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A stand level application of efficiency analysis to understand efficacy of fertilization and thinning with drought in a loblolly pine plantation

Noah T. Shephard [a], Omkar Joshi [a,*], Andres Susaeta [b], Rodney E. Will [a]

[a] Department of Natural Resources Ecology and Management, Oklahoma State University, Stillwater, OK 74078, USA
[b] School of Forest Resources and Conservation, University of Florida, Gainesville, FL 32611, USA

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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.

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., 2016a, 2016b, 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

* Corresponding author.
E-mail address: omkar.joshi@okstate.edu (O. Joshi).

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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),

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 *yrs 5 to 12*	**Drought Treatment**	NA	**Stand Density** (yr 12) trees ha^{-1}	Price input	**Volume Growth** (yr 5 to 12) 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	Treatment	**Pulpwood** Mg ha^{-1}	Price Output	**Chip-n-Saw** Mg ha^{-1}	Price Output	**Sawlog** Mg ha^{-1}	Price Output	**Carbon stored** Mg C ha^{-1}
21 yr	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 (0.30)	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

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 cm 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).

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}

2.6. 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.

2.7. 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.

2.8. 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, Fig. 1). Fertilization and drought had a negative synergistic interaction. On average, fertilized-ambient (F, F-T) stands had the highest average scores ($\theta_O = 0.86$) and fertilized-drought

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

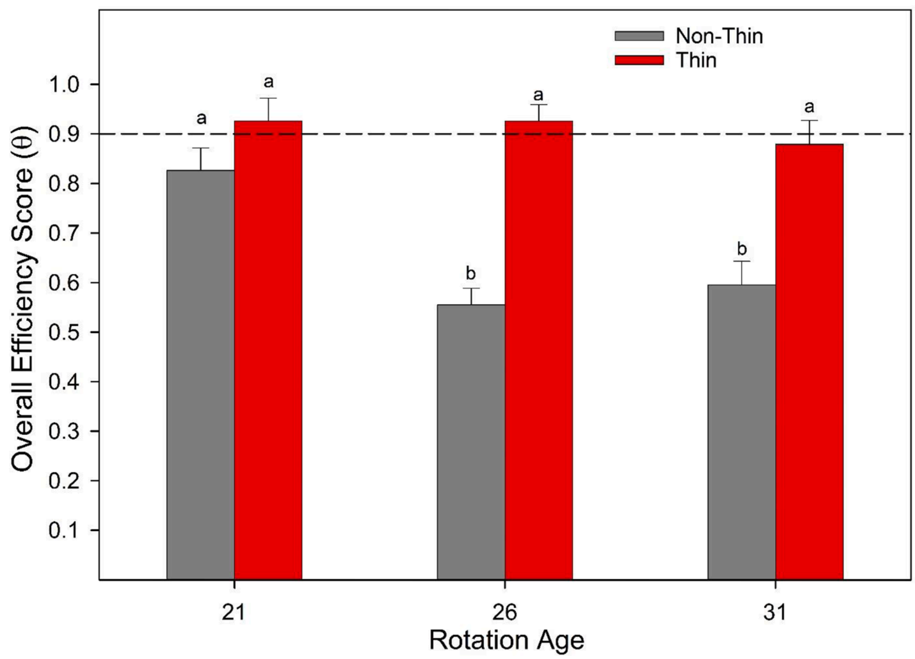

Fig. 1. Average overall efficiency score of thinning treatments for 21, 26, and 31-year rotations, i.e., age*thinning interaction (n = 16). Dashed line represents marginally inefficient threshold, θ = 0.9. Bars with different letters are significantly different ($p < 0.05$). Standard errors are presented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

(FD, FD-T) stands had one the lowest average scores ($\theta_O = 0.66$), 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 ($\theta_T = 1$), followed by C-T and D-T stands (average $\theta_T = 0.97$). In contrast, D, and FD stands demonstrated the lowest scores among treatments which decreased with stand age ($\theta_T < 0.83$) (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 $\theta_O = 0.70$; non-drought $\theta_O = 0.78$) at 26 years and 29% (drought $\theta_O = 0.61$; non-drought $\theta_O = 0.86$) at 31 years (Fig. 2). Drought effect increased with time since non-drought stressed plots increased in overall efficiency between 26 and 31 years, +10% (Fig. 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 (Fig. 3). Thinning produced a positive effect and decreased lost profit. All thinned stands

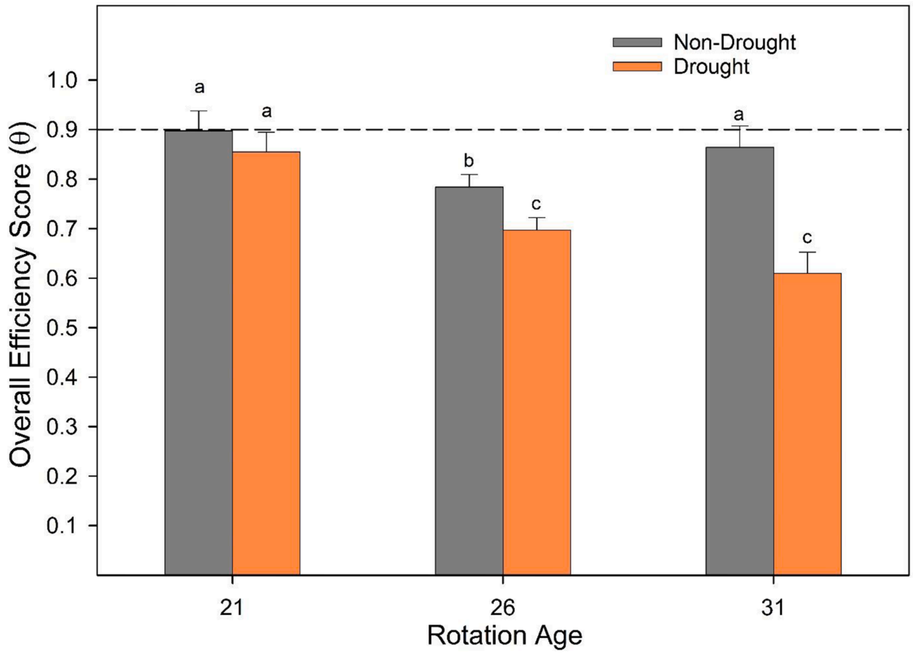

Fig. 2. Average overall efficiency score of drought treatments for 21, 26, and 31-year rotations, i.e., age*drought interaction (n = 16). Dashed line represents marginally inefficient threshold, θ = 0.9. Non-drought was C, C-T, F, and F-T. Drought was D, D-T, FD, and FD-T bars with different letters are significantly different ($p < 0.05$). Standard errors are presented above bars.

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

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%

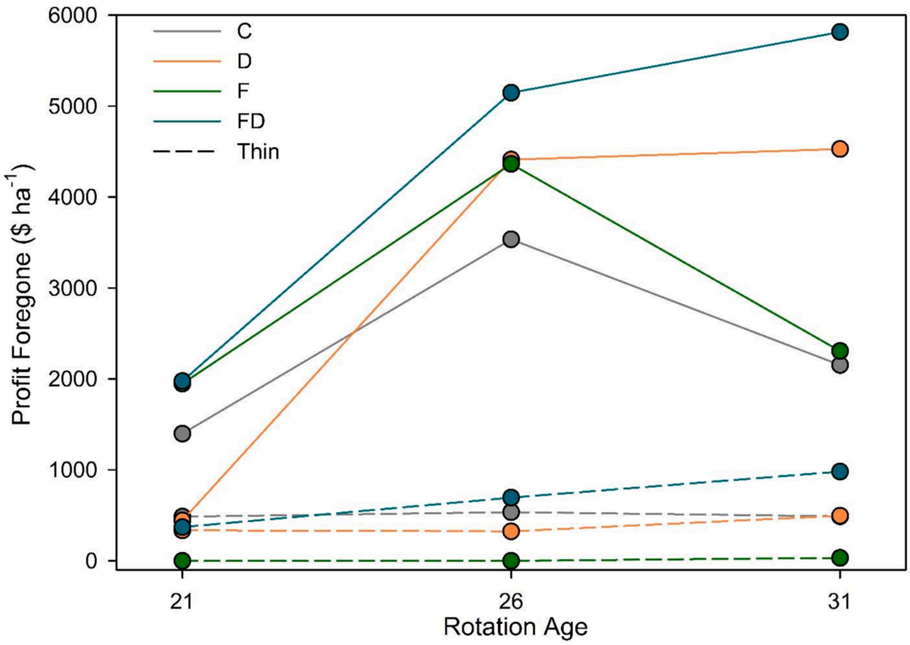

Fig. 3. Profit foregone due to non-zero slacks of all treatment combinations for 21, 26, and 31-year rotations (n = 4). Abbreviations: Control (C), drought (D), and fertilized (F).

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 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 (Fig. 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 Fig. 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 (Fig. 2, Table 3). Lower density stands store less biomass and carbon than higher density stands (Burkes et al., 2003). The DEA, however, 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.

CRediT authorship contribution statement

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

Declaration of Competing Interest

None.

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