	1		891 (34.54)	0.26	140.24 (8.98)	4.14	
	Avg. NT	0.5		1541	0.15	223.05	3.6	
	Avg. T	0.5		913	0.26	142.56	8.2	
OUTPUT		**Pulpwood**		**Chip-n-Saw**		**Sawlog**		**Carbon stored**
21 yr	**Treatment**	Mg ha^{-1}	Price Output	Mg ha^{-1}	Price Output	Mg ha^{-1}	Price Output	Mg C ha^{-1}
	C	74.52 (2.79)	28.32	107.81 (13.12)	33.64	113.88 (5.83)	42.51	204.94 (6.52)
	C-T	51.88 (3.15)	46.45	46.37 (.30)	46.36	124.09 (3.07)	42.94	147.26 (1.14)
	D	64.16 (6.72)	28.32	142.69 (9.34)	33.64	62.24 (12.37)	42.51	92.18 (8.51)
	D-T	57.15 (5.50)	45.61	41.73 (10.28)	43.86	93.88 (6.36)	42.86	129.64 (4.31)
	F	71.52 (4.75)	28.32	106.34 (12.21)	33.64	118.00 (17.96)	42.51	207.89 (8.57)
	F-T	48.75 (3.84)	48.17	69.26 (4.05)	46.52	159.60 (3.34)	43.68	183.95 (6.05)
	FD	66.1 (6.84)	28.32	135.17 (8.18)	33.64	79.18 (17.78)	42.51	194.17 (11.60)
	FD-T	44.04 (2.63)	47.69	59.26 (6.76)	46.11	118.79 (8.88)	43.12	147.13 (7.99)
	Avg. NT	69.08	28.32	123	33.64	93.33	42.51	174.8
	Avg. T	50.46	46.98	54.16	45.71	121.54	43.15	138.23
26 yr	C	89.93 (1.75)	22.19	64.53 (5.13)	26.36	184.16 (6.48)	33.31	229.68 (7.07)
	C-T	51.88 (3.15)	46.45	45.71 (3.01)	46.52	180.61 (4.32)	33.77	169.29 (2.26)
	D	75.77 (4.51)	22.19	101.27 (9.4)	26.36	145.25 (13.18)	33.31	214.90 (9.41)
	D-T	59.61 (5.18)	45.35	31.26 (8.31)	46.44	154.01 (5.67)	33.57	145.00 (4.76)
	F	87.45 (6.03)	22.19	66.14 (11.52)	26.36	185.25 (15.40)	33.31	233.12 (8.62)
	F-T	49.12 (4.19)	48.12	67.97 (3.70)	46.52	227.2 (4.22)	34.53	210.17 (5.99)
	FD	79.71 (7.22)	22.19	89.34 (12.03)	26.36	159.85 (17.62)	33.31	216.03 (12.26)
	FD-T	48.52 (2.23)	46.94	51.72 (6.71)	46.52	179.7 (10.84)	33.75	163.46 (9.11)
	Avg. NT	83.22	22.19	80.32	26.36	168.63	33.31	223.43
	Avg. T	52.28	46.72	49.17	46.5	185.38	33.91	171.98
31 yr	C	102.84 (1.27)	17.39	42.81 (3.95)	20.65	230.19 (6.94)	26.1	244.46 (7.06)
	C-T	51.88 (3.15)	46.45	45.71 (3.01)	46.52	242.29 (6.69)	26.54	194.45 (3.91)
	D	90.39 (3.63)	17.39	78.5 (9.51)	20.65	189.23 (11.58)	26.1	229.25 (9.98)
	D-T	59.61 (5.18)	45.35	31.18 (8.35)	46.52	190.88 (6.35)	26.38	163.84 (5.27)
	F	103.58 (5.48)	17.39	40.11 (8.03)	20.65	231.55 (12.57)	26.1	246.56 (8.15)
	F-T	49.12 (4.19)	48.12	67.97 (3.70)	46.52	280.65 (3.17)	27.37	237.18 (5.85)
	FD	89.99 (7.28)	17.39	82.01 (12.25)	20.65	188.94 (16.98)	26.1	227.76 (12.12)
	FD-T	48.52 (2.23)	46.94	51.72 (6.71)	46.52	213.12 (11.57)	26.58	182.34 (10.02)
	Avg. NT	96.7	17.39	60.86	20.65	209.98	26.1	232.01
	Avg. T	52.28	46.72	49.15	46.52	231.74	26.72	194.45

TABLE 2. Costs and revenues used for price model to obtain profit efficiencies

Activities	Costs
Cost	
Site preparation	\$349.37 per hectare
Plantation	\$232.65 per hectare
Fertilization	\$239.66 per hectare
Thinning	\$11.39 Mg^{-1}
Revenue	
Pulpwood	\$25.16 Mg^{-1}
Chip and Saw(CNS)	\$29.38 Mg^{-1}
Sawtimber	\$43.34 Mg^{-1}

TABLE 3. Technical, price, and overall efficiency scores across 21, 26, and 31-year rotations, for eight treatment combinations (n=4). Abbreviations: control (C), drought (D), fertilized (F), and thinning (T). Distinctly inefficient treatments, θ < 0.9, are in bold. Average values (Avg.) represent non-thinned (NT) and thinned (T) treatments.

	Technical efficiency (θ_T)				**Profit efficiency** (θ_P)				**Overall efficiency** (θ_O)			
Treatment	21	26	31	Avg.	21	26	31	Avg.	21	26	31	Avg.
C	0.92	**0.85**	**0.89**	**0.89**	**0.89**	**0.74**	**0.83**	**0.82**	**0.82**	**0.64**	**0.76**	**0.74**
C-T	0.97	0.97	0.97	0.97	0.96	0.96	0.96	0.96	0.94	0.94	0.94	0.94
D	0.93	**0.83**	**0.79**	**0.85**	0.94	**0.64**	**0.61**	**0.73**	0.88	**0.54**	**0.49**	**0.64**
D-T	0.99	1	0.93	0.97	0.97	1	0.95	0.96	0.96	1	0.88	0.93
F	0.96	**0.84**	0.94	0.91	**0.86**	**0.66**	**0.80**	**0.78**	**0.83**	**0.55**	**0.77**	**0.72**
F-T	1	1	1	1	1	1	1	1	1	1	1	1
FD	0.91	**0.79**	**0.67**	**0.79**	**0.84**	**0.61**	**0.55**	**0.67**	**0.77**	**0.49**	**0.37**	**0.54**
FD-T	**0.83**	**0.86**	**0.78**	**0.82**	0.96	0.93	0.90	0.93	0.81	**0.80**	**0.70**	**0.77**
Avg. NT	0.93	**0.83**	**0.82**	**0.86**	0.97	0.96	0.95	0.96	**0.88**	**0.66**	**0.70**	**0.75**
Avg. T	0.95	0.96	0.92	0.94	**0.88**	**0.66**	**0.70**	**0.75**	0.97	0.96	0.95	0.96

TABLE 4. Average input and output technical slacks for rotation ages of 21, 26, and 31-year (yr) rotations for eight treatment combinations (n=4). Abbreviations: Control (C), drought (D), fertilized (F), and thinning (T). Slacks are input surpluses and output shortages determined from DEA optimization functions. Average values (Avg.) represent non-thinned (NT) and thinned (T) treatments.

INPUT SLACKS

	Drought			**Stand Density: yr 12** (tree ha^{-1})			**Volume Growth: yr 5 to 12** (m^3 ha^{-1})		
Treatment	21	26	31	21	26	31	21	26	31
C	0	0	0	11.67	110.21	29.88	0	9.98	2.96
C-T	0	0	0	31.00	30.55	19.43	2.71	2.31	0
D	0	0.12	0.22	30.10	102.74	71.70	0	0	0
D-T	0	0	0.20	17.64	0	13.91	0	0	0
F	0	0	0	30.29	49.60	7.28	3.04	12.13	0
F-T	0	0	0	0	0	0	0	0	0
FD	0	0.12	0.46	38.61	125.91	35.42	0	1.38	0
FD-T	0.42	0.34	0.56	50.93	42.98	52.40	4.69	3.75	4.07
Avg. NT	0	0.06	0.17	27.67	97.12	36.07	0.76	5.87	0.74
Avg. T	0.10	0.08	0.19	24.89	18.38	21.43	1.85	1.52	1.02

OUTPUT SLACKS

	Pulpwood (Mg ha^{-1})			**Chip-n-Saw** (Mg ha^{-1})			**Sawlog** (Mg ha^{-1})			**Carbon Stored** (Mg C ha^{-1})		
Treatment	21	26	31	21	26	31	21	26	31	21	26	31
C	0	0	0	0	0	5.52	31.80	81.22	70.48	24.47	29.88	30.51
C-T	0	0	0	0.62	0.56	2.01	1.81	2.85	2.96	1.28	1.78	5.24
D	0	0	0	0	0	0	17.90	69.23	102.26	8.65	28.70	45.65
D-T	0	0	0	0	0	0	1.19	0	2.01	0.42	0	1.84
F	0	0	0	0	6.40	2.73	16.09	75.72	35.80	8.24	29.15	17.04
F-T	0	0	0	0	0	0	0	0	0	0	0	0
FD	0	0	0	0	0	0	34.31	103.09	166.06	23.46	45.91	83.19
FD-T	0.05	0	0	0.20	0	0	0.43	2.43	6.54	1.19	3.26	5.96
Avg. NT	0	0	0	0	1.60	2.06	25.02	82.31	93.65	16.20	33.41	44.10
Avg. T	0.01	0	0	0.21	0.14	0.50	0.86	1.32	2.88	0.72	1.26	3.26

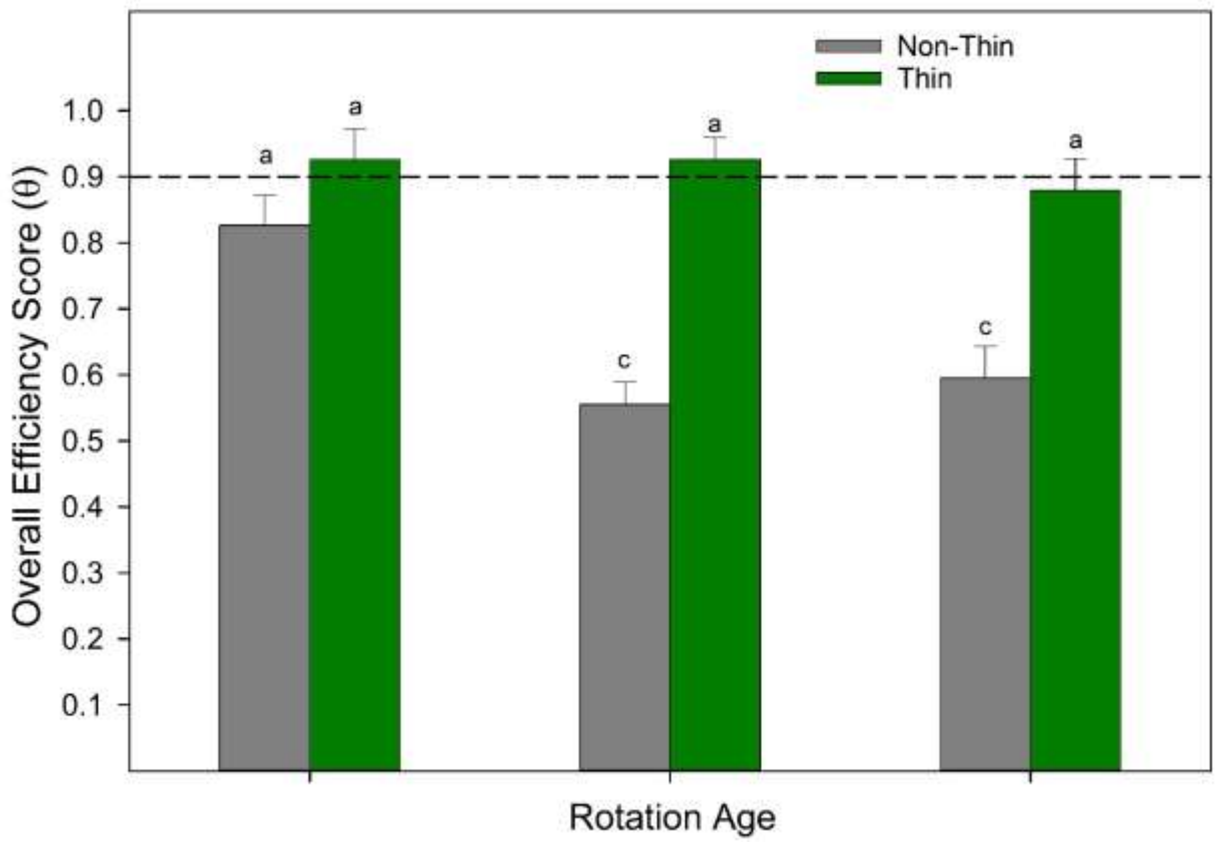


FIGURE 1: Average overall efficiency score of thinning treatments for 21, 26, and 31-year rotations, i.e., age*thinning interaction (n=16). Dashed line represents marginally inefficient threshold, θ= 0.9. Bars with different letters are significantly different ($p<0.05$). Standard errors are presented above bars.

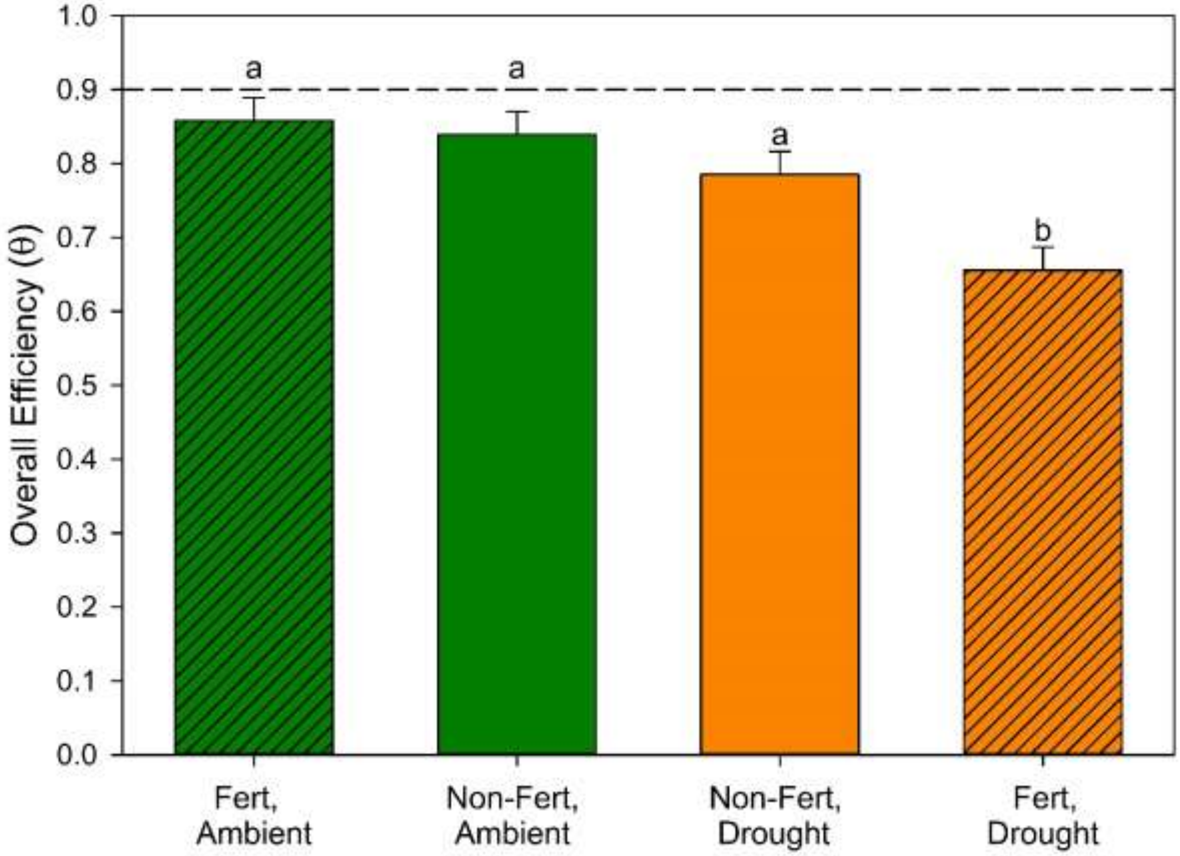


FIGURE 2. Average overall efficiency score for fertilization and drought treatments, i.e., fertilzation*drought interaction (n=8). Dashed line represents marginally inefficient threshold, $\theta = 0.9$. 'Fert' is fertilization. Fert, ambient (F, F-T); non-fert, ambient (C, C-T); non-fert, drought (D, D-T); and fert, drought (FD, FD-T). Bars with different letters are significantly different ($p<0.05$). Standard errors are presented above bars.

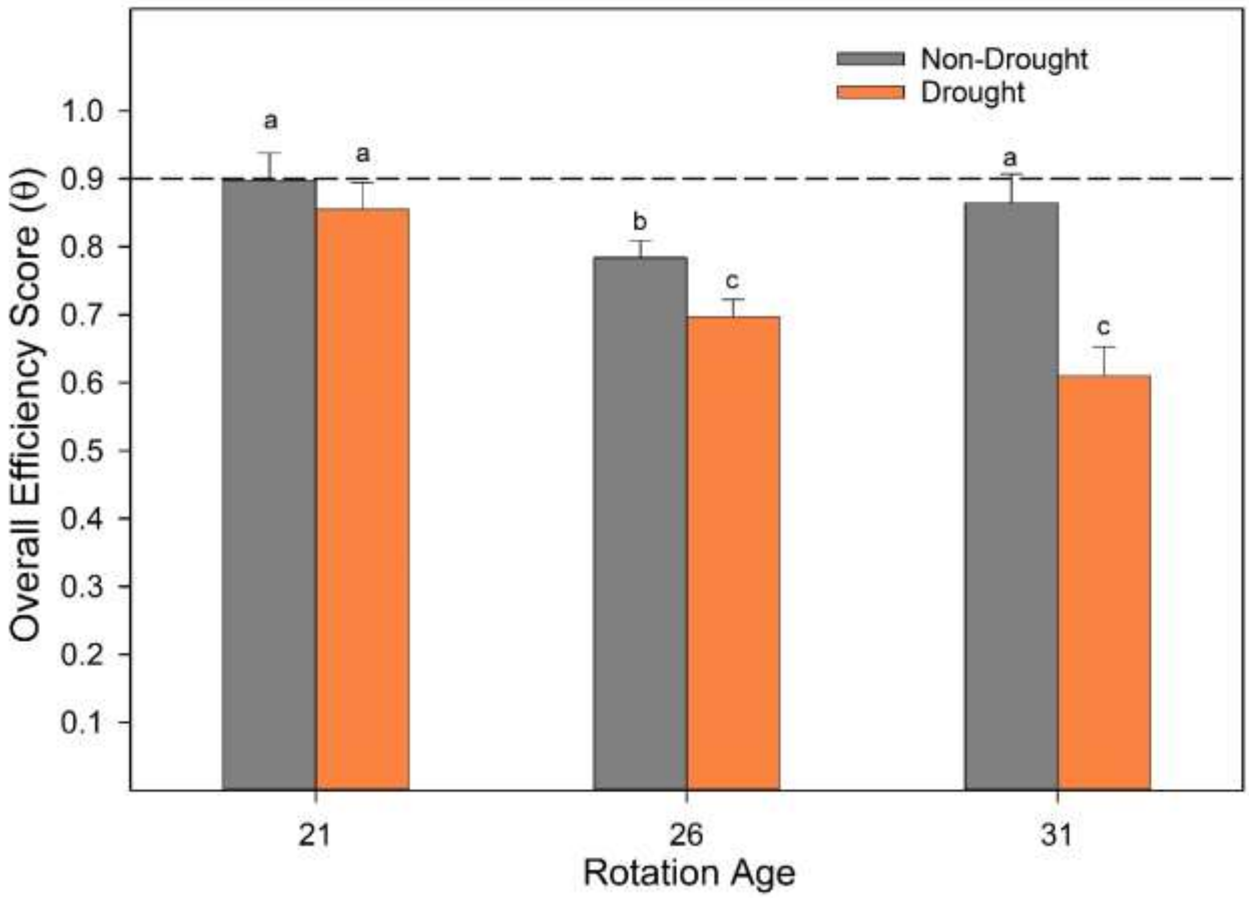


FIGURE 3: Average overall efficiency score of drought treatments for 21, 26, and 31-year rotations, i.e., age*drought interaction (n=16). Dashed line represents marginally inefficient threshold, θ= 0.9. Non-drought was C, C-T, F, and F-T. Drought was D, D-T, FD, and FD-T Bars with different letters are significantly different ($p<0.05$). Standard errors are presented above bars.

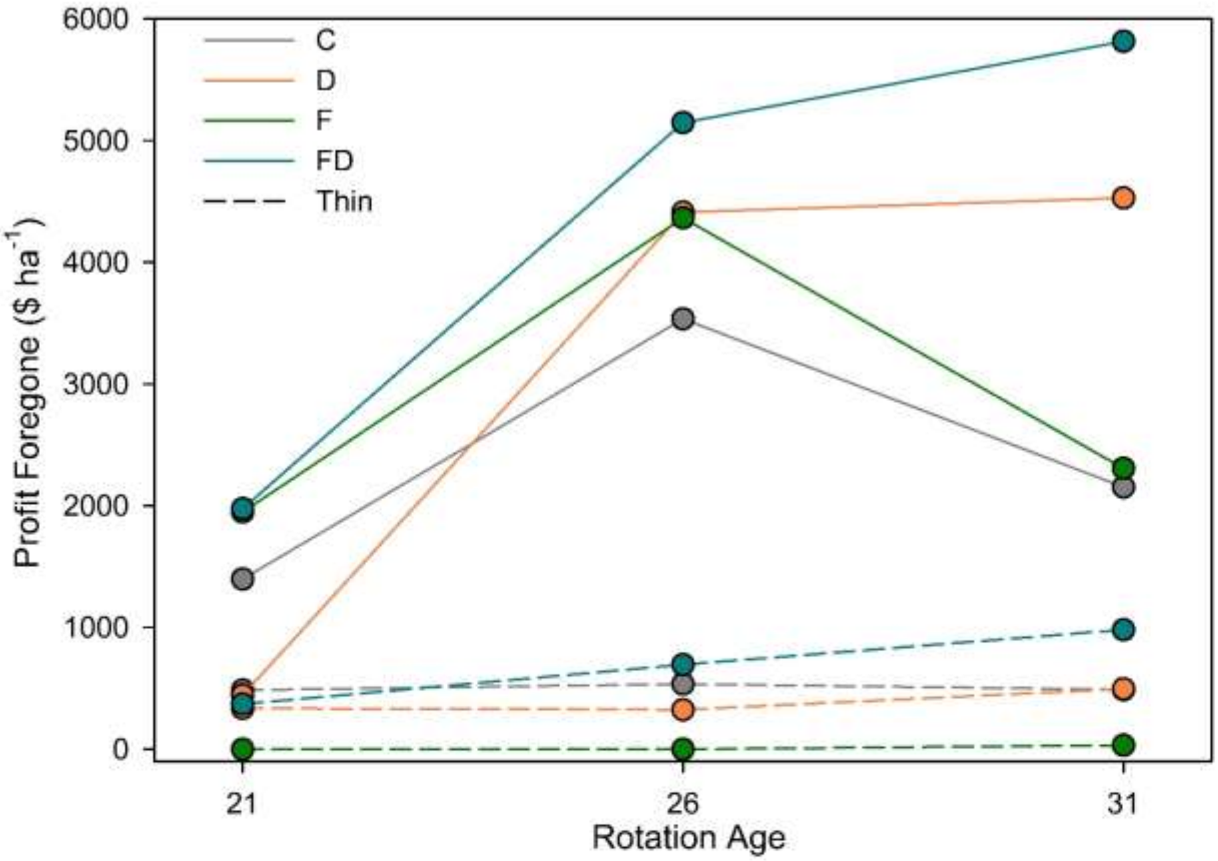
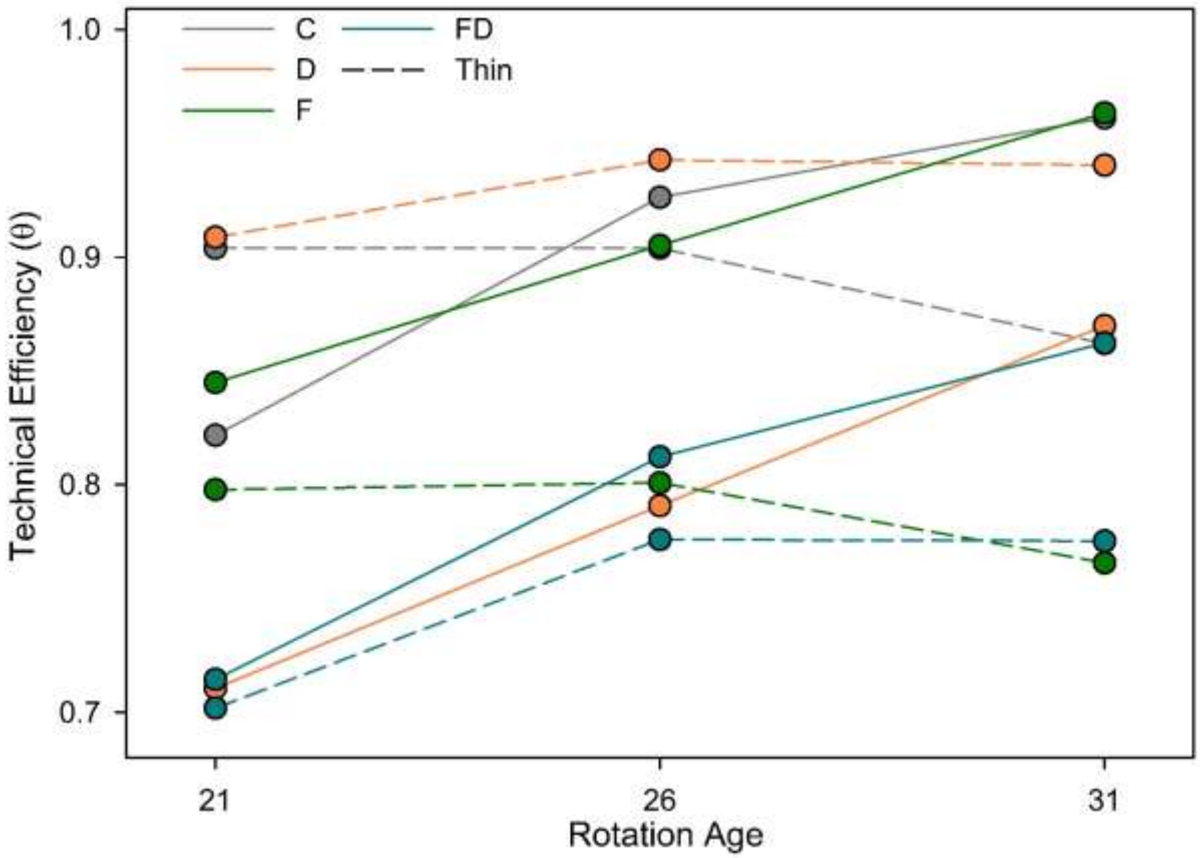


FIGURE 4: Profit foregone due to non-zero slacks of all treatment combinations for 21, 26, and 31-year rotations (n=4). Abbreviations: Control (C), drought (D), and fertilized (F).



SUPPLEMENTARY FIGURE 1: Technical 'pulpwood production' efficiency across 21, 26, and 31-year rotations (n=4). Chip-n-saw, sawtimber, and carbon storage were excluded from DEA models, only pulpwood production is included as an output. Abbreviations: Control (C), drought (D), and fertilized (F).
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CHAPTER V

CONCLUSION

Results from Chapters III and IV provided insight on how expected drought conditions could alter loblolly pine silvicultural regimes in southeastern Oklahoma. From both a growth and efficiency perspective, drought conditions were proven to be harmful for timber production. Thinning proved to be useful, even under drought, as it increased stem growth and radiation capture, and enhanced the ability of a stand to produce high-value sawtimber product across 21, 26, and 31-year rotation ages. Fertilization increased growth in droughted treatments and compensated biologically, however from a resource-cost perspective, fertilization incurred negative consequences.

The long-term, mid-rotation growth results from Chapter III showed that simulated-drought from age 5 to 12 decreased aboveground growth by 7% and fertilization at age 5 and 10 increased aboveground growth by 8%. Each treatment had similar effects in terms of magnitude, thus offset one another, and resulted in mid-rotation fertilization compensating for simulated drought. Thinning in fertilized plots highlighted complementary treatment effects, and increased canopy radiation capture by 5%. Over the course of eight years, drought-induced plots rebounded from dry periods, and demonstrated increased diameter growth, +10%, during wet periods. Growth relationships from fertilization, thinning, and drought treatments suggest that traditional loblolly pine silviculture will remain productive in the near future.

Chapter IV resource-use analysis also supported traditional silviculture under the current climate, but indicated drought to reduce fertilization efficacy. Thinning increased efficiency by 32%, as compared to non-thinned stands, and remained a management staple. Drought decreased efficiency after 26 years and suggests negative drought consequences to increase with time. Fertilization effects were dependent on soil moisture availability. Fertilized-thinned stands, without drought, proved to be the most efficient regimes. However, fertilization with drought decreased efficiency by 24%. Results provide novel insight by comparing different silvicultural options using a data-driven, resource-use approach, and suggests fertilization failed to compensate for sustained drought.

The research presented provides important information on management options to timberland owners experiencing drought. As anticipated climate change consequences, primarily decreased soil moisture, threatens the sustainability of southern pine plantations, thinning is essential to ensure future productivity. From the contrasting growth and efficiency results, it remains to be seen if fertilization will be generally beneficial or harmful over a rotation age, and warns fertilization to be used with caution under drought. Drought-induced trees proved to be vigorous after meteorological drought and suggests western loblolly pine to be drought-resilient. Ultimately, results provide hope for the future productivity of loblolly pine and supports future research to expand on long-term drought effects.

VITA

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Master of Science

Thesis: LONG-TERM ABOVEGROUND GROWTH, CANOPY DYNAMICS, AND ECONOMIC IMPLICATIONS FROM THROUGHFALL EXCLUSION, FERTILIZATION, AND THINNING IN SOUTHEASTERN OKLAHOMA, USA

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