



Effects of establishment fertilization on Landsat-assessed leaf area development of loblolly pine stands

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ABSTRACT

Loblolly pine (*Pinus taeda* L.) plantations in the southeastern United States are among the world's most intensively managed forest plantations. Under intensive management, a common practice is fertilizing at establishment. The objective of this study was to investigate the effect of establishment fertilization on leaf area development of loblolly pine plantation stands ($n = 3997$) over 16 years compared to stands that did not receive nutrient additions at planting. Leaf area index (LAI) is a meaningful biophysical indicator of vigor and an important functional and structural element of a planted stand. The study area was stratified by plant hardness zone to account for climatic differences and soil type (texture and drainage class), using the Cooperative Research in Forest Fertilization (CRIFF) groupings. LAI was estimated from Landsat imagery to create trajectories of mean stand LAI over 16 years. Establishment fertilization, on average, (1) increased stand LAI beginning at year two, with a peak at years six and seven, and (2) decreased the time required for a stand to reach a winter LAI of 1.5 by almost two years. Fertilization responses varied by climate zone and soil drainage class, where the warmest zones benefited the most, particularly in poorly drained soils. Past year 10, the differences in LAI between fertilized and unfertilized stands were not practically important. Using Landsat data in a cloud-computing environment, we demonstrated the benefits of establishment fertilization to stand LAI development using a large sample over the native range of loblolly pine.

1. Introduction

Pines (*Pinus* spp.) in the southeastern United States (U.S.), such as loblolly pine (*P. taeda* L.) and others, are important commercial species, meeting much of the demand for lumber and pulpwood in the U.S. (Adegbiroti et al., 2002; Jokela et al., 2010, 2004; Zhao et al., 2016). Jokela et al. (2010) stated that forests in the southeastern U.S. have seen a significant evolution in forest management practices over the last 60 years. The acreage of planted pine in the U.S. increased from ~800,000 ha in 1952 to over 16 million hectares in 2010 (Carter et al., 2015) and now accounts for nearly half of the southern forest area (Zhao et al., 2016). While the acreage of southern pine stands receiving fertilization

treatments has grown from 80,000 ha in 1990 to more than 485,000 ha in 2004 (Jokela et al., 2010) fertilization treatments have decreased, generally, since then to 240,000 ha in 2016 (Albaugh et al., 2019). Changes in economic conditions and new research have been mentioned as reasons for the decline in acreage fertilized (Albaugh et al., 2019).

Effective silviculture is essential to improve yields of plantations in the southeastern U.S. Intensive management aims to address site-related resource limitations to optimize stand value (Allen et al., 2005). Southern pine plantations are among the most intensively managed forests in the world (Zhao et al., 2016). Accurate and timely information is essential in making correct management decisions. Collecting such information has been predominantly field-based, which is costly and challenging to scale

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up. We hope to help inform management decisions by investigating the effects of establishment fertilization on leaf area development of loblolly pine stands over time using remote sensing data (Blinnetal, 2019).

1.1. Fertilization of planted stands

With plantations in the southeastern U.S. being some of the most intensively managed stands in the world, it is crucial to identify what intensive means. Extensive management can be considered natural regeneration of a harvested stand without site improvement or directed management. In contrast, intensive management involves calculated decisions and routine interventions to maximize yield from harvest to harvest. Conditions of the land on which stands are planted, and the surrounding environment, are referred to as site conditions. In intensive management regimes, these site conditions are evaluated and individually optimized for a given stand's productivity (Allenetal, 2005). Managers use these strategies to minimize costs per unit area and maximize productivity.

In the southeastern U.S., pine plantation growth (increase in merchantable volume per unit area per year; used throughout) is commonly limited by soil nutrient availability and deficiencies of nitrogen (N) and phosphorous (P) (Albaughetal, 2021;Cohrsetal, 2020; Comerford, 1985;Foxetal, 2007;Jokelaetal, 2010). Accordingly, fertilization is an important component of intensive management. It is significant to note that multiple studies have indicated that water limitations are less impactful than nutrient deficiencies, regardless of soil type (Allenetal, 2005;Comerford, 1985;Foxetal, 2007;Jokelaetal, 2010). There are two epochs within a stand's lifecycle when fertilizations typically happen; at the time of planting and mid-rotation (Foxetal, 2007). Other studies have concluded that soil nutrient supply may be more important than genetic and climatic limitations as a variable affecting potential productivity and maximum basal area accretion in the southeastern U.S. (Comerford, 1985;Foxetal, 2007;Jokela, 2004; Jokelaetal, 2010).

1.2. Leaf area index

Leaf area index (LAI) is the total surface area of leaves per unit area of ground (for this research, the unit area of ground is the size of a Landsat pixel: 900 m²) (Curranetal, 1992). LAI determines the amount of radiation intercepted. (VoseandAllen, 1988). LAI can be measured by examining litterfall, but it is time-consuming. Research has shown that silvicultural inputs like fertilizer additions can increase LAI in loblolly pine stands, and LAI can be used as an indicator of the effectiveness of those additions (Albaughetal, 1998;Blinnetal, 2019;Campoeetal, 2013; Samuelsonetal, 2014). These studies have shown that remotely sensed LAI can be accurately estimated and used as an indicator for stand productivity (Albaughetal, 1998;Blinnetal, 2019;Campoeetal, 2013; Samuelsonetal, 2014). Experiments on loblolly pine across different locations and ages found a strong, positive, and linear relationship between leaf biomass and productivity (Teskeyetal, 1987;Vose, 1988). Over time, equations have been developed to estimate LAI using different remote sensing instruments (e.g., Landsat, Sentinel-2), which can be used to estimate LAI over a large region (Blinnetal, 2019;Floresetal, 2006). Flores et al. (2006) focused on Landsat 5(TM), while Blinn et al. (2019) focused on Landsat 7 (ETM+) and Landsat 8 (OLI). This research uses the Blinn et al. (2019) equation, as our data is corrected for surface reflectance and has a similar spatial extent, plus needs a longer time series than Sentinel can provide (Blinnetal, 2019).

1.3. Objectives

Our goal for this research was to investigate the effect of establishment fertilization on loblolly pine plantation leaf area development over time using Landsat time series data. Our objectives were to: (1) examine differences in leaf area development over time and peak leaf area

between stands fertilized at establishment (received no other recorded interventions) and those that received no fertilization at establishment or mid-rotation, no recorded thinning, and no recorded vegetation management after establishment, and (2) determine whether or not impacts of establishment fertilization on leaf area development are influenced by soil group or hardiness zone.

While numerous studies have shown different responses to fertilization under differing conditions, they are limited to plots in fertilizer trials, which do not completely span the geographic extent of loblolly pine plantations. Using remote sensing to monitor changes in LAI over time allows researchers to examine fertilizer response at a regional scale. This research will allow for a more customized approach to determining the timing of subsequent fertilizations and/or scheduling additional interventions as a given stand progresses through its lifecycle.

2. Materials and methods

2.1. Study area

This study was conducted across 11 states in the southeastern U.S. The number of loblolly pine stands found in each state can be seen in Fig. 1.

2.2. Studied plantations

Plantation stands used in the study were drawn from International Paper (IP) Company's record of former (prior to divestment in 2006) land holdings across the southeastern U.S. Within these holdings, there were 131,891 stand records, which contained stands of differing tree species, including both hardwoods and pine. We filtered this dataset according to the following criteria:

- Major species: loblolly pine
- Secondary species: none
- Year established: after 1990 and before 1999
- Year fertilized: within two years of year established or none
- Soil code: any non-blank record
- Year of last vegetation management: none
- Year of last harvest: none or before year established

In total, 39,422 stands were recorded to have a major species of loblolly pine with no record of a secondary species on the site. Of those, 3997 met the requirements mentioned above. The selected stands were buffered inwards by 30 m (Landsat spatial resolution) to account for mixed pixels along stand edges. Only stands larger than 10 acres (~4 ha) were included to ensure an adequate number of pixels would be used in obtaining the mean stand LAI value. This size limitation resulted in a minimum of 45 pixels per stand used to calculate LAI. Stand shape varied from a single polygon (19.3 acres (7.8 ha)) to multiple polygons (three separate polygons totaling 206.1 acres (83.4 ha)) (Fig. 2).

Competing vegetation for the stands used in this study was controlled at establishment using standard prescriptions (e.g., chemical site prep and herbaceous weed control). No subsequent vegetation control was recorded for either treatment in the study. After establishment, both treatment groups were treated the same as mentioned in the criteria bullets above.

2.3. Treatment types, soils, and hardiness zones

Stands were further filtered into two groups or removed from evaluation if specific criteria for each group were not met (e.g., no soil attributes recorded). The two treatment groups were: *Fertilized* (1515 stands) and *No Intervention* (2482 stands). A *Fertilized* stand must have been fertilized within two years of the recorded establishment year and with no other management interventions after the establishment year. A *No Intervention* stand must not have had any management interventions

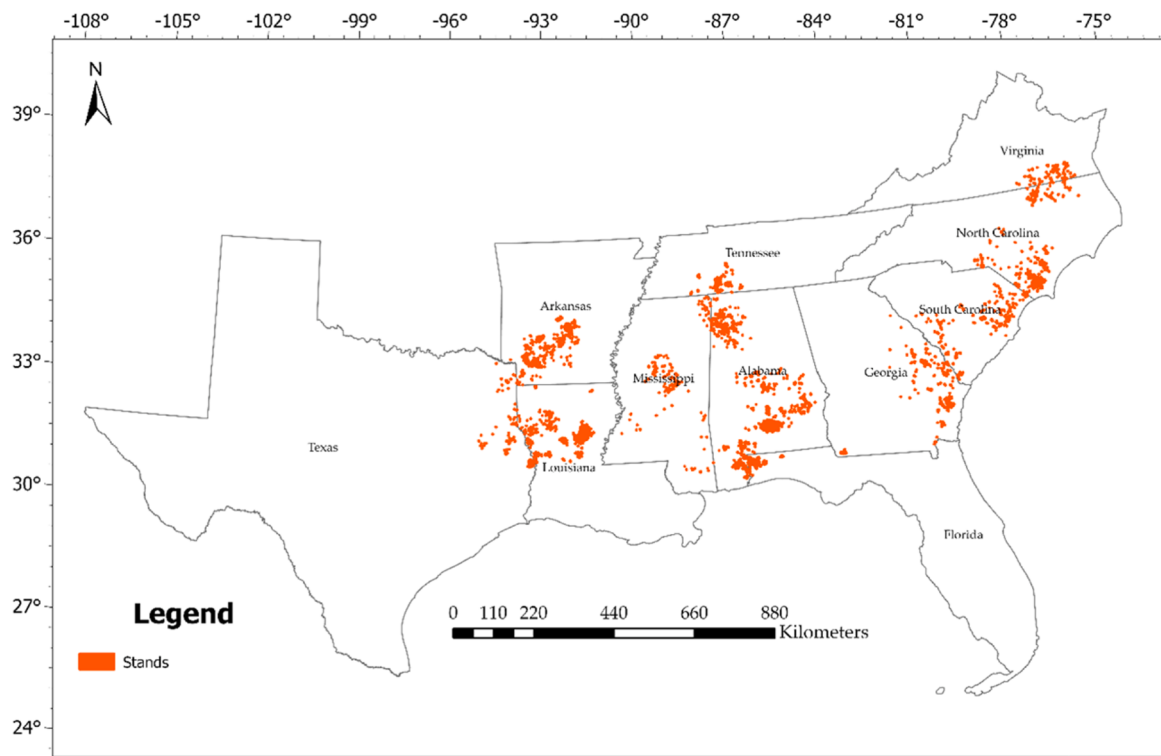


Fig. 1. The orange dots show the extent of the study area and the representation of stands used in this study for each state.

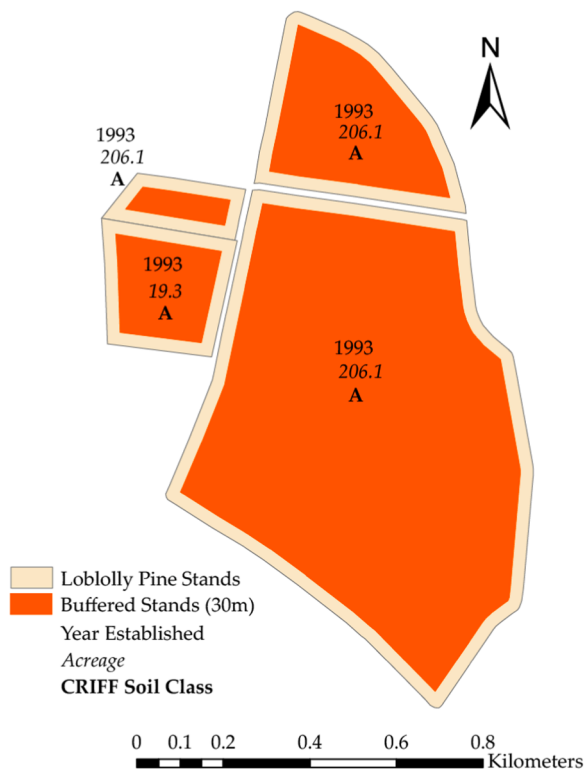


Fig. 2. Sample of neighboring stands that shows what a stand in the dataset could be: a single polygon (19.3 ha) or multiple polygons (totaling 206.1 ha) associated with a unique ID. The original shape is shown in light yellow with the buffered shape overlaid in orange, indicating how edge pixels were accounted for.

since the recorded establishment year. Since stands were selected from a company's landholdings, some bias in the type of sites is inherent as deficient sites would be more likely to receive fertilization.

We extracted the CRIFF (Cooperative Research in Forest Fertilization) soil group for each stand. CRIFF groups were developed to make fertilization prescriptions and are based on broad soil drainage classes and depth of soils to a subsoil layer (typically clays) (Dickensetal, 2004; JokelaandLong, 2015). For this study, the CRIFF groups were used as the soil groupings for each treatment type. Within the data set, there were A-H CRIFF groups. However, only A, B, E, and F were common enough to be included. The CRIFF groups used are summarized in Table 1.

In CRIFF groups A and B, approximately 52% and 53%, respectively, of the stands were fertilized. In comparison, roughly 31% of the stands were fertilized in CRIFF groups E and F. This is in line with research that suggests poorly drained, clayey soils have a strong response to fertilizer additions (PritchettandComerford, 1982;ScottandBliss, 2012;Wellsetal, 1973). We also stratified the stands by hardness zones (Table 1) to assess the expected ranges of perennial plants (Krakauer, 2012, 2018).

Table 1
CRIFF group definitions (Dickensetal, 2004;JokelaandLong, 2015) and hardness zones used, defined by average annual minimum winter temperature.

CRIFF Group	Definition
A	Surface layer < 20 in (50.8 cm), with finer textured soil horizon below; very poor to somewhat poorly drained
B	Surface layer > 20 in (50.8 cm), with finer textured soil horizon below; very poor to somewhat poorly drained
E	Surface layer < 20 in (50.8 cm), with finer textured soil horizon below; moderately well to well drained
F	Surface layer > 20 in (50.8 cm), with finer textured soil horizon below; moderately well to well drained
Zone	Average Annual Minimum Winter Temperature
7a	0 to 5 °F (−17.8 to −15 °C)
7b	5 to 10 °F (−15 to −12.2 °C)
8a	10 to 15 °F (−12.2 to −9.4 °C)
8b	15 to 20 °F (−9.4 to −6.7 °C)

Hardiness zone determinations take into account elevation, proximity to the coast, and temperature inversions using Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate data (Daly et al., 2012). Across the southeastern U.S., virtually all loblolly seedlings are a product of tree improvement programs. Research has found that moving seed sources across multiple hardiness zones is not recommended (McKeand et al., 2006, 2003; Schmidting, 2001).

After stands were stratified by soil type and hardiness zone, some groups were too small (<60 stands) to be used in the final analysis due to extreme data imbalances (Table 2). Since there were only six fertilized samples in the 7aE combination we removed it. 7a is the most northerly hardiness zone in our study area and there were very few fertilized stands in that area. Fig. 3 shows the extent of the hardiness zones and how many stands are in each. Hardiness zone 7a contained 158 stands, and it is the northernmost zone in our study area. Split across four soil types, only one of the well-drained soil classes (i.e., Group E) had enough stands to compare across treatment types. Approximately 83% of the total stands in this study fell in hardiness zone 8a (second most southern) or 8b (most southern), where these hardiness zones have an average lowest winter temperature between 10–15°F (−12.2 to −9.4 °C) and 15–20°F (−9.4 to −6.7 °C), respectively, making them less likely to have a sustained damaging cold period. The cold tolerances of seed sources and the nurseries they originated from are unknown.

2.4. Landsat and Google earth engine

The Landsat program has provided global coverage of multispectral Earth resource satellite imagery since 1972. As a medium-resolution sensor with a 16-day repeat cycle, it works well for large-scale analyses over time (Landsat:Agloballand-observingprogram,2003). To access these data, we used Google Earth Engine (GEE), which is uniquely suitable for this type of analysis. GEE is a cloud platform supported and run by Google which provides the ability to conduct extensive regional studies over time by providing access to a suite of geographic data sets and satellite data streams, including the Landsat archive.

We used imagery starting in 1984 from the Landsat collection, including Landsat 5 TM (Thematic Mapper), Landsat 7 ETM+ (Enhanced Thematic Mapper Plus), and Landsat 8 OLI (Operational Land Imager). In the GEE code editor, the imagery was used to create Landsat-derived LAI using surface reflectance data. Using USGS Tier 1 surface reflectance data allowed us to have uniformity between scenes and sensors where each scene was atmospherically corrected to account for atmospheric distortions. Landsat 8 uses Land Surface Reflectance Code (LaSRC), while Landsat 5 and Landsat 7 use the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) algorithm (version 3.4.0) to generate surface reflectance scenes (Masek et al., 2006; Vermote et al., 2016). Each scene used in this analysis was cloud masked and processed in the same fashion. Once all scenes were processed, the simple ratio (SR) (NIR/Red) (wavelengths used shown in Table 3) (Birth and McVey, 1968) was computed and LAI was derived (equation defined in 2.5 below) (Blinn et al., 2019).

Table 2

Stands by hardiness zone (H-Zone) and soil type. The light blue values indicate factorial combinations left out of the quantitative analysis.

H-Zone		A Soils	B Soils	E Soils	F Soils	Total
7a	Fertilized	0	0	6	0	6
	No Intervention	1	0	151	0	152
7b	Fertilized	38	1	51	10	100
	No Intervention	24	2	405	11	442
8a	Fertilized	266	59	437	64	826
	No Intervention	268	102	577	90	1037
8b	Fertilized	234	95	197	57	583
	No Intervention	205	32	429	185	851
	Fertilized					1515
	No Intervention					2482

After computing an LAI image from each raw scene, the time series of scenes from all three sensors were combined into a single chronological data set. This data set was then filtered to winter scenes (December, January, and February) between 1990 and 2020. We first derived the mean LAI value for each using the stand boundaries. Then using these values, we derived stand-level mean LAI values for each year, which were output as a CSV with 31 timestamps from 1990–2020 for each stand. An overview of this process is provided in Fig. 4.

2.5. LAI generation and application

LAI is commonly used in silvicultural decision support (e.g., stands with low leaf area were found to respond to fertilization because it indicates that the stands were nutrient deficient) (Allen et al., 2005; Blinn et al., 2019; Rubilar et al., 2018). We analyzed stands by using leaf area levels to indicate how actively a stand was growing. And using LAI across time at the stand level, we can review an increase in a stand's LAI and its trajectory. Through trajectories of LAI by treatment type and controlling for soils and hardiness zones, we can evaluate the effectiveness of fertilizations over the control. By leveraging the attribute data of when each stand was planted, a common starting point for each trajectory was established. LAI was calculated using the equation ($LAI = -0.00212 + 0.3329SR$) (Blinn et al., 2019) since the equation was developed for loblolly pine and surface reflectance Landsat data. The equation was applied within the Google Earth Engine (GEE) interface prior to downloading data. The spatial extent of our study area precluded us from examining all pixels in each stand individually. GEE provides methods to garner statistics for a given area which allowed us to reduce the volume of data to a single LAI value per stand per winter. Winter LAI was chosen to minimize the effect of any new competing vegetation after stands were established and competing vegetation was initially addressed. Winter LAI is roughly 50% of peak pine LAI.

2.6. Evaluating LAI trajectories

The data from GEE were used to create LAI trajectories for each stand by year from establishment. We plotted the mean LAI across all stands for each year to look for spatial and temporal differences between *Fertilized* and *No Intervention* trajectories. Trajectories were also examined by treatment type and by stratifications. A more robust evaluation of these trajectories was conducted using general linear mixed models (GLMM).

A GLMM was fit to determine if there were statistically significant differences in the LAI response with respect to fertilization (SAS 9.4 Proc GLIMMIX; Appendix A). Within the GLMM, radial smoothing splines were used to smooth the time series (rsmooth option). Site IDs for each stand were designated as a random subject effect within treatments to account for repeated measurements at each site over the 13 years of the study. The commonly used Newton-Raphson convergence method and the Kenward-Roger degrees of freedom estimation options were used to fit the model (Kenward and Roger, 1997). The best linear unbiased predictors were calculated for the model which includes the fixed effects for *Fertilizer* and *No Intervention* and accounts for repeated measures within Site IDs across all years established by hardiness zone and soil type. The nature of the radial smoothing model does not provide for calculating differences in the *Fertilized* versus *No Intervention* by years. To visualize the differences between the two groups across the years, 95% confidence intervals on the differences in the *Fertilized* versus *No Intervention* group were calculated using the BLUPs from the model. Confidence intervals on the difference of the *Fertilized* versus *No Intervention* group means with lower bounds greater than zero can be interpreted as the *Fertilized* LAI response being significantly greater than the *No Intervention* response. 95% confidence intervals were used. Soil and hardiness zone combinations with less than 60 stands were excluded from the comparison, as those combinations had extreme data imbalances. Additionally, cumulative LAI for the first six years was collected for hardiness

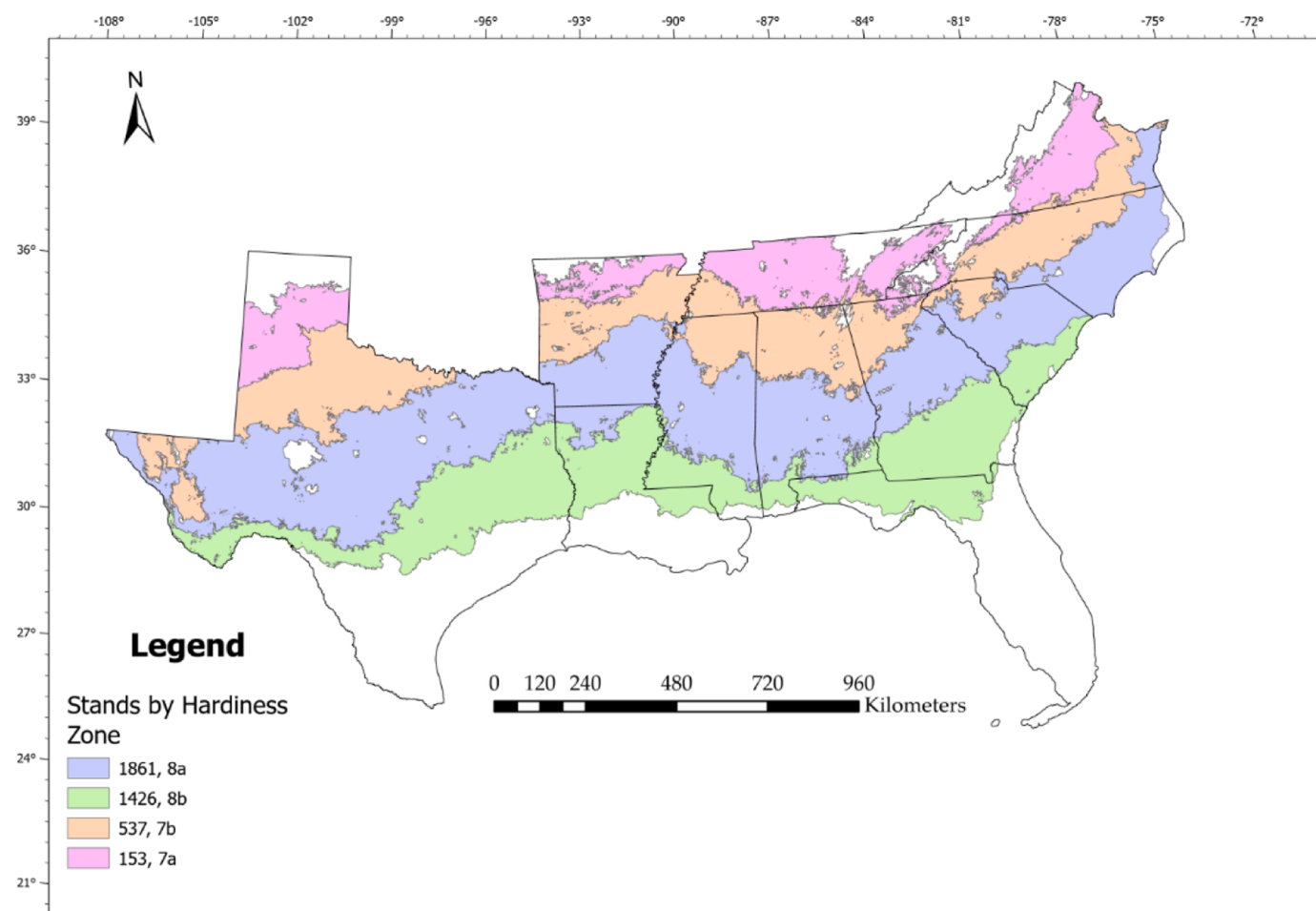


Fig. 3. Study area extent showing the four hardiness zones evaluated and the number of stands in each hardiness zone. States are delineated for reference.

Table 3

Differences in bandwidths used across Landsat sensors (micrometers).

Landsat Mission	Red	Near Infrared (NIR)
5	0.63-0.69	0.76-0.90
7	0.63-0.69	0.77-0.90
8	0.64-0.67	0.85-0.88

zone-soil type combinations to identify and highlight differences across combination types and treatments.

To compare the treatments and stratifications an LAI value of 1.5 units was chosen, as it represents the low end of the expected range of LAI in a mature pine stand during winter (Foxetal, 2006;VoseandAllen, 1988). Fig 5.

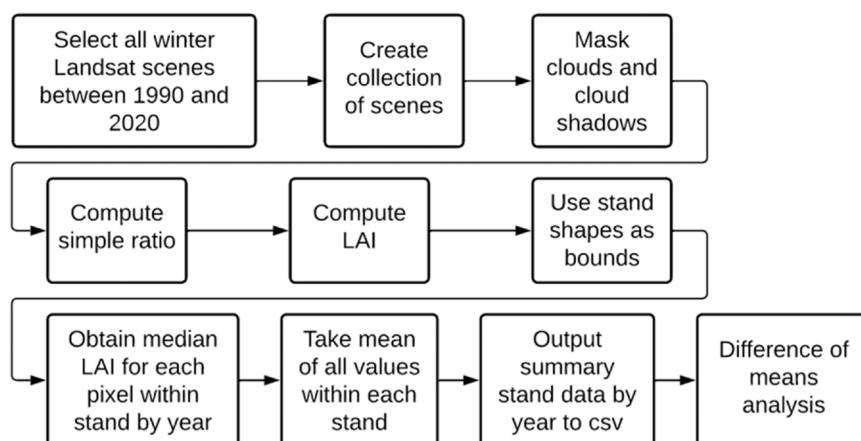


Fig. 4. Flow chart of GEE code and process to prepare data for analysis.

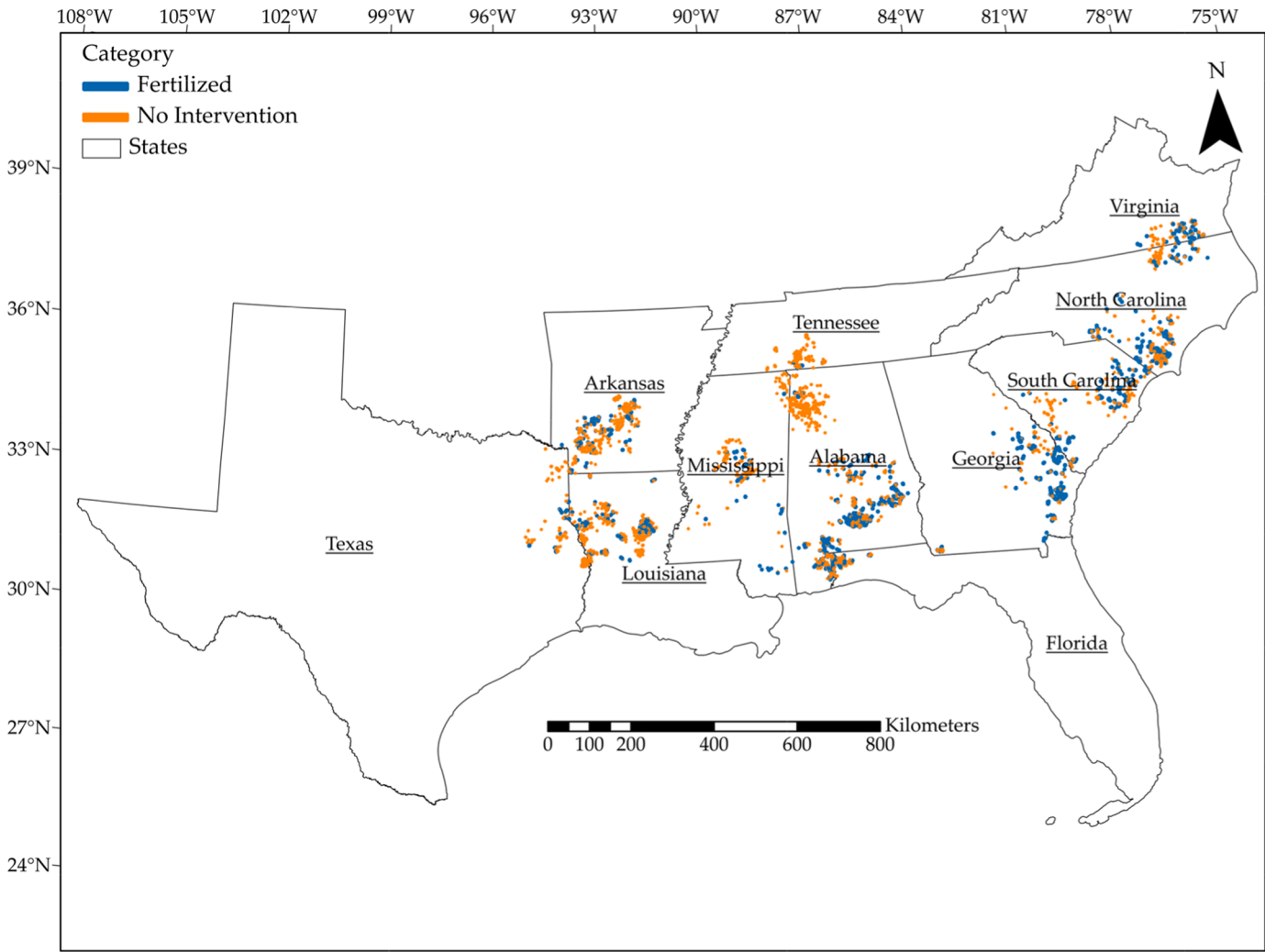


Fig. 5. Extent of treatment types across study area. Data include 3997 total stands, 1515 *Fertilized* stands, and 2482 *No Intervention* stands.

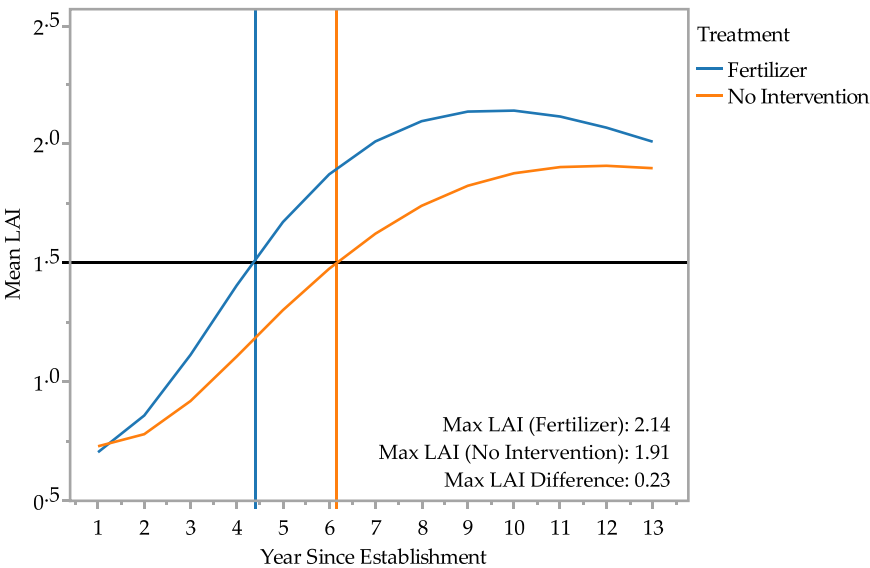


Fig. 6. LAI trajectory over time by treatment type. Vertical lines indicate when each treatment type reached 1.5 units of winter LAI.

3. Results

3.1. LAI trajectories of loblolly pine stands

According to Fox et al. (2007), the amount of leaf area in a stand is the primary factor when determining growth rate. Comparing the two treatment types, *Fertilized* stands reach a LAI of 1.5 approximately two years earlier than *No Intervention* stands (Fig. 6). Jokela et al. (1991) indicate that the response period, in part, varies according to soil and climatic conditions. Through our stratifications we saw that *Fertilized* stands across hardiness zones had consistently higher leaf area than *No Intervention* stands (Fig. 7). Hardiness zone 7a *Fertilized* was removed due to the low number of stands.

When combining the stratifications, the response of stands that were *Fertilized* compared to stands that had *No Intervention* for each soil type and hardiness zone shows the two colder hardiness zones (i.e., 7a and 7b) curves peak later than those in the two warmest hardiness zones (i.e., 8a and 8b) (Fig. 9). The stands in the two warmest hardiness zones (i.e., 8a and 8b Fig. 9) reach peak difference in years 5–7. Poorly drained soils in the most southern and warmest temperature zone (i.e., soils A and B in hardiness zone 8b) have a higher mean than well-drained soils in the same hardiness zone (i.e., Soils E and F). The two most northerly zones (i.e., hardiness zones 7a and 7b) reach peak LAI later by 4 or 5 years (for well-drained soils at year 9 for 7a and year 10 for 7b).

These same stands and hardiness zones were also stratified by soil type to assess fertilization interactions by CRIFF group. The coldest hardiness zone (i.e., 7a) has by far the fewest stands, which was removed from the final analysis for only having six samples in the *Fertilized* class.

3.2. Analysis of differences in mean LAI

When the treatments were compared without either stratification, the *Fertilized* group significantly differed from the *No Intervention* group for years two through 13 with a maximum difference at year six (mean

LAI difference: ~ 0.38). Differences in mean LAI between the two groups as a result of the SAS analysis (Fig. 8) show that the *Fertilized* stands were significantly different for years two through 13 ranging from 0.75 to 0.38 mean LAI difference. Difference in means across stratifications (Fig. 9) show that the effect of fertilization ends differently depending on soil type and hardiness zone. For some soil group hardiness zone combinations year five is the maximum mean LAI difference.

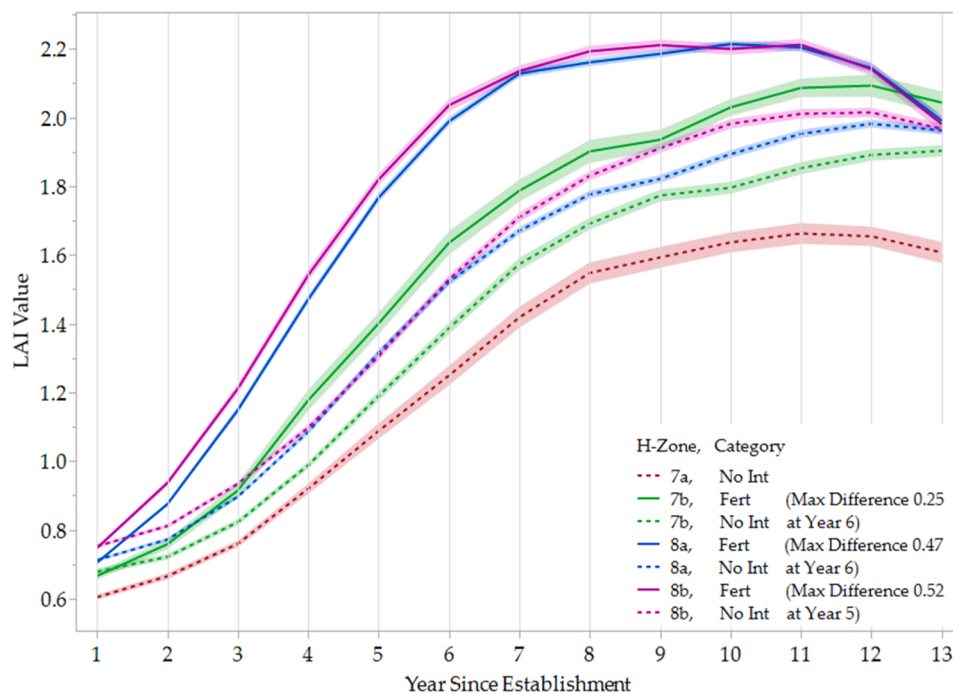
3.3. Increase in LAI across treatment type, soil group, and hardiness zone

We examined each treatment and how fast their leaf areas developed over time. The *Fertilized* treatment reached the threshold LAI value of 1.5 units almost two years earlier, and this largely held true across hardiness zones (Fig. 6). Stratified curves of LAI for each soil type and hardiness zone combination show that the stands *Fertilized* at establishment reached 1.5 units of LAI around two years earlier than the stands with *No Intervention*. Across all combination types, except for the two coldest hardiness zones (i.e., 7a and 7b), the trajectories reached 1.5 units of LAI by year 6. Individual Soil/Hardiness Zone combination trajectories can be found in Appendix B.

The accumulated annual increment of LAI over the first six years (Fig. 10) shows *Fertilized* stands accumulate more LAI for all soil types and hardiness zones when compared to *No Intervention* stands. Fisher's LSD shows that pairwise differences between *Fertilized* and *No Intervention* within each soil/hardiness zone combination significantly differed at $p < 0.0001$. The *Fertilized* stands in the two coldest hardiness zones (i.e., 7a and 7b) have lower cumulative LAI over the first six years compared to warmer climate zones, as they are all below one unit of LAI.

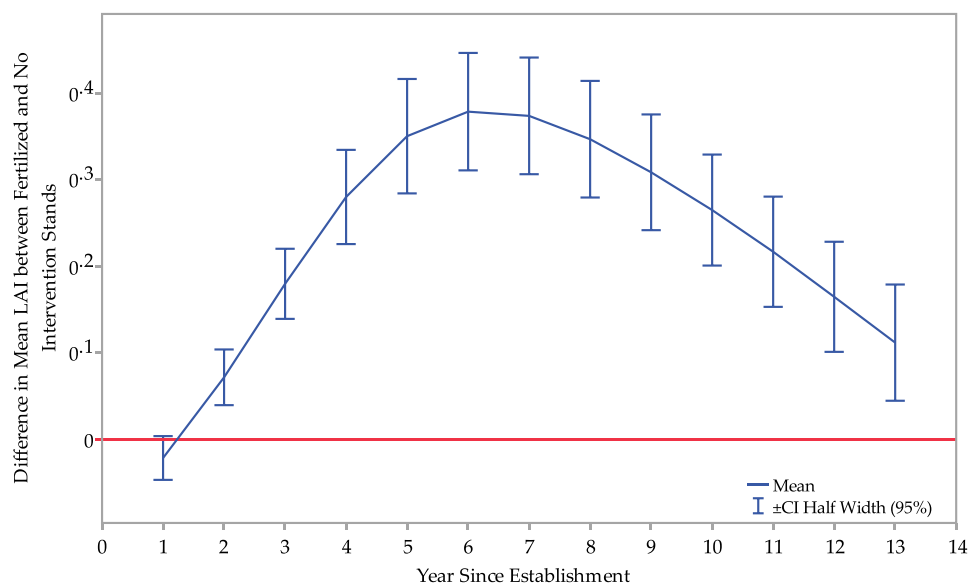
4. Discussion

The southeastern U.S. is a globally important producer of wood products (Allen et al., 2005; Fox et al., 2006). Many industrial land-owners have investments across the region, requiring management



Error band is constructed using 1 standard error from the mean.

Fig. 7. Stand-level mean LAI trajectories stratified by hardiness zone and separated by treatment type. Colors are the same for both treatment categories for a hardiness zone where *Fertilized* stands are represented by a solid line and the *No Intervention* stands are represented by a dashed line. Maximum differences between the treatment types are listed in the legend.



Each error bar is constructed using $\pm$ CI Half Width.

Fig. 8. In all years after year one, *Fertilized* stands had a significantly greater response than the *No Intervention* control, with the mean winter LAI difference on the y-axis.

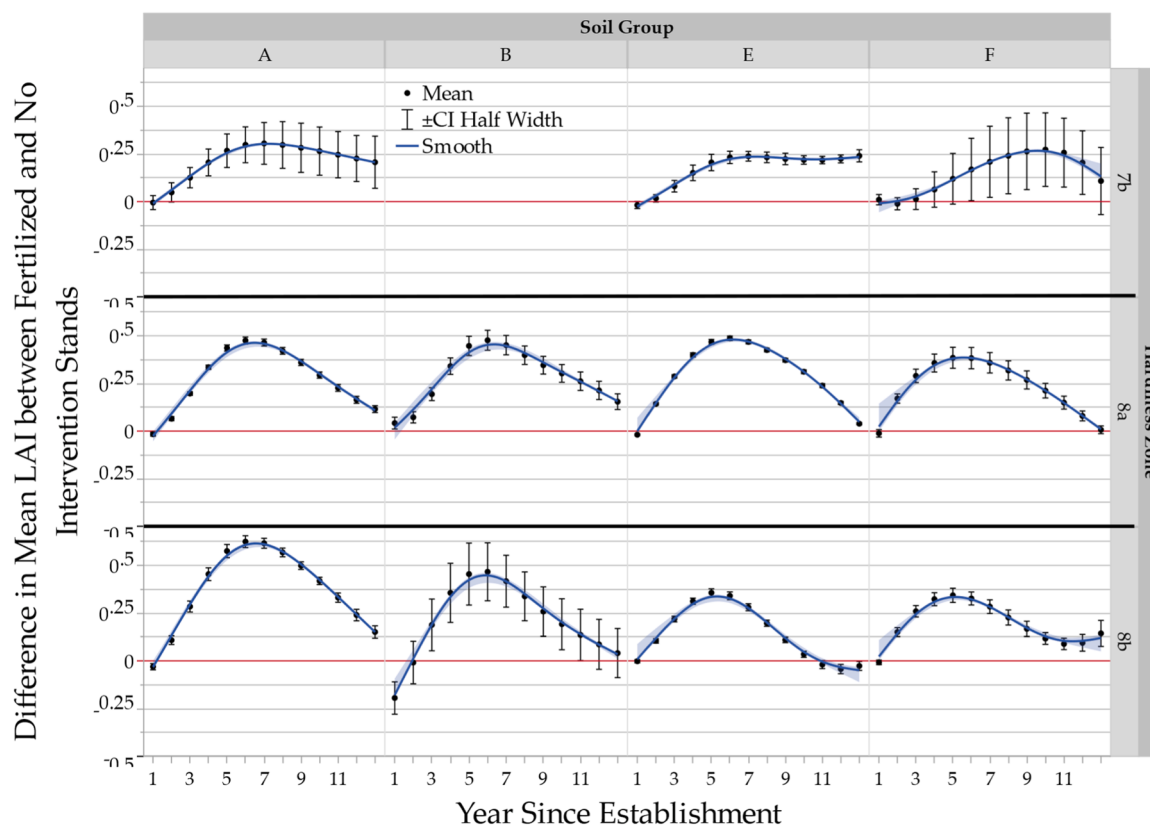


Fig. 9. Trajectories of LAI difference stratified by soil group and hardiness zone above the red zero line indicate *Fertilized* stands have a greater LAI than *No Intervention* stands. Confidence intervals (95%) are also displayed and are not significant if they overlap the zero line.

approaches that depend on geographic location. Determining whether to fertilize is a critical component of management decisions for plantations in the southeastern U.S. Prior studies have shown that a stand's response to establishment fertilization ends around year eight and is highest between years five and seven (Albaugh et al., 2021; Comerford and Fisher, 1984; Dickens et al., 2004; Jokela and Long, 2015). Our study allows us to

see when a *Fertilized* stand's advantage reaches a peak over the control (Fig. 9), and for many of the combination types their advantage peaks at year five (i.e., 8bE, 8bF, 8aF) or year six (i.e., 8aA, 8aB, 8aE, 8bA, 8bB). This ability to assess fertilization effects longitudinally is unique because it can be applied across the region and for any stand where soil group and hardiness zones are known. Studies focusing on fertilization at

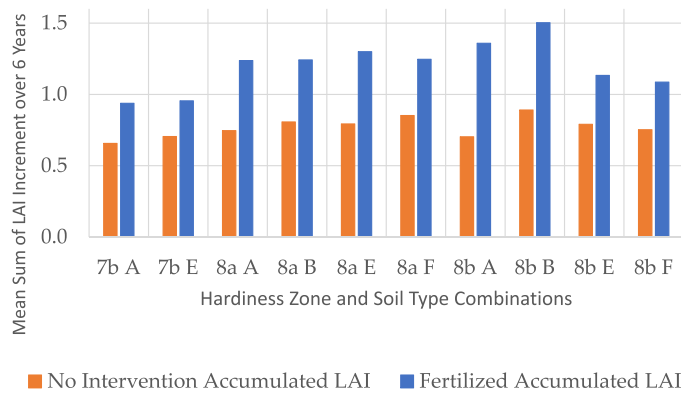


Fig. 10. Accumulated annual increment of LAI differences over the first six years by treatment type and stratification. All are significantly different at $p < 0.0001$.

establishment are less common, and the available studies compared combinations of fertilization and herbaceous weed control to a control (Jokela and Martin, 2000) or types of fertilization on early tree growth (Gentetal, 1986). Both Gent et al. (1986) and Jokela and Martin (2000) used the fifth year as an initial measurement mark, and Jokela and Martin (2000) remeasured the stands in the eighth year (Gentetal, 1986; Jokela and Martin, 2000). Jones et al. (2010) examined a fertilized control with different site preparation and herbaceous weed control intensities (Jones et al., 2010). The differences among treatments were assessed at the three to five-year mark. All three of these studies found that the treatment effect is greatest around year five. However, knowing the year of maximum treatment effect does not elucidate the yearly effect of fertilization. Our study was able to monitor LAI yearly from establishment to year 13. This extensive time series provides a way to delve into the long-term LAI dynamics of fertilization across the landscape.

Albaugh et al. (2021) measured incremental growth response for loblolly pine in the southeastern U.S., over time, for varying amounts of nitrogen applied mid-rotation (Albaugh et al., 2021). Their study had the largest sample size (32 sites) and the most geographic variation (9 states) of all relevant prior studies. Albaugh et al. (2021) noticed that growth response to fertilization decreased over time (Albaugh et al., 2021). We also found that LAI increases until a specific time and then trends downward. The time it takes for LAI to crest varies with soil and climate. However, the LAI at year six is greater for *Fertilized* stands than those with *no intervention* across all hardiness zones and soil types tested. *Fertilized* stands, overall, were most significantly different at years 6 and 7, which is in line with research that establishment fertilization (specifically N addition) has an average effective length of 5–7 years (Albaugh et al., 2021; Comerford and Fisher, 1984; Dickens et al., 2004; Fox et al., 2007; Jokela and Long, 2015). The most significant differences between the treatment types occurred around year six for most soil type and hardiness zone combinations, except for well-drained soils in the two most northerly hardiness zones (7aE, 7bE, and 7bF). This timing supports the expectation of an amplified response from fertilization and then a decrease after year 6/7. Albaugh et al. (2021) show that the fertilizer response duration appears related to the amount of nitrogen remaining in the foliage (Albaugh et al., 2021).

Winter LAI reaches 1.5 one to two years later in the two colder hardiness zones (7a and 7b) than in the two warmest hardiness zones (8a and 8b) regardless of soil type. There is a 10-degree average minimum temperature difference between the two coldest and the two warmest hardiness zones (7a and b and 8a and b) and very different growing season lengths. More northerly hardiness zones lead to slower gains in LAI. *Fertilized* stands ended up with the greatest LAI overall but, *Fertilized* stands in the warmest hardiness zone (8b) appear to benefit the most from a combination of warmer temperatures and establishment

fertilization, particularly in poorly drained soils (i.e., soils A and B). LAI reaching 1.5 units one to two years earlier in the warmer hardiness zones is important because LAI can also be related to stem growth. Albaugh et al. (1998) showed that growth per unit of LAI (or stem volume growth efficiency) increased 21% with fertilization. Across the study area, stands were treated for competition at establishment, significantly reducing the competition as indicated by Clabo and Dickens (2023), who showed that competition control was effective for at least six years after application. It is possible that later in a stand's development, competition could be impacting LAI, and the degree of the impact could differ across soils and climates. To dampen this effect (in part), we used winter LAI to remove all but competing evergreen vegetation.

Across most scenarios, *Fertilized* stands reach peak LAI three years or more before *No Intervention* stands reach their peak LAI. These zonal differences lead to the possibility of management decisions being tailored to hardiness zones. Zonal differences are supported by Schmidtling (2001), who found that yearly average minimum temperature is the most important climatic variable related to tree growth and survival. Forest managers benefit more from establishment fertilization in the warmest hardiness zones (i.e., 8a and 8b) than in the colder hardiness zones (i.e., 7a and 7b).

In some hardiness zone/soil group combinations, such as in the warmest hardiness zone on poorly drained soils with a surface layer greater than 20 in (50.8 cm) (i.e., 8b CRIF soil group B), a stand's advantage of establishment fertilization over the control can end as early as year five. Hardiness zone 8b is the warmest and furthest south in this study and the least likely of the four zones to experience a damaging freeze. Soil groups A and B are poorly drained to somewhat poorly drained soils. Soil group A has a soil surface layer of less than 20 in, and soil group B has a soil surface layer greater than 20 in. Water availability in these poorly drained soils may have allowed the stands to take up the added nutrients more readily than in well-drained soils (i.e., soils E and F). These soils are also more likely to have higher amounts of organic material because of poor drainage, which means they will generally have higher potential productivity.

The ability of remotely sensed LAI to be an indicator of effectiveness for fertilizer additions (Albaugh et al., 1998; Blinn et al., 2019; Campo et al., 2013; Samuelson et al., 2014) is well established. In our study, we were able to see stand closure (where LAI levels off), supporting studies like (Chen et al., 2022).

One of the principal advantages of using remote sensing to study early stand development is the ability to analyze a large number of stands across space and time. Across the literature, studies have been limited by small sample sizes and the substantive geographic variation across the Southeast. No prior study, even if regional in scope, has had more than 32 sites (Campo et al., 2013; Comerford and Fisher, 1984; Pritchett and Comerford, 1982; Scott and Bliss, 2012; Well et al., 1973). Our study had 3997 stands which allowed us to compare climatic and edaphic variables that would not have been possible in the past. This large sample size, two orders of magnitude larger than any previous study, was made possible by access to a large dataset of stand attributes, cloud-based computing via GEE, and Landsat time series stacks dating back to the mid-1980 s. GEE allowed us to create a large dataset of LAI values, both temporally and spatially (Gorelick et al., 2017).

5. Conclusions

The study has several important findings pertinent to loblolly pine plantation silviculture in the southeastern U.S., one being a stand's response to establishment fertilization peaking as early as year 7 in the warmest part of our study area. Remote sensing can help managers plan by observing trends on their lands over time from past harvests. Current stands in production can be monitored using this study's method for changes in leaf area trajectory from establishment to canopy closure so additional management interventions can be better tailored to individual stands at the right time. Thanks to Landsat and GEE, LAI trajectories

can be produced across the entire Southeast, giving land managers a new way to monitor stand development and plan treatments over the entire spatial extent of their landholdings.

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CRediT authorship contribution statement

Schroeder Todd A.: Writing – review & editing. **Rakestraw Jim:** Writing – review & editing. **Thomas Valerie A.:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Writing – review & editing. **Wynne Randolph H.:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **House Matthew N:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Van Mullekom Jennifer H.:** Writing – review & editing. **Carter David R.:** Writing – review & editing. **Cook Rachel L.:** Writing – review & editing.

Declaration of Competing Interest

This manuscript has not been published and is not under consideration for publication elsewhere. We have no conflicts of interest to disclose, other than one of the authors, Rachel L. Cook, is on the editorial board for Forest Ecology and Management.

Data availability

The authors do not have permission to share data.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.foreco.2023.121655](https://doi.org/10.1016/j.foreco.2023.121655).

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