Abstract

PEDUZZI, ALICIA. Leaf Area Assessments of the Overstory and Understory Vegetation in Pine Plantations Located in South Georgia and North Florida, US. (Under the direction of Dr. H. Lee Allen).

Leaf Area Index (LAI) was estimated in summer 2005 and winter 2006 for overstory and understory in loblolly pine and slash pine plantations at ages 7 and 10 year-old and on poorly, somewhat poorly and moderately-well drained soils located in the flatwoods region. Additionally, stand and site factors such as basal area, pine dominant height, understory height and understory coverage were estimated for each of the 40 plots established, and leaf area index and vegetation indices (SR, NDVI, VI and EVI) were calculated using remote sensing imagery. The objectives of this study were to determine the understory (competing vegetation) and overstory (crop-trees) leaf area index, to relate the variation in understory and overstory LAI to stand and site factors and to examine the relationships among understory and overstory leaf area index and spectral reflectance data captured by satellite imagery. Leaf area index values observed for the overstory were low in most of the plots (around 2 m^2m^{-2} in slash pine and around 3 m^2m^{-2} in loblolly pine), while the understory LAI was very high (around 2 m^2m^{-2}), which can be attributed to the lack of canopy closure observed in all plots. A negative relationship was observed between the overstory and the understory, where the higher the understory LAI the lower the overstory LAI. No significant differences were found in the understory LAI values across soil drainage classes. Low heights and short crown lengths were generally observed and could be explained by nutrient deficiency in most of the sites; which could be attributable to the belowground competition for water and nutrients. LAI and basal area were not correlated. Total LAI (overstory LAI plus understory LAI) estimated values on the ground were high and weakly

correlated with the Landsat-derived vegetation indices, and the LAI values estimated with a LAI model were typically half of the values estimated on the ground. These results could be influenced by the contribution of different backgrounds, such as soil moisture and understory vegetation, plus the saturated response of the vegetation indices at high LAI values. Significant correlations were observed between the vegetation indices (SR and NDVI) and stand and site factors, suggesting that the satellite derived indices were more related to the stand biophysical parameters than in situ LAI estimates.

LEAF AREA ASSESSMENTS OF OVERSTORY AND UNDERSTORY VEGETATION IN PINE PLANTATIONS LOCATED IN SOUTH GEORGIA AND NORTH FLORIDA, US.

By

ALICIA PEDUZZI

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H. Lee Allen Chair of Advisory Committee	Marcia L. Gumpertz
Stacy A. C. Nelson	Randolph H. Wynne

Biography

Alicia Peduzzi was born in Montevideo, Uruguay in 1976. At the age of three, she moved with her family to Valencia, Venezuela where she graduated from high school in 1992. She then entered the University of Los Andes in the city of Mérida, Venezuela where she received the degree of Forest Engineer in February 2001.

In 2000 she did an internship with Smurfit Cartón de Venezuela, evaluating and analyzing genetic and silvicultural trials of *Eucalyptus urophylla* and *Gmelina arborea*, two species planted and managed intensively in Venezuela. In March 2001 she moved to United States where she started the process of learning English as her second language while working initially in the Smithsonian Natural History Museum in Washington DC and later in the Museum of Natural Sciences in Raleigh, NC. In fall 2004 she applied to the graduate program in the Department of Forestry at the North Carolina State University where she studied her master program under the guidance of Dr. Lee Allen with special interest in silviculture, geographic information science, and remote sensing applications. In fall 2006, she entered the graduate program in the Department of Forestry at the Virginia Polytechnic Institute and State University where she is currently pursuing her doctorate program.

Acknowledgments

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I would also like to thank everybody that collaborated in the field data collection, especially to my husband José Luis Zerpa, who spent several days helping me during the establishment of the plots under very hot and humid conditions typical of summer in north Florida, also to José Alvarez, Cristián Montes, Rafael Rubilar, and Lee Allen. Thanks to Tim Albaugh for guiding me in the use of field instruments and Leandra Blevins for helping me with logistics. To the personnel of Rayonier James Ulmer, Alan Wilson, and Ben Cazell for providing the information and logistic needed to develop this project.

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Introduction

The southern United States has 40% of all US timberland (Smith et al., 2002) and is currently the region that produces the largest amount of industrial timber in the world (Prestemon and Abt, 2002). Several decades of forest research provide the foundation for silvicultural practices that sustain the current levels of wood production. For example in the last 20 years, pine productivity has been improved by the beneficial effects of site preparation, vegetation control, fertilization and tree improvement programs (Allen, 2001; Clason, 1998; Jokela et al., 2004; Neary et al., 1990; Shiver et al., 1990; Swindel et al., 1988). Unfortunately, current growth rates in southeastern plantations are still below optimum levels (Albaugh et al., 1998; Allen and Albaugh, 2000; Allen et al., 2005; Jokela et al., 2000). However, significant gains are possible based on identifying and ameliorating the site resource factors that may be limiting productivity (Adegbidi et al., 2002; Albaugh et al., 1998; Allen and Albaugh, 2000; Allen et al., 2005; Colbert et al., 1990; Neary et al., 1990).

Low nutrient availability and the interspecific competition for resources from herbaceous and woody plants are recognized as the primary factors limiting pine growth in the South. The Flatwoods of Georgia and Florida are one of the areas where the greatest opportunities exist to increase the growth with proper management (i.e. fertilizer additions, competition control) (Adegbidi et al., 2005; Adegbidi et al., 2002; Borders et al., 2004; Colbert et al., 1990; Martin and Jokela, 2004; Shiver, 2004; Swindel et al., 1988). This region is characterized by soils varying from well drained sands to very poorly drained clays. Typically, somewhat poorly drained soils are most productive sites followed by poorly drained and moderately well drained soils (Fox, 2004).

Bedding is widely used in the Flatwoods for improving aeration on poorly drained soils, controlling competing vegetation, especially woody shrubs (Lauer and Glover, 1999; Lauer and Zutter, 2001; Lauer and Glover, 1998; Zutter and Miller, 1998). Pre-plant herbicide treatments are also used to control woody shrubs and herbaceous vegetation (Lauer and Zutter, 2001). The woody evergreen shrub species found in the Lower Coastal Plain can compete aggressively with pines throughout the whole rotation (Miller et al., 2003; Oppenheimer et al., 1989; Quicke et al., 1996; Yeiser and Ezell, 2004) and both loblolly pine and slash pine have demonstrated positive growth responses when competing vegetation was controlled at plantation establishment or during the rotation (Allen and Albaugh, 2000; D'Anierí et al., 1986; Fortson et al., 1996; Fox, 2004; Lauer and Glover, 1999; Pritchett and Comerford, 1982; Shiver, 2004; Shiver et al., 1990; Swindel et al., 1988). Results from studies where vegetation control was applied have shown significant increases in growth (Colbert et al., 1990; Miller et al., 1991), foliar N, P, and B (Albaugh et al., 2003), and leaf area (Zutter et al., 1986).

The amount of leaf surface area present over a given unit of ground surface area (leaf area index - LAI) was described by Gholz et al. (1997) as “a primary determinant of the productive capacity of forests”. Productivity has been found to have a strong relationship with leaf biomass and LAI (Albaugh et al., 1998; Colbert et al., 1990; Gower et al., 1994; Vose and Allen, 1988). This relationship holds true for both the pine crop and competing vegetation so leaf area of competing vegetation may prove useful in quantifying competing vegetation effects on pine productivity. The method mostly used to quantify and/or measure woody and herbaceous species is a direct measurement that requires the clipping, drying, and weighing of vegetation. This procedure is time consuming and costly. Using leaf area estimations to monitor competition could significantly reduce these costs.

Since the 1960's, advances in remote sensing and computing have allowed researchers to use this technology to monitor vegetation changes. Previous research has shown that satellite data can be used to accurately estimate LAI (Curran et al., 1992; Flores, 2003; Gholz et al., 1997; Gholz et al., 1991; Jensen and Binford, 2004). Photosynthetically active vegetation shows a high chlorophyll absorption in the blue and red wavelengths, and a high reflectance in the near infrared region (Jensen, 2005). Thus, there is a direct relationship between biomass measurements and vegetation response in the near infrared. As the vegetation canopy matures, it will reflect more NIR (near infrared) energy while absorbing more R (Williams et al., 2005) radiant flux. Based on the NIR and R relationship, many vegetation indices (VI) have been developed, and related to LAI. Generally, there is a positive relationship between LAI and the difference between NIR and R. Most of the vegetation indices combine information from the near infrared and red wavelengths (i.e. simple ratio (SR), normalized difference vegetation index (NDVI), the vegetation index, etc.).

Remote sensing relies on superficial observation of reflectance from the canopy layer; and background variations, such as soil, litter and understory vegetation can affect the relationship between NIR and R wavelengths and consequently the vegetation index.

Understory vegetation is usually treated as a source of error especially in the assessment of leaf area index (LAI), and LAI estimates rarely distinguish between the overstory and understory. Townsend and Walsh (2001) classified forested wetland communities in the southeast US using a multi-temporal approach with leaf-off and leaf-on images to successfully identify mixes of deciduous and evergreen species. This approach was also used by Flores et al. (2003), to effectively estimate LAI of evergreen overstory and the deciduous understory component. However, Riaño (2003) working in Mediterranean ecosystems, where both the overstory and understory were evergreen, was unable to separate overstory and understory vegetation using this approach.

The objectives for this study were to:

- Determine the understory (competing vegetation) and overstory (crop-tree) leaf area index.
- Relate the variation in understory and overstory leaf area index to stand and site factors.
- Examine the relationships among understory and overstory leaf area index and spectral reflectance data captured by satellite imagery.

Methodology

Site Description

This study was undertaken in Nassau County and Baker County in Florida, and Charlton County and Ware County in Georgia (Figure 1). The climate is characterized by warm and humid summers and mild winters. The temperature from June through October averages 26ºC, while the rest of the year temperature averages 17º C. About 65 % of the total annual precipitation (an average of 132.8 cm) falls in summer, in the rest of the months during a year the average is about 7.62 cm (NOAA, 2006; USDA and NRCS, 1991). Forest plantations, located within these counties are mainly of loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliotti* L.). Soils are typically low in fertility and have developed from Pleistocene marine deposits. They are poorly to moderately-well drained loamy to sandy soils of the Ultisol and Spodosol orders. The evergreen understory vegetation of the flatwoods is a complex mixture, with gallberry (*Ilex glabra* (L.) Gran) and sawpalmetto (*Serenoa repens* (Bartr.) Small), as the predominant species. Other species found are ti-ti (*Cyrilla racemiflora* L.), fetterbush (*Lyonia lucida* (Lam) K. Koch), staggerbush (*Lyonia ferruginea* (Walter) Nutall), sweetbay (*Magnolia virginiana* L.), blueberries (*Vaccinium* spp.), saw greenbrier (*Smilax bona-nox* L.), cat greenbrier (*Smilax glauca* Walt.), roundleaf greenbrier (*Smilax rotundifolia* L.), american holly (*Ilex opaca* Ait.), red maple (*Acer rubrum* L.), sweetgum (*Liquidambar styraciflua* L.), yellow poplar (*Liriodendron tulipifera* L.), poison ivy (*Toxicodendron radicans* (L.) Kuntze), *Rubus* spp., wire grass (*Aristida stricta* Michx.), bluestems (*Andropogon* spp.), low panic grasses (*Dichantellium* spp.) and bracken fern (*Pteridium aquilinum* (L.) Kuhn) (Lauer and Glover, 1999; Miller et al., 1999; Oppenheimer et al., 1989).

Plot establishment

Plots were established in 7 and 10 year old plantations growing on poorly and somewhat poorly drained soils for loblolly pine and poorly and moderately well drained soils for slash pine. A total of 5 plots were established for each category of stand age, drainage class and pine species, providing a total of 40 plots, 20 for each pine species. Plots dimensions were 1 ha (100m x 100m). The plots were established with a buffer with at least 30 meters to minimize the influence of different land uses (i.e. roads, natural forest, etc.) in the remote sensing estimation of leaf area index. Each plot was georeferenced with a Trimble GeoXT

GPS unit, accuracy <1m and real-time accuracy <1m. There were 15 plots of loblolly pine located in Nassau County, 5 plots of loblolly pine and 4 plots of slash pine (9 plots total) in Ware County and the rest 16 plots of slash pine were located between Charlton and Baker County (Figure1).

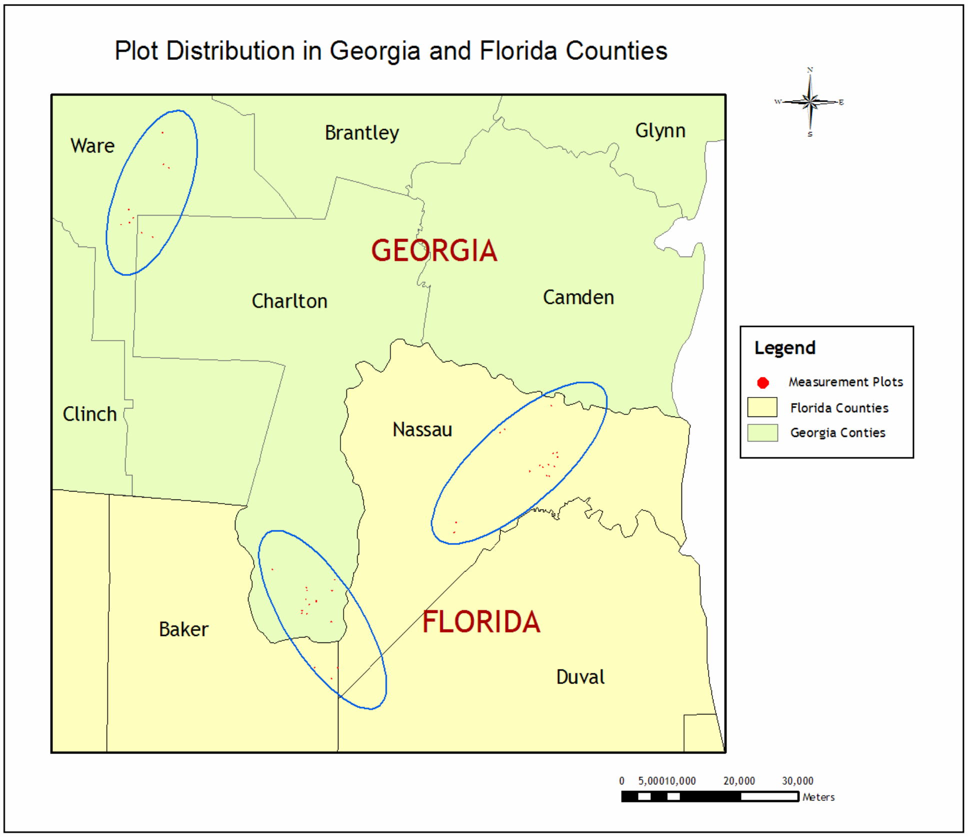

Figure 1. Map of plots distribution among Georgia Counties and Florida Counties.

Leaf Area Index

Leaf area index estimations were made on each plot during late summer (August 10 to September 5, 2005) and winter (February 3 to March 19, 2006), using a LiCor LAI-2000

Plant Canopy Analyzer. Above canopy measurements were made by placing an instrument in an open field adjacent to the stand to be measured. Readings were recorded every 15 seconds during the same time that the below canopy measurements were acquired. Two below-canopy measurements were made; one with the instrument at ground level facing upwards and reading both the understory and overstory vegetation, and another reading was taken in the same point with the instrument held over the understory layer facing upwards and reading only the overstory layer. The difference in radiation between the above canopy measurement and the ground level measurement was used to estimate the total LAI. The difference in radiation between the above canopy measurement and the below overstory measurement was used to estimate the overstory LAI. The difference between the total LAI and the overstory LAI was used as the understory LAI estimation. Due to the instrument's design, measurements were taken under diffuse sky conditions to insure that the sensor measured only indirect light. Therefore, measurements were taken between 7:00 am to 9:00 am and 4:00 pm to 7:00 pm. EST, during the dawn and predusk periods, with the instrument facing north and using a 90º view cap. Sampling points were distributed systematically in the plots along a transect perpendicular to the tree-rows. Two transects were used, one close to the plot edge and the other in the middle of the plot. Fifteen sample points were selected at equal distances along each transect (Figure 2), resulting in a total of 30 readings taken for each of the measurements (for total LAI and crop-tree LAI). The calculation of LAI was accomplished using the FV-2000 software which averaged the 30 readings of the total and of the overstory layer separately for each plot. The canopy model used to calculate LAI was Horizontal; ring number 5 was masked to reduce the error introduced by the stem and branches of pine trees. The option of skipping records with transmittance >1 was used in order to avoid bad readings that can alter the mean values of LAI per plot. The above canopy values were matched in time of the below canopy values.

Preliminary analysis indicated that total winter LAI values and consequently understory winter LAI values were higher in winter than in summer for several plots. One of the possible explanations is the large amount of dead needles (needle drape) that were hanging on the shrubs part of the understory layer, during winter. For this reason, total winter LAI and understory winter LAI estimates were excluded from further analysis.

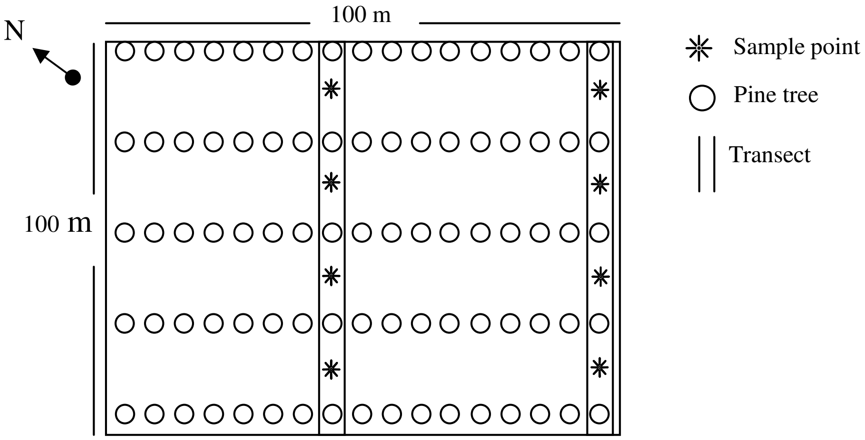

Figure 2. Graphic representation (not a scale) of LAI sampling points within the plot.

Leaf area index estimates using the LiCor LAI-2000 have been subject to criticism; however, several previous studies have shown the validity of this instrument (Albaugh et al., 1998; Gatch et al., 2002; Harrington et al., 2002). However, it was noticed that when dark gray cloudy skies were present, readings increased considerably because of the contribution of scattered radiation, and those plots were re-measured under normal sky conditions. A similar situation happened to Gatch et al. (2002), who observed that when the instrument was used under cloudy sky conditions readings averaged were 7 percent greater than the readings obtained under clear sky conditions.

Stand Measures

During winter 2006, basal area, pine dominant height, understory height and understory coverage were estimated at every other LAI sampling point, for a total of 14 sample points per plot. Stand basal area was assessed using a prism factor No. 10 or No. 5, depending on the diameter of the trees in each plot. The height of the tallest tree at each sampling point was measured using a Hagön Vertex III hypsometer. The predominant height of the understory was estimated using a pole and the understory coverage percentage was visually estimated by the same person. The radius of the area observed was approximately 5 meters from the center of the sampling point. Basal area, dominant height measured, understory height and understory coverage estimates were averaged for each plot.

Image analysis

LANDSAT TM imagery was acquired from path 17 and row 39 for June, 16 2005 and for February, 27 2006. The two images purchased from the USGS were already georeferenced with a UTM projection, North American Datum 1927, Zone 17 N using the nearest neighborhood resampling technique. The scene from June 2005 was not 100% cloud free; however, it was the best image available closest to the time when the ground truth data were collected. Landsat TM imagery is characterized by having 7 bands including the thermal, but for this study only bands 1 (0.45 – 0.52 μm) blue, 3 (0.63-0.69 μm) red and 4 (0.76-0.90 μm) near infrared were used to calculate the vegetation indices. The red and infrared bands are designed to sense the chlorophyll absorption region and to determine vegetation types, vigor and biomass content (Lillesand and Kiefer, 2000). The spatial resolution of Landsat (30m x 30m); allowed for 9 (3 by 3) cells to be included within each 1 ha measurement plot.

Image processing included radiometric correction undertaken by converting the digital numbers (DN) from each band into absolute radiance (L). Gain and offset values were acquired from the correction processing report file.

$$L = \text{gain}\,(DN - \text{offset})$$

The radiance values were converted to exoatmospheric reflectance using the Chander and Markham (2003) formula:

$$R_i = \frac{\pi L_i d^2}{Es_i \cos\theta}$$

Where L_i: Spectral radiance at sensor for band *i* (watts/(m^2.sr.µm)),

d: Earth-Sun distance in astronomical units,

E_{Si}: Mean solar exoatmospheric irradiance for band *i* (watts/(m^2.µm)),

θ : Solar zenith angle (degrees)

Vegetation indices

Four vegetation indices were calculated from the Landsat data including:

Simple Ratio (SR), this is the ratio of the red reflected radiant flux to the near-infrared radiant flux (Birth and McVey, 1968).

$$SR = \frac{\rho_{red}}{\rho_{nir}}$$

The Normalized Difference Vegetation Index (NDVI) was developed in 1974 (Rouse et al.) and is functionally equivalent to the SR. This index is the ratio between the difference of the near-infrared and red bands and the addition of the same bands.

$$\mathrm{NDVI} = \frac{\rho_{nir} - \rho_{red}}{\rho_{red} + \rho_{nir}}$$

The Vegetation Index (VI) is simply the difference between bands 4 and 3, near-infrared and red.

$$\mathrm{VI} = \rho_{nir} - \rho_{red}$$

Enhanced Vegetation Index (EVI) is a modified NDVI with a soil adjustment factor (Huete et al., 1997). There are three coefficients empirically determined C1, C2, L and a gain factor G.

$$\mathrm{EVI} = \mathrm{G} \quad \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + C_1 * \rho_{red} - C_2 * \rho_{blue} + L} \quad (1 + L)$$

Where $C_1 = 6.0$, $C_2 = 7.5$, $L = 1.0$, $G = 2.5$

In addition to these four vegetation indices, LAI was calculated from SR using the model developed by Flores et al. (2006):

$$\mathrm{LAI} = 0.56 * \mathrm{SR} - 0.83$$

Leaf area index values were obtained for each of the georeferenced plots, which were processed using GPS Pathfinder Office software from Trimble and ArcMap from ESRI.

Images were processed using ERDAS Imagine software and the indices and model were calculated using its Spatial Modeler option from Leica Geosystems.

Statistical analysis

Analysis of variance (ANOVA) was applied to test for age and drainage class effects on leaf area estimates for each of the species. Correlation analyses and linear regressions were used to examine the relationship between LAI from the overstory and from the understory and site factors, such as, drainage class, basal area, height, and understory height and coverage. The effect of age, soil drainage, and their interaction were evaluated for the total LAI (overstory LAI and understory LAI together), overstory LAI, and understory LAI. Additionally, statistical analyses were also performed to examine the relationship between the LAI estimated using the LiCor LAI-2000 and the vegetation indices calculated from the satellite data. One slash pine plot was not included in the image analysis, due to a shift in the coordinates of the image coverage area for 2005 and 2006, leaving this plot outside of the image. Diagnostics checks were applied for the presence of outliers. There were three points identified as outliers in the summer data set and another four in the winter dataset. Thus, these observations were checked to see if there were influential points using Cook's D, DFFITS and COVRATIO. For summer, the plots 19, 33, and 34 were outliers, but only 19 and 34 were determined by Cook's D and DFFITS as influential points. For winter, the plots 8, 13, 14, and 18 (all loblolly plots) were identified as outliers and were all influential (by Cook's D, DFFITS, DFBETAS and COVRATIO), and additionally plot 31 was identified by COVRATIO as an observation that decreased the precision of the estimates. In order to see if the relationship among the LAI estimated on the ground and the LAI and indices estimated from the image would improve, these points or extreme values were once eliminated from the data set (Figures 3 and 4) and a correlation analysis was applied again. Statistical analyses were performed at a significance level of $\alpha > 0.05$ using SAS System Software.

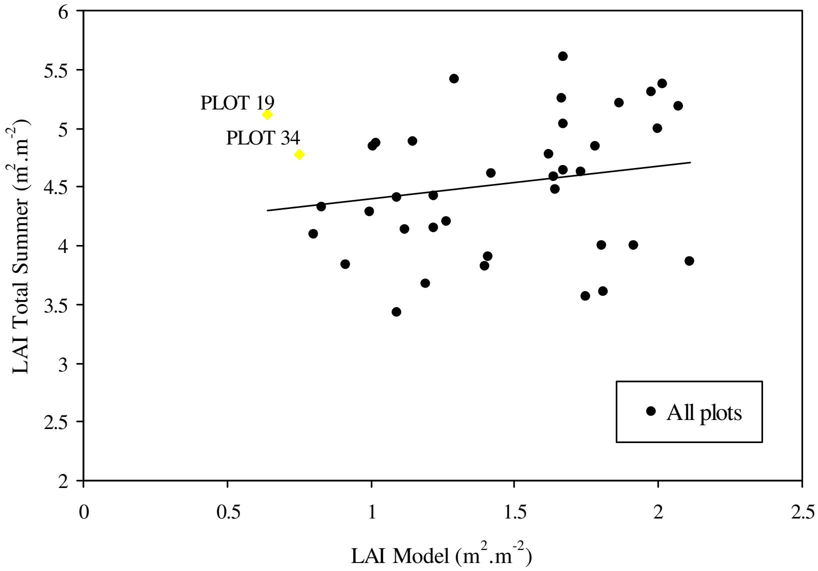

Figure 3. Plots eliminated from summer data set, due to results from the diagnostics of outliers and influential points.

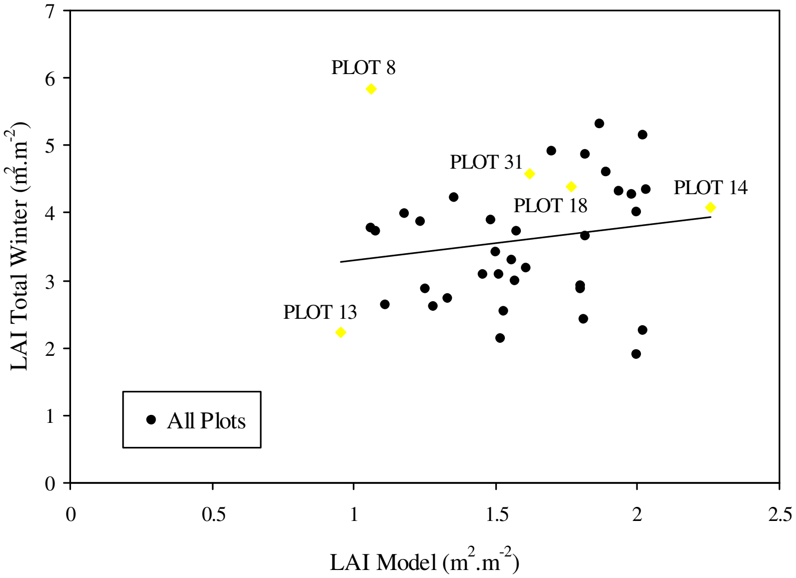

Figure 4. Plots eliminated from winter data set, due to results from the diagnostics of outliers and influential points.

Results

Basal area values for loblolly pine ranged from 18.9 to 29.8 m^2ha^{-1} and for slash pine from 7.7 to 23.6 m^2ha^{-1} across all plots (Appendices 1 and 2). For loblolly pine, the lowest value was observed at age 7 on a somewhat poorly drained soil, and the highest value was registered at age 10 on a poorly drained soil (Appendix 1). Slash pine had its lowest value at age 10 on a moderately well drained soil, and its highest value was at age 7 on a poorly drained soil (Appendix 2). Height for loblolly pine was lowest (11.4 m) for a 7 year old plantation and on a somewhat poorly drained soil; its highest value (14.7 m) was for a 10 year old plantation on a poorly drained soil (Appendix 1). The minimum value registered for height in slash pine was 7.2 m and the maximum was 14.3 m (Appendix 2). Crown length in loblolly pine varied from 6.8 to 8.6 m, both values were encountered on somewhat poorly drained soils and at different ages (7 and 10 respectively) (Appendix 1). Crown length values in slash pine ranged from 4.1 meters to 6.6 meters for all the plots (Appendix 2). Site Index values (Appendix 1 and 2) were high for the region, due to that only the dominant tree height per each sampling point was measured. Understory height in loblolly pine ranged between 1.4 and 1.9 meters (Appendix 1) and 0.8 m to 1.9 m for slash pine (Appendix 2). Understory coverage for loblolly pine varied from 25 to 95%. Surprisingly these two extreme values were found on two 7 year old somewhat poorly drained plots (Appendix 1).

Leaf area index

The total LAI estimates for loblolly pine stands (overstory plus the understory vegetation) averaged 4.8 m^2m^{-2} (S_E= 0.5) during summer (Table 1), and no significant differences were observed among the categories age and soil drainage (Table 2). For slash pine stands, total

LAI estimates for summer averaged 4.3 m^2m^{-2} ($S_{E=}$ 0.4) and there were no significant differences for age and soil drainage, although the interaction age and soil drainage class was statistically significant (Table 4). The 7 year old moderately drained sites had the highest total LAI (4.8 m^2m^{-2}) ($S_{E=}$ 0.4) (Table 3).

Overstory LAI estimates in winter averaged 2.5 m^2m^{-2} ($S_{E=}$ 0.5) for loblolly pine. In contrast with summer, there were significant differences observed among soil drainage classes in winter. Poorly drained stands had higher overstory LAI values than somewhat poorly drained stands. The overstory LAI estimates for slash pine averaged 1.3 m^2m^{-2} ($S_{E=}$ 0.4), and similar to summer the overstory LAI, they differed significantly by age - soil drainage category. The largest understory LAI value was observed in a 7 year old stand on a moderately-well drained soil.

Seasonal differences in the overstory LAI estimates were evaluated for all plots. For loblolly pine, one of the 7 year old poorly drained plots showed a higher value for winter than for summer. Another 10 year old poorly drained plot had a difference of 0.1 $m^2.m^{-2}$ between summer LAI and winter LAI. The remaining loblolly pine plots lost between 15% and 35% of their foliage. In slash pine, the plot with the smallest difference (0.4 m^2m^{-2}) was a 10 year old stand on a poorly drained soil. Curiously, the plot with the largest difference (1.1 m^2m^{-2}) was also of the same age –drainage class category. The relative differences for overstory LAI in slash pine ranged between 20% and 35% (See Figure 5).

Table 1. Loblolly pine leaf area means and standard errors for leaf area estimates for each age - soil drainage condition.

Loblolly	Overall Mean	Age / Soil Drainage Means				Standard Error*
		7 Poorly	7 Somewhat Poorly	10 Poorly	10 Somewhat Poorly	
Total summer LAI	4.8	4.6	4.7	4.7	5.1	0.507
Overstory summer LAI	3.1	3.2	3.4	3.2	2.6	0.589
Understory summer LAI	1.7	1.4	1.3	1.5	2.4	0.544
Overstory winter LAI	2.5	2.7	2.3	2.8	2.1	0.466

Table 2. P-values for age, soil drainage, and age x soil drainage effects on loblolly pine leaf area.

Loblolly	Age	Soil drainage	Age x soil drainage
Total summer LAI	0.286	0.442	0.642
Overstory summer LAI	0.238	0.549	0.214
Understory summer LAI	0.032	0.205	0.085
Overstory winter LAI	0.673	0.034	0.451

Table 3. Slash pine leaf area means and standard errors for leaf area estimates for each age - soil drainage condition.

Slash	Overall Mean	Age/Soil drainage Means				Standard Error*
		7 Poorly	7 Moderately	10 Poorly	10 Moderately	
Total summer LAI	4.3	4.1	4.8	4.3	4.0	0.386
Overstory summer LAI	2.0	1.6	2.2	2.1	1.9	0.419
Understory summer LAI	2.3	2.5	2.5	2.2	2.0	0.232
Overstory winter LAI	1.3	0.9	1.6	1.3	1.2	0.361

Table 4. P-values for age, soil drainage, and age x soil drainage effects on slash pine leaf area.

Slash	Age	Soil drainage	Interaction age and soil drainage
Total summer LAI	0.140	0.316	0.024
Overstory summer LAI	0.708	0.233	0.089
Understory summer LAI	0.008	0.449	0.449
Overstory winter LAI	0.957	0.154	0.046

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* Note: Standard Error of the mean was calculated as $SE = \sqrt{\frac{MSE}{5}}$

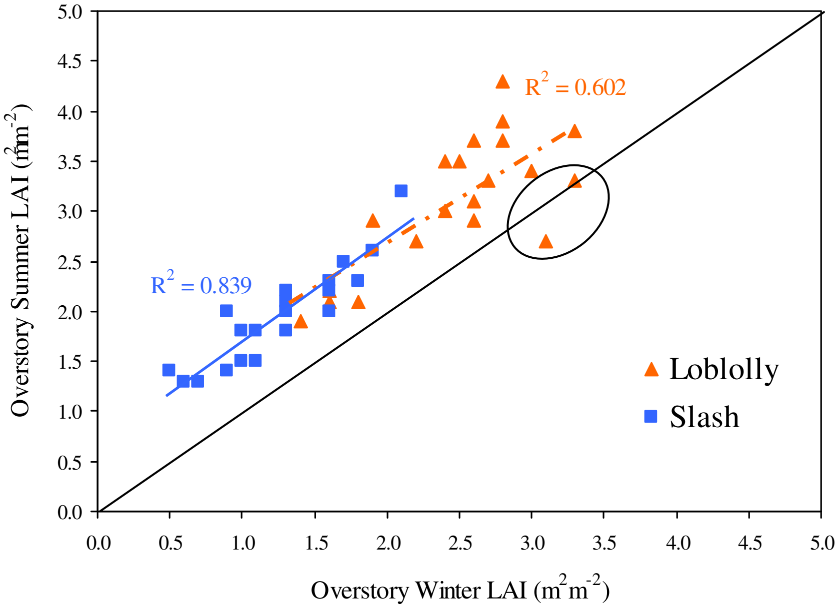

Figure 5. Relationship between overstory summer LAI and overstory winter LAI for slash pine and loblolly pine. The points inside the circle represent the plots of loblolly pine, which value of LAI in winter was almost the same or higher than in summer.

Summer overstory and understory LAI were strongly correlated (-0.694) for loblolly pine, while for slash pine the correlation was negative but very weak -0.297 (Table 5, Figure 6). Summer and winter overstory LAIs were strongly and positively correlated for loblolly pine (0.776), and also for slash pine (0.916). Loblolly pine also showed a strong negative correlation between winter overstory LAI and summer understory LAI.

Correlations among stand and site factors

There were no significant correlations between LAI and basal area for either loblolly pine or slash pine (Table 5). Height was significantly correlated with basal area for loblolly (0.541) and slash pine (0.598). Crown length in loblolly pine was significantly correlated with height (0.597) and understory height (-0.408). In slash pine, crown length was significant correlated with basal area (0.623) and height (0.619) and site index (0.517). Understory height in loblolly pine was no correlated with any stand variables, while in slash pine it was significantly correlated with basal area (0.543) and height (0.689) and site index (0.661). Understory coverage in loblolly pine was correlated negatively with basal area and site index. In contrast, the understory coverage in slash pine was no correlated with any stand other variable.

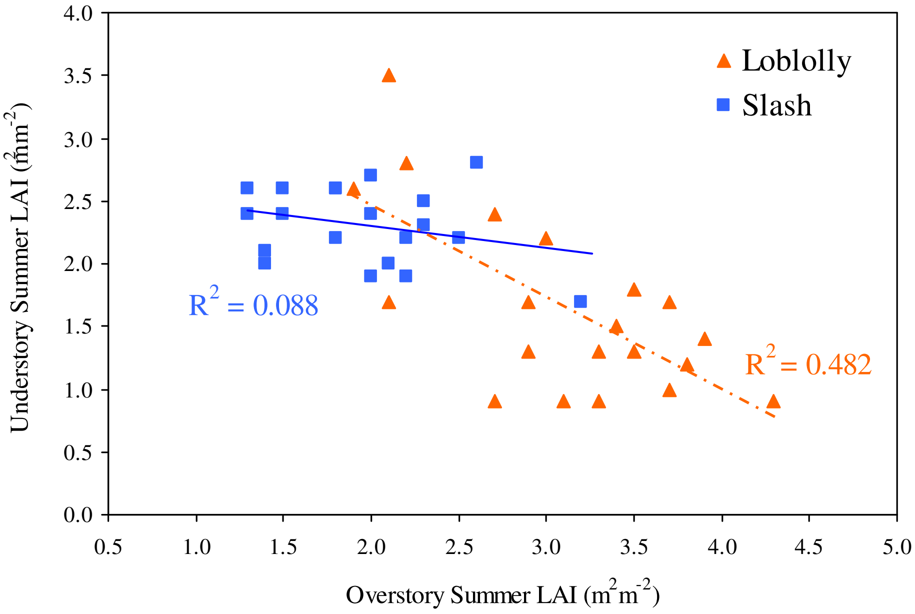

Figure 6. Relationship between overstory LAI and understory LAI during summer time. Data corresponds to the 20 plots measured for each of the pine species.

Remote Sensing Data

For the summer 2005 data, correlations between LiCor LAI and the vegetation indices were not significant (Table 6). The correlation results were improved when the outliers were removed but correlations were only significant for loblolly pine (Table 6). Correlations among all the indices were strong (around 0.9). Simple Ratio and NDVI where also included in the correlation analysis by species with the stand and site factor variables (Table 5).

Table 5. Pearson correlation coefficients among leaf area and stand characteristics for loblolly pine (unfilled background) and slash pine (filled background) n = 20/pine sp.

	Total Summer LAI (m^{2}m^{-2})	Overstory Summer LAI (m^{2}m^{-2})	Understory Summer LAI (m^{2}m^{-2})	Ratio Overstory/ Understory Summer	Overstory Winter LAI (m^{2}m^{-2})	Basal Area (m^{2}ha^{-1})	Site Index (m)	Height (m)	Crown Length (m)	Understory Height (m)	Understory Coverage (%)	SR Summer	SR Winter	NDVI Summer	NDVI Winter
Total Summer LAI (m^{2}m^{-2})	1	**0.807**	0.324	**0.492**	**0.862**	0.347	0.177	-0.099	0.364	-0.204	-0.105	-0.294	-0.092	-0.295	-0.119
Overstory Summer LAI (m^{2}m^{-2})	0.317	1	-0.297	**0.898**	**0.916**	0.181	-0.055	0.017	0.388	-0.185	-0.037	-0.368	-0.050	-0.362	-0.031
Understory Summer LAI (m^{2}m^{-2})	**0.463**	**-0.694**	1	**-0.653**	-0.073	0.271	0.374	-0.189	-0.032	-0.033	-0.111	0.116	-0.009	0.104	-0.146
Ratio Overstory/ Understory	-0.161	**0.819**	**-0.887**	1	**0.730**	0.089	-0.146	0.126	0.422	-0.130	-0.016	-0.339	-0.009	-0.328	0.041
Overstory Winter LAI (m^{2}m^{-2})	0.027	**0.776**	**-0.705**	**0.746**	1	0.211	-0.014	-0.024	0.343	-0.218	-0.145	-0.279	-0.023	-0.279	-0.023
Basal Area (m^{2}ha^{-1})	0.308	0.332	-0.076	0.182	0.414	1	**0.681**	**0.598**	**0.623**	**0.543**	-0.128	0.350	**0.626**	0.334	**0.580**
Site Index (m)	0.047	**0.522**	**0.452**	0.284	0.354	0.123	1	**0.540**	**0.517**	**0.661**	-0.232	**0.461**	**0.735**	**0.431**	**0.697**
Height (m)	**0.455**	0.267	0.096	0.129	0.375	**0.541**	0.011	1	**0.619**	**0.689**	-0.007	**0.548**	**0.708**	**0.521**	**0.701**
Crown Length (m)	0.265	-0.175	0.365	-0.176	0.012	0.036	-0.143	**0.597**	1	0.288	-0.123	0.127	**0.486**	0.144	**0.495**
Understory Height (m)	-0.055	0.245	-0.271	0.260	0.188	0.103	0.307	-0.179	-0.408	1	0.082	**0.727**	**0.824**	**0.708**	**0.793**
Understory Coverage (%)	-0.203	-0.271	0.099	-0.242	-0.103	**-0.555**	**-0.478**	-0.187	0.043	0.055	1	0.142	-0.066	0.126	-0.138
SR Summer	0.306	0.268	-0.018	0.147	0.122	0.245	**0.440**	0.280	0.213	0.125	-0.411	1	0.630	0.990	0.564
SR Winter	0.186	**0.616**	**-0.434**	**0.537**	**0.516**	0.331	**0.508**	0.184	-0.030	0.070	-0.351	0.586	1	0.602	0.988
NDVI Summer	0.246	0.272	-0.068	0.196	0.142	0.245	0.402	0.268	0.170	0.156	-0.392	0.985	0.546	1	0.533
NDVI Winter	0.238	**0.576**	-0.358	**0.464**	**0.485**	0.325	**0.438**	0.223	0.040	0.036	-0.295	0.586	0.985	0.555	1

Pearson correlation coefficient significance at a p-value 0.05 = 0.423
Site Index for loblolly pine was calculated using Clutter and Lenhart (1968) equation, and for slash pine was used Pienaar et al. (1990) equation. Both equations used an index age of 25 years.

There were significant correlations in summer for loblolly pine between SR and site index (0.440), and for slash pine between SR and site index (0.461), SR and height (0.548), SR and understory height (0.727), NDVI and site index (0.431), NDVI and height (0.521) and, NDVI and understory height (0.708). In winter, simple ratio was correlated for loblolly with the overstory summer ground LAI (0.616) as well as with the understory (-0.434), the overstory/understory ratio (0.537), with the overstory winter ground LAI (0.516) and with site index (0.508). In loblolly pine, NDVI from the winter image was correlated with overstory summer ground LAI (0.576), the overstory/understory ratio (0.464) and with overstory winter ground LAI (0.438). For slash pine, correlations were stronger in winter than in summer. SR was correlated with basal area (0.626), site index (0.735), height (0.708), crown length (0.486), and understory height (0.824). Winter NDVI from winter was significantly correlated with basal area (0.580), site index (0.697), height (0.701), crown length (0.495), and understory height (0.793).

For the winter 2006 data with outliers removed, LiCor LAI estimates were significantly correlated with LAI from the Flores model, SR and NDVI. For slash pine, all the correlations were significant. LiCor LAI and EVI correlations were also significant for the whole dataset (n = 34). The results from R-square and stepwise selection showed that the highest R^2 value was 0.628, when using Simple Ratio and LAI model values. Figures 7 and 8 show the relationships between NDVI and total LAI (understory and overstory) estimated with the LiCor LAI-2000. Loblolly pine showed a positive relationship while slash pine had a negative relationship with NDVI.

Table 6. Pearson correlation coefficients for the entire data set and with outliers removed for LAI estimated from the ground and the different vegetation indices. Landsat Image from summer 2005.

	Total LAI 2005					
	all plots	all plots without outliers	loblolly	loblolly without outliers	slash	slash without outliers
	n = 39	n = 37	n = 20	n = 19	n = 19	n = 18
LAI (Flores model)	0.185	0.234	0.306	0.484	-0.294	-0.336
SR	0.184	0.234	0.306	0.486	-0.294	-0.337
NDVI	0.147	0.227	0.246	0.473	-0.295	-0.347
VI	0.144	0.219	0.328	0.547	-0.301	-0.327
EVI	-0.138	-0.193	-0.302	-0.503	0.340	0.388

Significant values of Pearson correlation coefficient:

n = 18 0.05 = 0.444 n = 19 0.05 = 0.433 n = 20 0.05 = 0.423

n = 35 0.05 = 0.325 n = 40 0.05 = 0.304

Table 7. Pearson correlation coefficients for the entire data set and with outlier removed for LAI estimated from the ground and the different vegetation indices. Landsat Image from winter 2006.

	Total LAI 2006					
	all plots	all plots without outliers	loblolly	loblolly without outliers	slash	slash without outliers
	n = 39	n = 34	n = 20	n = 16	n = 19	n = 18
LAI (Flores model)	0.169	0.215	0.325	0.567	-0.451	-0.616
SR	0.158	0.2	0.325	0.561	-0.451	-0.618
NDVI	0.145	0.156	0.367	0.522	-0.464	-0.656
VI	-0.149	-0.207	0.258	0.376	-0.429	-0.583
EVI	-0.22	0.353	0.246	0.266	-0.397	-0.591

Significant values of Pearson correlation coefficient:

n = 16 0.05 = 0.468 n = 18 0.05 = 0.444 n = 19 0.05 = 0.433

n = 20 0.05 = 0.423 n = 35 0.05 = 0.325 n = 40 0.05 = 0.304

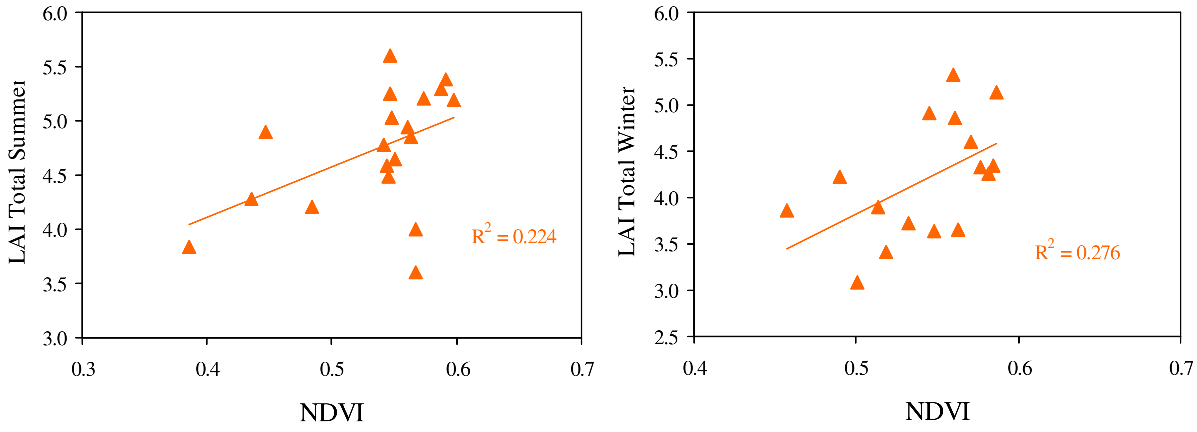

Figure 7. Relationship between NDVI and Total LAI for loblolly pine in summer 2005 and winter 2006. Sample size for summer was n = 19 and for winter was n = 16.

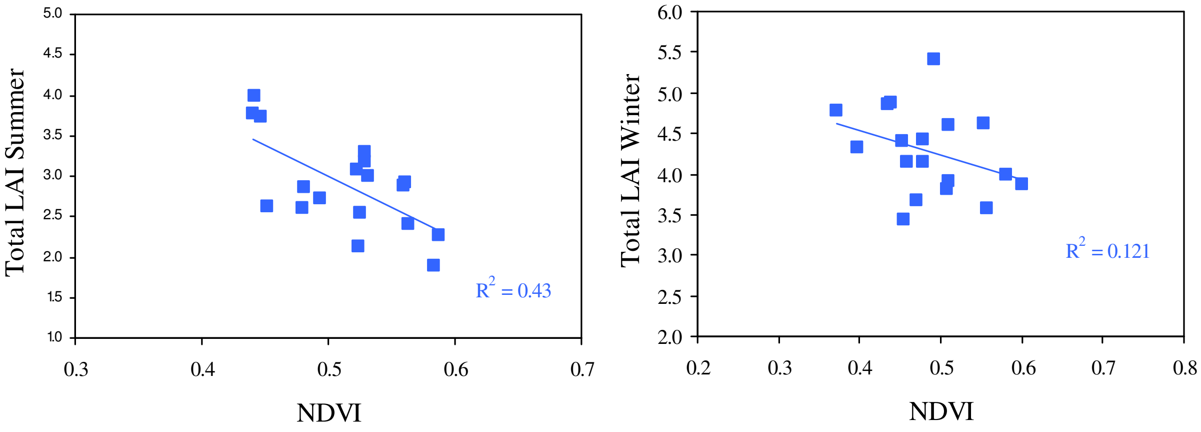

Figure 8. Relationship between NDVI and Total LAI for slash pine in summer 2005 and winter 2006. Sample size for summer and winter was n = 18.

The relationships between LiCor LAI and the LAI estimated from the Flores model are shown in Figure 9. Slash pine correlations were negative, while loblolly pine correlations were positive.

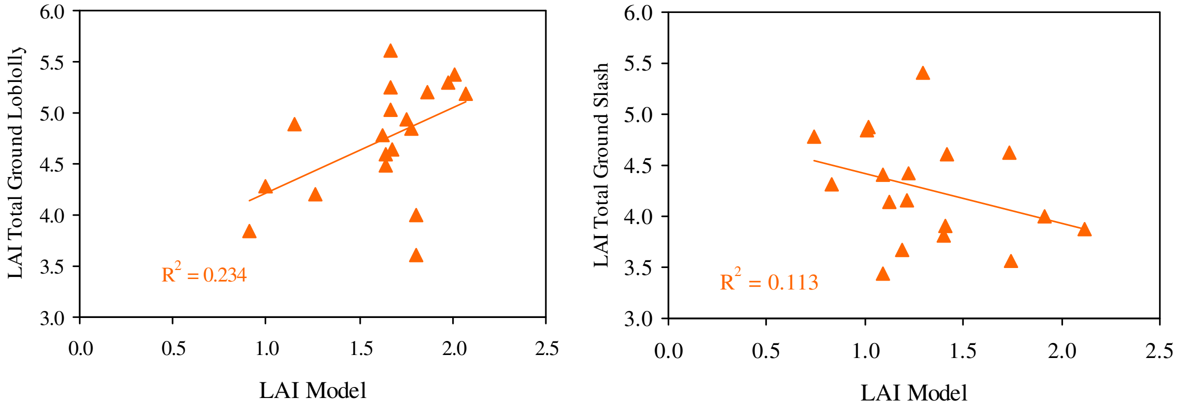

Figure 9. Relationships between the LAI estimated from the model and the LAI estimated on the ground with the LiCor 2000. The datasets used were from summer 2005 and after the outliers had been removed. For loblolly pine the sample size was n = 19 and for slash pine was n = 18.

Discussion

Leaf area index and stand site factors

Leaf area index values observed in the overstory were low in most of the plots, ranging from 1.9 to 4.3 m^2m^{-2} for loblolly and from 1.3 to 3.2 m^2m^{-2} for slash, similar to previously observed LAI values where a typical range of peak leaf area index values for unfertilized loblolly pine plantations located across the southeast were between 1.5 and 3.7 m^2m^{-2} (Rojas, 2005; Sampson and Allen, 1999). Vose and Allen (1988) suggested that for fertilized stands LAI could be at least 4 m^2m^{-2}, and Sampson et. al. (1999) suggested that the southern pines can biologically possible reach a LAI of 4.0 and 4.5 m^2m^{-2}. It can be concluded that for most of the plots the LAI results are falling into what Sampson et al. (1997) called Sustainable LAI threshold, where low nutrient availability or high competition restrains the pine leaf area production. In the case of slash, there were five plots that showed a basal area of 10 m^2ha^{-1} or lower, which represents a Suboptimal LAI threshold with high levels of understory competition and poor growth rates.

LAI for the understory vegetation varied between 0.9 and 3.5 m^2m^{-2}, indicating that the high levels of understory LAI may be due to the still open canopy observed in all plots. For understory, light might be the most important factor affecting plant survival, growth, and microsite distribution. Light availability in the understory will be dependent on the crop leaf area index and canopy gaps. While leaf area index increases, the amount of time, size and peak of direct solar irradiance (sunflecks) that penetrates the canopy decreases (Chazdon, 1988; Chen, 2003; Kinkla et al., 1992). Increasing the stand leaf area, will accelerate canopy closure in young stands, allowing reduced light penetration through the canopy. Consequently, the understory vegetation will be shaded out. The effect that the speed canopy development, as well as the density of the stand, has on the competing vegetation, will probably be as good as a herbicide application effect (Zutter and Miller, 1998).

Clearly, the understory vegetation was not significantly different across soil drainage classes. LAI values were not significant, and understory coverage and understory height were similar among soil drainage classes. Oppenheimer et al. (1989) tested interactions among different drainage classes and treatments and found that they were no significant. In addition to this, Neary et al. (1990) did not find significant differences for the understory biomass in loblolly and slash stands.

The inverse relationship between overstory and understory LAI represents competition for light between these two strata. Low values of the overstory summer LAI estimated for both pine species (similar to what an unfertilized stand would have), as well as low height and short crown length estimations could be explained by a nutrient deficiency in most of the sites; which can be attributable to the belowground competition for water and nutrients (Morris et al., 1993). High values of understory summer LAI estimations could be explained by the positive effect of a past fertilization still benefiting competing vegetation growth. Among the four types of long-term growth response, type D theoretically describes what happens when the competing vegetation gains more than pine trees after fertilization, subsequently pine growth decreases to be less than the stands where fertilizer was not applied (Nilsson and Allen, 2003). This situation might explain the plots where the overstory LAI was very low compared with the understory LAI. Neary et al. (1990), found that not only did fertilization increase the understory biomass, but also, understory composition reduced the slash pine productivity gained from fertilization by one-half. Gallberry and other woody shrubs species are characterized by having a denser root system than young pine, which probably allows them to rapidly obtain available nutrients from the soil or added fertilizer. When the density of gallberry increased from 0 to >28 stems m^{-2}, loblolly pine decreased its DBH from 6.5 cm to <1.0 cm. Slash pine followed a similar trend.

Besides nutrient limitations, water availability could be considered as one of the factors affecting leaf area index. However, in the South soil water availability may not play the most important role in pine productivity (Albaugh et al., 1998; Colbert et al., 1990; Jokela et al., 2004; Sampson and Allen, 1999). Additionally, the wet soils found in the coastal plain have a water table that is relatively high for most of the growing season. The driest soils were moderately drained soils, which do not get completely dry during a year (Borders et al., 2004). Additionally, soil drainage class, precipitation, soil water holding capacity, and water deficit were not correlated with leaf area index (Forest Nutrition Cooperative, 1991).

The lack of correlation between LAI and basal area was expected, since it has been observed in previous studies that LAI is strongly related to basal area while stands are still young, but as soon as the stand gets older, the basal area becomes an accumulation of past pine growth and its relationship with current LAI becomes weaker. This has been attributed to the nutrient demand that overpasses the nutrient supply (Vose and Allen, 1988).

Remote sensing vegetation indices and LAI

Total LAI estimated with the LiCor LAI-2000 was weakly correlated with vegetation indices. LAI values estimated using the simple ratio and Flores et al. (2006) model were typically half of the values estimated on the ground. There are difficulties associated with leaf area estimations using remote sensing data. The interception, scattering, and emission of the electromagnetic radiation from leaves are related to forest canopy structure. As such, they depend on the spatial arrangement of leaves, branches, and stems, as well as the contribution of different backgrounds, such as soil (soil properties and moisture content) and understory vegetation. However, previous research has demonstrated that the calculation of LAI using multispectral imagery (Curran et al., 1992; Flores et al., 2006; Iiames et al., 2004; Jensen and Binford, 2004) has been a success. Rautiainen (2005) found that the greater the canopy closure, the stronger the correlation between LAI and reflectance data. When viewed from above, open canopies allow the understory to be easily seen and therefore increase its contribution to reflectance (Eriksson et al., 2006). Even given these known complications, the Landsat-derived vegetation indices (SR and NDVI) were significantly correlated with the stand biophysical characteristics and the ground measured LAI was not. This is likely due in part to reduced accuracy in the LiCor LAI-2000 estimations of the stands with a still open canopy. Other research has also showed that multispectral imagery can be significantly correlated to stand attributes. Lefsky et al. (2001) evaluated the performance of Landsat TM imagery to predict forest structural attributes in a natural forest located in Oregon. Using a single image to predict foliage biomass resulted in a R^2 of 46%. There was a significant increase in the R^2 when two images were used, with the best predicted attributes (R^2 over 60%) being basal area, biomass, and maximum height. Given the linear relationship between vegetation indices and LAI prior to saturation (see next paragraph), it thus appears that in this case that multispectral satellite data estimate stand LAI more accurately than the direct measurement of LAI on the ground.

Another difficulty in estimating leaf area is that in regions with high LAI (around 4.0), vegetation indices have an asymptotic or saturated response. Since the range of total LAI (understory and overstory together) for all plots was between 3.4 and 5.6 m^2m^{-2} for summer 2005, these values were all located in the saturation region. Therefore, the relationship between the vegetation indices and LAI from the ground was probably also affected by the narrow range of LAI values.

More research is needed to develop a technique or model that could distinguish the evergreen understory from the evergreen overstory when using remote sensing data. The use of distinct characteristics of spectral reflectance is an aspect that would enable separation of vegetation that otherwise looks the same in visible wavelengths (Fyfe, 2003; Bin, 1999). Using differences in spectral reflectance of the understory and overstory vegetation may provide a method to separate the two. Recent reviews (Andersen et al., 2003; Drake et al., 2002; Lefsky et al., 2002; Riaño et al., 2004) have shown that actively sensed airborne laser scanning (LIDAR) technology has the potential to distinguish the understory. Lidar sensors directly measure the three-dimensional distribution of plant canopies as well as subcanopies.

In forest management, leaf area can be effectively used as an indicator of growth, where low values of leaf area index indicate low productivity. Fortunately, if productivity problems are diagnosed early, fertilization prescriptions can be adapted to the stand and site needs. LAI estimates can be used to monitor and quantify competing vegetation and to identify those stands where vegetation control should be applied. The relationship observed between overstory LAI and understory LAI indicates that when silvicultural treatments, such as vegetation control and fertilization, increase pine LAI, the conditions for competing vegetation growth will be much poorer.

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APPENDIX

Appendix 1. Loblolly pine data collected for each of the plots n=20.

Plot	Age	Soil Drainage	Overstory summer LAI (m^{2}.m^{-2})	Understory summer LAI (m^{2}.m^{-2})	Overstory winter LAI (m^{2}.m^{-2})	Understory winter LAI (m^{2}.m^{-2})	Difference Overstory LAI (m^{2}.m^{-2})	Difference Understory LAI (m^{2}.m^{-2})	Basal Area (m^{2}.ha^{-1})	Site Index (m)	Dominant Height (m)	Crown Length (m)	Understory height (m)	Understory coverage (%)
5	7	P	3.1	0.9	2.6	2.1	0.5	-1.2	25.1	27	13.4	7.5	1.7	42
6	7	P	2.7	0.9	3.1	1.2	-0.4	-0.3	22.8	26	12.7	8.0	1.7	71
9	7	P	3.5	1.8	2.4	2.9	1.1	-1.1	28.9	28	13.7	7.7	1.8	44
10	7	P	2.9	1.7	2.6	2.3	0.3	-0.6	27.4	27	13.1	7.7	1.7	38
17	7	P	3.7	1.7	2.8	1.5	0.8	0.2	20.8	27	13.5	7.9	1.6	70
11	7	S	3.9	1.4	2.8	1.5	1.1	-0.2	25.4	26	12.1	6.3	1.8	62
12	7	S	2.9	1.3	1.9	1.2	1.0	0.1	19.3	25	11.4	6.8	1.6	62
13	7	S	2.1	1.7	1.6	0.7	0.5	1.1	20.7	26	11.9	6.8	1.7	68
14	7	S	4.3	0.9	2.8	1.2	1.5	-0.3	27.1	28	14.1	7.7	1.7	23
16	7	S	3.7	1.0	2.6	1.1	1.2	0.0	18.9	27	12.9	7.8	1.8	94
1	10	P	2.2	2.8	1.6	2.0	0.6	0.8	25.9	23	12.9	7.6	1.8	63
2	10	P	3.8	1.2	3.3	1.9	0.6	-0.7	29.8	26	14.7	7.7	1.4	42
3	10	P	3.4	1.5	3.0	0.9	0.4	0.6	26.6	25	14.5	7.3	1.9	88
4	10	P	3.3	1.3	2.7	2.2	0.7	-0.9	23.6	25	14.6	7.9	1.6	63
15	10	P	3.3	0.9	3.3	0.6	0.1	0.3	25.7	24	13.5	7.6	1.7	83
7	10	S	3.5	1.3	2.5	1.7	1.0	-0.4	24.9	24	13.6	8.2	1.6	53
8	10	S	2.1	3.5	1.8	4.1	0.3	-0.5	23.0	25	14.3	8.6	1.6	53
18	10	S	3.0	2.2	2.4	2.1	0.6	0.2	24.9	24	13.8	7.7	1.6	70
19	10	S	2.7	2.4	2.2	1.5	0.4	0.9	23.0	24	13.1	8.2	1.4	74
20	10	S	1.9	2.6	1.4	2.0	0.5	0.6	22.6	24	13.5	7.9	1.4	85

Appendix 2. Slash pine data collected for each of the plots n=20.

Plot	Age	Soil Drainage	Overstory summer LAI (m^2.m^{-2})	Understory summer LAI (m^2.m^{-2})	Overstory winter LAI (m^2.m^{-2})	Understory winter LAI (m^2.m^{-2})	Difference Overstory LAI (m^2.m^{-2})	Difference Understory LAI (m^2.m^{-2})	Basal Area (m^2.ha^{-1})	Site Index (m)	Dominant Height (m)	Crown Length (m)	Understory height (m)	Understory coverage (%)
21	7	P	1.8	2.2	1.1	1.2	0.7	1.1	16.8	27	10.4	5.3	1.8	84
24	7	P	1.8	2.6	1.0	1.8	0.8	0.8	22.1	27	10.7	6.2	1.3	74
26	7	P	1.3	2.4	0.6	1.5	0.7	0.9	13.3	25	9.9	5.5	1.5	63
39	7	P	1.3	2.6	0.7	1.9	0.6	0.7	10.2	26	10.0	5.3	1.3	65
40	7	P	1.8	2.6	1.3	1.6	0.5	1.0	23.6	25	9.8	5.4	1.5	69
30	7	M	2.6	2.8	1.9	2.1	0.7	0.7	22.0	24	9.5	5.6	1.3	84
31	7	M	2.3	2.5	1.6	3.0	0.8	-0.5	13.7	25	9.6	5.3	1.3	71
32	7	M	2.3	2.3	1.8	1.3	0.5	1.0	12.5	24	9.4	5.0	1.2	55
34	7	M	2.5	2.2	1.7	1.0	0.9	1.2	10.9	23	8.9	5.0	1.1	80
35	7	M	1.5	2.6	1.0	2.8	0.5	-0.2	8.4	19	7.2	4.1	0.9	78
22	10	P	1.4	2.1	0.5	1.4	0.9	0.8	17.9	27	14.3	5.5	1.9	90
23	10	P	1.5	2.4	1.1	1.4	0.4	1.1	21.2	26	13.7	5.0	1.9	70
33	10	P	2.2	2.2	1.3	1.3	0.9	0.9	21.0	23	12.0	6.0	1.2	62
37	10	P	2.0	2.7	1.6	1.3	0.4	1.3	17.6	24	12.7	6.6	1.3	76
38	10	P	3.2	1.7	2.1	0.9	1.1	0.8	18.6	24	12.5	6.5	1.3	70
25	10	M	2.1	2.0	1.3	1.8	0.8	0.2	14.5	21	10.9	5.0	1.5	69
27	10	M	2.2	1.9	1.6	1.7	0.7	0.2	12.1	21	10.9	6.0	1.5	81
28	10	M	2.0	1.9	0.9	2.0	1.0	-0.1	8.5	16	8.4	4.7	1.2	82
29	10	M	2.0	2.4	1.3	2.4	0.7	0.0	8.4	18	9.4	4.8	1.1	80
36	10	M	1.4	2.0	0.9	1.7	0.5	0.3	7.7	17	9.0	4.6	0.8	81

Appendix 3. Data estimated from summer 2005 satellite imagery per plot.

Plot	Species	Age	Soil Drainage	Total LAI summer (LiCor)	LAI (model)	SR	NDVI	VI	EVI
5	Loblolly	7	P	4.00	1.805	3.623	0.567	56.583	-0.089
6	Loblolly	7	P	3.61	1.808	3.626	0.567	55.727	-0.090
9	Loblolly	7	P	5.30	1.976	3.855	0.587	62.273	-0.094
10	Loblolly	7	P	4.64	1.671	3.446	0.550	54.000	-0.086
17	Loblolly	7	P	5.38	2.013	3.900	0.591	61.071	-0.094
11	Loblolly	7	S	5.25	1.667	3.443	0.547	55.700	-0.088
12	Loblolly	7	S	4.20	1.266	2.913	0.484	51.727	-0.082
13	Loblolly	7	S	3.84	0.912	2.431	0.386	40.364	-0.068
14	Loblolly	7	S	5.21	1.867	3.704	0.574	56.727	-0.089
16	Loblolly	7	S	4.78	1.623	3.388	0.541	58.083	-0.088
1	Loblolly	10	P	4.94	1.756	3.558	0.561	55.091	-0.087
2	Loblolly	10	P	5.03	1.668	3.438	0.548	52.000	-0.085
3	Loblolly	10	P	4.89	1.148	2.744	0.447	43.364	-0.073
4	Loblolly	10	P	4.59	1.640	3.406	0.544	54.600	-0.086
15	Loblolly	10	P	4.28	0.998	2.550	0.435	43.300	-0.073
7	Loblolly	10	S	4.85	1.781	3.592	0.563	56.750	-0.087
8	Loblolly	10	S	5.61	1.668	3.452	0.547	60.083	-0.091
18	Loblolly	10	S	5.19	2.070	3.976	0.598	62.750	-0.096
19	Loblolly	10	S	5.11	0.641	2.062	0.312	32.455	-0.061
20	Loblolly	10	S	4.48	1.643	3.404	0.546	50.909	-0.084
21	Slash	7	P	4.00	1.917	3.775	0.580	60.417	-0.094
26	Slash	7	P	3.67	1.187	2.803	0.471	46.333	-0.077
39	Slash	7	P	3.91	1.409	3.105	0.510	54.417	-0.082
40	Slash	7	P	4.42	1.224	2.858	0.479	51.200	-0.079
30	Slash	7	M	5.41	1.295	2.946	0.492	47.091	-0.076
31	Slash	7	M	4.85	1.011	2.567	0.434	44.273	-0.073
32	Slash	7	M	4.61	1.417	3.110	0.510	50.000	-0.080
34	Slash	7	M	4.78	0.745	2.211	0.371	42.700	-0.068
35	Slash	7	M	4.09	0.800	2.286	0.389	43.167	-0.067
22	Slash	10	P	3.57	1.746	3.547	0.558	57.100	-0.090
23	Slash	10	P	3.87	2.115	4.041	0.600	65.818	-0.098
33	Slash	10	P	4.32	0.830	2.324	0.398	39.200	-0.067
37	Slash	10	P	4.63	1.732	3.536	0.554	60.400	-0.090
38	Slash	10	P	4.87	1.017	2.576	0.439	43.455	-0.072
25	Slash	10	M	4.15	1.216	2.841	0.478	46.091	-0.076
27	Slash	10	M	4.14	1.121	2.716	0.458	45.091	-0.074
28	Slash	10	M	3.82	1.400	3.090	0.508	52.333	-0.083
29	Slash	10	M	4.41	1.088	2.674	0.453	47.250	-0.077
36	Slash	10	M	3.43	1.090	2.674	0.455	45.546	-0.075

Appendix 4. Data estimated from winter 2006 satellite imagery per plot.

Plot	Species	Age	Soil Drainage	Total LAI winter (LiCor)	LAI (model)	SR	NDVI	VI	EVI
5	Loblolly	7	P	4.61	1.892	3.669	0.571	36.167	0.014
6	Loblolly	7	P	4.34	2.033	3.853	0.585	39.182	0.014
9	Loblolly	7	P	5.32	1.865	3.632	0.560	35.636	0.014
10	Loblolly	7	P	4.92	1.696	3.421	0.545	34.727	0.013
17	Loblolly	7	P	4.33	1.934	3.730	0.576	38.500	0.015
11	Loblolly	7	S	4.26	1.980	3.787	0.582	38.600	0.015
12	Loblolly	7	S	3.09	1.456	3.117	0.501	33.727	0.013
13	Loblolly	7	S	2.24	0.952	2.461	0.391	27.455	0.011
14	Loblolly	7	S	4.08	2.255	4.130	0.610	40.636	0.016
16	Loblolly	7	S	3.65	1.819	3.579	0.563	36.000	0.015
1	Loblolly	10	P	3.63	1.704	3.432	0.548	34.546	0.013
2	Loblolly	10	P	5.14	2.021	3.841	0.586	39.500	0.015
3	Loblolly	10	P	3.90	1.484	3.149	0.513	32.182	0.013
4	Loblolly	10	P	4.86	1.814	3.567	0.561	34.800	0.013
15	Loblolly	10	P	3.86	1.237	2.829	0.458	29.000	0.012
7	Loblolly	10	S	4.22	1.355	2.980	0.490	29.583	0.012
8	Loblolly	10	S	5.84	1.061	2.609	0.442	28.667	0.012
18	Loblolly	10	S	4.40	1.765	3.515	0.555	36.583	0.014
19	Loblolly	10	S	3.73	1.576	3.280	0.532	36.182	0.014
20	Loblolly	10	S	3.42	1.502	3.176	0.519	32.909	0.013
21	Slash	7	P	2.26	2.022	3.851	0.587	41.417	0.016
26	Slash	7	P	2.13	1.520	3.207	0.524	35.000	0.014
39	Slash	7	P	2.61	1.277	2.895	0.480	33.833	0.014
40	Slash	7	P	2.93	1.799	3.568	0.561	39.400	0.015
30	Slash	7	M	3.99	1.178	2.758	0.442	31.364	0.013
31	Slash	7	M	4.57	1.619	3.338	0.539	37.364	0.015
32	Slash	7	M	3.18	1.608	3.322	0.529	38.000	0.015
34	Slash	7	M	2.72	1.328	2.960	0.494	33.300	0.013
35	Slash	7	M	3.78	1.064	2.617	0.441	30.833	0.013
22	Slash	10	P	1.90	2.003	3.826	0.583	41.100	0.016
23	Slash	10	P	2.41	1.811	3.593	0.564	42.091	0.016
33	Slash	10	P	2.55	1.527	3.223	0.526	37.500	0.015
37	Slash	10	P	2.88	1.800	3.567	0.559	38.900	0.015
38	Slash	10	P	3.00	1.571	3.275	0.532	36.546	0.014
25	Slash	10	M	3.08	1.515	3.203	0.523	36.091	0.014
27	Slash	10	M	3.30	1.564	3.267	0.529	37.000	0.015
28	Slash	10	M	2.87	1.251	2.864	0.481	34.000	0.014
29	Slash	10	M	3.73	1.083	2.645	0.447	32.583	0.013
36	Slash	10	M	2.63	1.107	2.675	0.452	31.273	0.013

Appendix 5. Plot coordinates for loblolly pine.

	Point 1		**Point 2**		**Point 3**		**Point 4**	
Plot	**Latitude**	**Longitude**	**Latitude**	**Longitude**	**Latitude**	**Longitude**	**Latitude**	**Longitude**
1	30.690393936	-81.757356520	30.690813695	-81.758273517	30.689983106	-81.758779120	30.689560627	-81.757861384
2	30.684606986	-81.764996260	30.683919799	-81.765689268	30.684483145	-81.766562187	30.685211193	-81.765885410
3	30.654741180	-81.665017681	30.653852415	-81.664715463	30.654150640	-81.663683304	30.655015637	-81.663970390
4	30.647393294	-81.662623594	30.647107823	-81.663611078	30.647967359	-81.663920571	30.648264587	-81.662910280
5	30.634563126	-81.695404156	30.634971698	-81.694454266	30.635741580	-81.694861846	30.635388096	-81.695831531
6	30.631797327	-81.689015348	30.632661953	-81.689455701	30.632276495	-81.690355396	30.631495156	-81.689934300
7	30.530227158	-81.845969708	30.530963740	-81.845362125	30.531474252	-81.846219970	30.530744801	-81.846828893
8	30.546385780	-81.843023205	30.546358301	-81.841979700	30.545394889	-81.841891533	30.545404687	-81.842936005
9	30.619172871	-81.678875431	30.618963517	-81.677776874	30.618090075	-81.678016588	30.618283079	-81.679053158
10	30.618239657	-81.682147826	30.618733751	-81.683031057	30.619473827	-81.682437860	30.619016843	-81.681547847
11	30.635935012	-81.680387388	30.636550498	-81.679639893	30.635981178	-81.678841137	30.635354741	-81.679588389
12	30.633346866	-81.667960093	30.633541115	-81.668965878	30.632460890	-81.668229630	30.632672013	-81.669262282
13	30.653982701	-81.671154206	30.653245334	-81.670539418	30.652732952	-81.671407951	30.653468442	-81.672012036
14	30.626249352	-81.713024504	30.625760809	-81.712151731	30.625014984	-81.712716287	30.625488226	-81.713603266
15	30.726892012	-81.675854967	30.727139042	-81.674862907	30.726261034	-81.674625529	30.726015174	-81.675628865
16	30.999352335	-82.445227420	30.998441951	-82.445201817	30.998459518	-82.444132457	30.999349337	-82.444133166
17	31.001838783	-82.430058806	31.001870450	-82.429026427	31.002766837	-82.428972828	31.002766810	-82.430003756
18	30.986775731	-82.408696405	30.986185315	-82.407912306	30.986830153	-82.407134874	30.987411259	-82.407951612
19	31.092610037	-82.369676828	31.092645260	-82.370723391	31.091753523	-82.370809208	31.091705367	-82.369741605
20	31.086963349	-82.361400858	31.087659318	-82.360722474	31.087119690	-82.359852102	31.086376386	-82.360493429

Appendix 6. Plot coordinates for slash pine.

	Point 1		**Point 2**		**Point 3**		**Point 4**	
Plot	**Latitude**	**Longitude**	**Latitude**	**Longitude**	**Latitude**	**Longitude**	**Latitude**	**Longitude**
21	30.980826288	-82.388104286	30.980240195	-82.387277499	30.979568954	-82.388000400	30.980167085	-82.388824168
22	31.009840946	-82.424258040	31.010240142	-82.423330112	31.009436822	-82.422889203	31.009022008	-82.423826656
23	31.021281019	-82.431915139	31.021154399	-82.430875937	31.022052789	-82.430672510	31.022196489	-82.431729684
24	31.141345625	-82.373547079	31.140419949	-82.373738034	31.140238440	-82.372703564	31.141138630	-82.372511165
25	30.440463971	-82.062039443	30.439702711	-82.061487560	30.439224356	-82.062379261	30.439975666	-82.062959722
26	30.457174416	-82.056562445	30.457149841	-82.057630548	30.456254832	-82.057585736	30.456264624	-82.056554748
27	30.443417090	-82.107834748	30.444306441	-82.108014032	30.444410262	-82.106978220	30.443510600	-82.106799550
28	30.439248894	-82.107146014	30.440154234	-82.107254104	30.440236404	-82.106201425	30.439328895	-82.106102051
29	30.426241296	-82.107810253	30.427117184	-82.108102516	30.426809531	-82.109084573	30.425952412	-82.108792591
30	30.417960419	-82.103535858	30.418673104	-82.102872590	30.418106077	-82.102053401	30.417387208	-82.102699751
31	30.422721004	-82.090722498	30.421807611	-82.090624970	30.421913534	-82.089577690	30.422813999	-82.089689727
32	30.424040271	-82.090520351	30.423158847	-82.090343517	30.423279811	-82.089302180	30.424160686	-82.089455679
33	30.472193754	-82.168575892	30.471561970	-82.167834606	30.470943001	-82.168602526	30.471584178	-82.169336683
34	30.408490581	-82.114330821	30.409024764	-82.115168595	30.408316673	-82.115806303	30.407778582	-82.114975194
35	30.405187484	-82.115303373	30.404640677	-82.114475905	30.403922314	-82.115118970	30.404488336	-82.115942082
36	30.404718401	-82.106380374	30.404191086	-82.105527177	30.403470308	-82.106135789	30.403983164	-82.106991176
37	30.392680703	-82.063088678	30.391990068	-82.063781250	30.391415963	-82.062965207	30.392106432	-82.062292459
38	30.321964750	-82.092355762	30.321817494	-82.091334449	30.320937750	-82.091576051	30.321089346	-82.092595346
39	30.320805688	-82.049899967	30.320732031	-82.050937201	30.321629882	-82.051019550	30.321705395	-82.049982171
40	30.304482631	-82.062214015	30.305348243	-82.062533550	30.305599354	-82.061536773	30.304741033	-82.061230459