

LEAF AREA INDEX (LAI) OF LOBLOLLY PINE AND EMERGENT VEGETATION FOLLOWING A HARVEST

D. A. Sampson, D. M. Amatya, C. D. Blanton Lawson, R. W. Skaggs



ABSTRACT. Forests provide goods and services to society and, often, refugia for plants and animals; forest managers utilize silviculture to provide ecosystem services and to create habitat. On the Coastal Plain of North Carolina, forest management objectives typically include wood fiber production but may also include the maintenance of environmental quality and, sometimes, species diversity. Silvicultural prescriptions alter stand structure and development trajectories by influencing the competitive interactions among plant species for site resources. Early site intervention may include nutrient additions and/or vegetation control; in coastal loblolly pine (*Pinus taeda* L.) stands, herbaceous and arborescent species can dominate the site leaf area index (LAI) for many years after a harvest (followed by planting). LAI is an important structural and functional component of a forest stand. Many eco-hydrologic and water quality models do not accurately account for LAI as the process driver to evapotranspiration (ET), and thus they ignore the ecophysiological effects of LAI on site water balance and nutrient loading. We measured LAI of emergent vegetation following a harvest, mechanical site preparation, and then pine planting for a drained loblolly pine plantation in coastal North Carolina. For six years monthly, growing season estimates of LAI were obtained using a LI-COR LAI 2000 Plant Canopy Analyzer (PCA) for control (D1), thinned (D3), and harvested (D2) watersheds. In this article, we present results from the D2 treatment. In D2, we “harvested” all emergent vegetation in 18 randomly placed 1 m² clip plots for three growing seasons where we estimated LAI using species-pooled estimates of specific leaf area and total leaf dry mass (i.e., LAI_{CLIP}); PCA measurements were recorded prior to clipping (LAI_{PCA}). We also simulated loblolly pine seedling growth and development using the biogeochemical process model SECRETS-3PG to examine site differentiation in LAI. Four years post-harvest maximum LAI_{CLIP} exceeded 8 m² m⁻² (projected area basis). LAI_{PCA} underestimated LAI_{CLIP}; LAI_{CLIP} = 1.436 × LAI_{PCA} (r² = 0.53; p < 0.0001; n = 195). Corrected LAI_{PCA} estimates exceeded simulated pine LAI (LAI_{SIM}) for ~4.5 years post-planting. Emergent vegetation dominated the site for nearly five years and likely exerted a strong influence over site water balance and nutrient use during early stand development.

Keywords. Competition, Evapotranspiration, Hydrologic modeling, LAI, Plantation management, Weed control.

Following a harvest and mechanical site preparation, invasive herbaceous and arborescent species compete with newly planted loblolly pine (*Pinus taeda* L.) seedlings for available site resources (space, water, and nutrients) (e.g., Allen, 2001). Unchecked, these fast-growing species capture resources at the expense of the crop tree, often resulting in significant loss in yield (Balandier et al., 2006). In this case, early control (suppression) of emergent vegetation is needed to optimize volume and value production of planted loblolly pine (Jokela et al., 2000; Allen et

al., 2005). Although much focus has been placed on quantifying the direct impacts of competing vegetation on planted crop species (Miller et al., 1991; Pienaar and Shiver, 1993; Bailey and Borders, 2001), few have quantified the leaf area index (LAI) of competing species (Lautenschlager et al., 2000; Thevathasan et al., 2000), and none, that we are aware, have examined temporal variation in LAI of competing herbaceous species following a harvest and then planting. Differentiating LAI of competing vegetation from that of a crop species enables us to examine shifts in growing space and site dominance over time. It also enables an opportunity to more accurately model the evapotranspiration (ET) dynamics of the stand, and thus the often neglected water use by competing vegetation (e.g., McCarthy et al., 1992; McCarthy and Skaggs, 1992). This may be especially important for newly established stands following a harvest, where emergent vegetation may strongly impact the hydrologic budget by exerting the dominant control over site ET (e.g., Swank et al., 2001).

Loblolly pine is a fast-growing species that is well suited to intensive site management, largely because of its plastic and dynamic patterns in LAI; loblolly pine responds quickly to drought by dropping pre-senescent needles and, conversely, reacts quickly to improved soil nutritional conditions by adding flushes to the current (most recent) foliage cohort. North American loblolly pine retains, at most, three foliage cohorts (Sampson et al., 2003) and thus can respond quickly to silvicultural treatments such as vegetation suppression and

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The authors are **David Arthur Sampson**, Research Scientist, Global Institute of Sustainability, Arizona State University, Tempe, Arizona; **Devendra M. Amatya**, ASABE Member, Research Hydrologist, USDA Forest Service, Center for Forested Wetlands Research, Cordesville, South Carolina; **Christine D. Blanton Lawson**, ASABE Member, Environmental Engineer, North Carolina Department of Environment and Natural Resources, Division of Water Quality, Fayetteville, North Carolina; and **R. Wayne Skaggs**, ASABE Fellow, W. N. Reynolds Professor and Distinguished University Professor, Department of Biological and Engineering, North Carolina State University, Raleigh, North Carolina. **Corresponding author:** David Arthur Sampson, Global Institute of Sustainability, Arizona State University, 21 East 6th Street, Suite 126B, Tempe, AZ 85287; phone: 480-965-5811; fax: 480-965-8383; e-mail: david.a.sampson@asu.edu.

nutrient amendments (Albaugh et al., 2004; Jokela et al., 2004). Loblolly pine leaf area development, both annual and the trajectory of LAI from seedlings to a site maximum, follows a sigmoidal growth pattern (Adegbidi et al., 2002; Sampson et al., 2003; Jokela et al., 2004). Thus, LAI peaks every year, with maximum annual LAI generally occurring in late September prior to annual needle senescence (Sampson et al., 2003). Maximum stand LAI is achieved around four to eight years following planting, depending on inherent site fertility and/or nutritional amendments (Albaugh et al., 2004; Sampson et al., 2008).

LAI is a dominant attribute of stand structure; LAI determines canopy water interception and transpiration and therefore is needed to estimate evapotranspiration (ET) in eco-hydrologic models (Jensen et al., 1990; McCarthy and Skaggs, 1992; Arnold et al., 1998; Sun et al., 1998a, 2000; Amatya and Skaggs, 2001; Zhang et al., 2002; Li, 2007; Dai et al., 2010; Tian et al., 2009, 2011) and in water balance studies (Sun et al., 2010; Tian et al., 2010; Amatya et al., 2002; McCarthy et al., 1991; Amatya et al., 1996). Potential evapotranspiration (PET) models, such as the Penman-Monteith formulation (Monteith, 1965), are used to estimate PET of crop and reference crop vegetation (Jensen et al., 1990; Amatya et al., 1996; Amatya and Skaggs, 2008; Sun et al., 2010; Dai et al., 2010). McCarthy et al. (1992) used an empirical LAI function in a forest hydrologic model that was based on DRAINMOD (Skaggs, 1978) to simulate canopy interception, transpiration, and soil evaporation. McCarthy and Skaggs (1992) used the same LAI function to simulate the long-term water balance for the life cycle of a loblolly pine stand in eastern North Carolina. Simulated canopy interception, and soil evaporation and transpiration combined accounted for roughly 4% and 20%, respectively, of average rainfall using an LAI of $1 \text{ m}^2 \text{ m}^{-2}$ one year following harvest of a pine stand. However, Amatya et al. (2006), in a controlled watershed study, provided evidence to suggest that nearly 40% of annual rainfall may have been lost to evapotranspiration (ET) (obtained as the difference between rainfall and drainage outflow, ignoring minor storage). We postulate that the greater ET losses observed by Amatya et al. (2006) may have been due to the effects of ET by emergent vegetation in these wet pine flats that was not modeled by McCarthy and Skaggs (1992). Obviously, accurate estimates of site LAI are critical to modeling site water balance (Amatya et al., 1996; Amatya and Skaggs, 2001; Sun et al., 1998a, 1998b, 2010). Recently, Tian et al. (2010, 2012) developed a new version of the DRAINMOD-NII model (DRAINMOD-Forest) for predicting the fate of nitrogen (N) in managed pine forests using a forest productivity submodel to estimate LAI. However, DRAINMOD-Forest does not yet account for the LAI of the understory. As such, the model has been shown to substantially underestimate peak LAI (Tian, 2011).

LAI is difficult to measure, but direct and indirect approaches can often be used to estimate LAI. Direct estimates can be obtained from destructive harvesting methods. For herbaceous species (or low-stature species in general), clip plot techniques may be employed. This approach entails subsampling along random transects using a small sampling frame, generally $1 \text{ m} \times 1 \text{ m}$. All plant materials within the frame are clipped at the surface, field weighed, and then bagged for transport to the lab. Indirect estimates of LAI can be obtained using the LI-COR LAI 2000 Plant Canopy Analyzer (hereafter PCA). The PCA uses gap-fraction theory in

conjunction with estimates of undercanopy photosynthetically active radiation (PAR) from different view angles to estimate LAI. Although the PCA provides instantaneous estimates of LAI, many have demonstrated that the PCA generally underestimates LAI (Frassnacht et al., 1994; Stenborg et al., 1994; Sampson and Allen, 1995). Thus, local correction factors are typically developed, using more direct approaches, to correct for bias in PCA measurements.

Our objective was to quantify the LAI of emergent vegetation following planting and establishment of loblolly pine on the Coastal Plain of North Carolina. To accomplish this, we used eight years of PCA measurements that were verified using vegetation clip plot harvesting techniques. From this approach, we examined leaf moisture content and specific leaf mass (i.e., specific leaf area). We also simulated the LAI of the establishing loblolly pine stand using the forest process model SECRETS-3PG (Sampson et al., 2006) to partition LAI measurements between the emergent vegetation and the developing loblolly pine stand. This approach was warranted because no separate (empirical) estimates of pine LAI were possible; without vegetation control, emergent vegetation competes vigorously with planted loblolly pine on the Coastal Plain of North Carolina such that the pine canopy does not differentiate itself from competing vegetation until well after canopy closure, which, in this case, could take five to eight years or more.

METHODS

STUDY SITE

This study was conducted within a loblolly pine (*Pinus taeda* L.) plantation owned and managed by Weyerhaeuser Company in Carteret County, North Carolina ($34^\circ 48' \text{ N}$, $76^\circ 42' \text{ W}$). The mean annual temperature is 17° C , and the mean annual precipitation is 1460 mm. This research site consists of three artificially drained experimental watersheds (D1, D2, and D3), which are 24.72 ha, 23.62 ha, and 26.75 ha, respectively (fig. 1). The site is flat with a shallow water table (McCarthy et al., 1991). Soils belong to the hydric series: Deloss fine sandy loam (fine-loamy mixed thermic Typic Umbraquult). Each of the three experimental watersheds is drained by four lateral ditches measuring 1.4 to 1.8 m deep and 2.0 m wide at the surface and spaced 100 m apart (fig. 1). Site details and experimental and monitoring methods are more fully described by McCarthy et al. (1991) and Amatya et al. (1996).

The three artificial watersheds were planted in 1974 at a density of 2100 trees ha^{-1} with trees spaced 1.74 m apart and rows spaced 2.74 m apart (table 1). Watershed D1 has served as the control treatment since 1988. In 2008, watershed D1 was a 34-year-old mature pine plantation that underwent pre-commercial thinning in 1981 (thinned to 988 trees ha^{-1}) and commercial thinning in the later part of the growing season in 1988 (thinned to 370 trees ha^{-1}).

Watershed D2, also thinned in 1981, was harvested in July 1995. All stems larger than 8 cm (~ 3 in.) diameter at breast height (DBH) were removed from the site, the remaining material being cut and left on-site. Watershed D2 was planted in February 1997 with seedlings 30 to 46 cm tall spaced 1.52 m apart in rows spaced 3.66 m apart, for a density of 2100 seedlings ha^{-1} . The survival rate for D2 was 93%; in 2008, this plantation was 11 years old. Watershed D3 is currently a

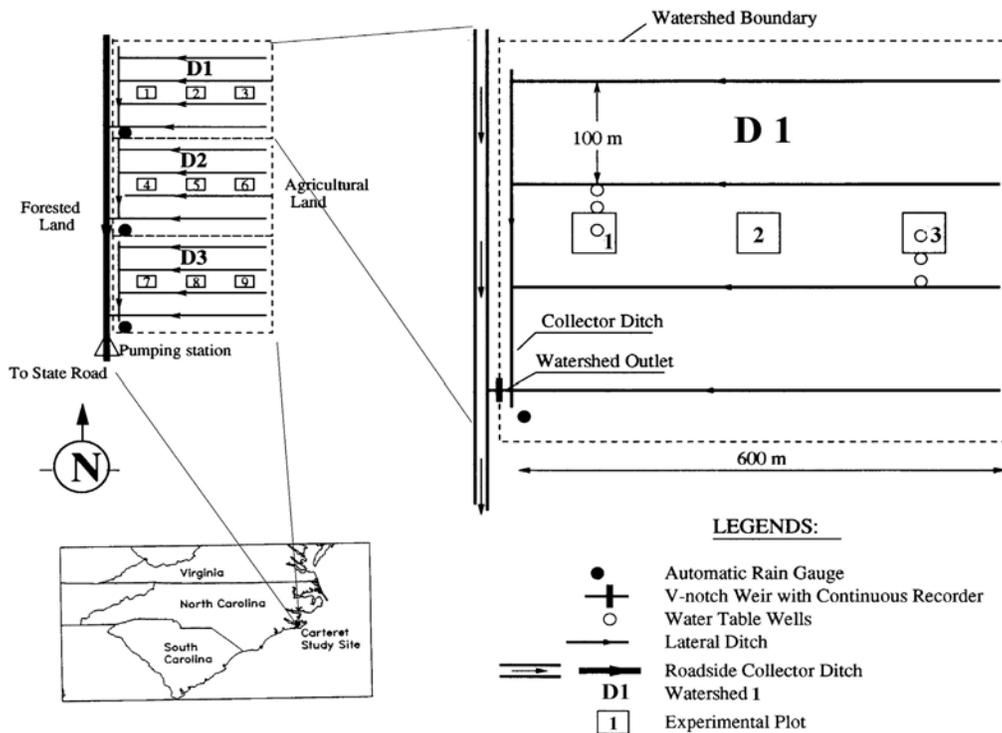


Figure 1. Location and study layout of three experimental watersheds on the Coastal Plain of North Carolina (Amatya et al., 2000).

Table 1. Detailed history of the management activities for the three loblolly pine plantation watersheds examined in this study.

Year	Event
1972 (July)	Site clear-cut.
1973	Site preparation and ditching.
1974	Trees planted (2100 trees ha ⁻¹).
1980	Precommercial thinning (988 trees ha ⁻¹).
1981	Aerial fertilization of urea (367 kg ha ⁻¹).
1988 (February)	Calibration I period; study begins.
1988 (October)	Commercial thinning (from 988 to 370 trees ha ⁻¹).
1989 (March-April)	Ground fertilization (140 kg ha ⁻¹ of di-ammonium phosphate and 435 kg ha ⁻¹ of urea).
1990 (March)	Calibration I period ends. Controlled drainage study begins on D2.
1994 (December)	Controlled drainage study ends.
1995 (February)	Orifice weir study begins on D3.
1995 (July)	D2 harvested. Harvest study begins on D2.
1996 (October)	Site preparation and bedding on D2.
1997 (February)	D2 replanted. Regeneration study begins for D2.
1999	Orifice weir study ends on D2.
2000 (February)	Calibration II period begins.
2002 (June)	D3 thinned by approximately 50% (185 trees ha ⁻¹).
2002 (July)	Effects of thinning study begins on D3.
2005 (September)	Aerial fertilization of D2 and D3 (115 kg ha ⁻¹ and 27 kg ha ⁻¹ of N and P, respectively in D2 and 172 kg ha ⁻¹ and 41 kg ha ⁻¹ in D3).

34-year-old pine plantation that received the same thinning treatment in 1988 as watersheds D1 and D2.

PLOT AND SUBPLOT LAYOUT

Within each watershed, three permanent base plots were established equidistant from one another along the long axis

of each rectangular watershed but centered along the short axis perpendicular to the drainage ditches. A line perpendicular to the lateral drainage ditches and passing through the center of each base plot was established as a base azimuth from which random transects, for use in the vegetation sampling and the LI-COR measurements, could later be established. On each sampling date, a random azimuth was obtained using a random number table to create a sampling transect. Six subplots (three on each side of the base plot) were established along each transect, equidistant from one another, using a 90 m long tape. The subplots were marked by colored flags and dated to prevent repeated sampling of the same location; if a current subplot intersected with a previously established one, it was placed adjacent.

DOMINANT SPECIES PRESENT

We did not record the relative or absolute distributions of plant species present at the start of the study or, for that matter, throughout the duration of the study. However, we did note the dominant species present at the start of the study and during data collection (table 2).

VEGETATION CLIP PLOT PROTOCOLS

FIELD PROCEDURES

Emergent vegetation was destructively sampled during the first week of each month on the day without rain starting in May 1996 over a three-year period for watershed D2. On each sampling date, for each subplot, a 1 m × 1 m × 0.075 m wooden open-ended frame was placed on the ground parallel to the transect and centered using the established flags. Five to six LI-COR LAI 2000 plant canopy analyzer (PCA) LAI measurements were then taken (more fully discussed below). Following the PCA measurements, the average height of all

Table 2. Species present at the study site at the time of study installation and during data collection.

Common Name	Scientific Name
American beautyberry	<i>Callicarpa americana</i>
Blue stem	<i>Andropogon gerardii</i>
Bracken fern	<i>Pteridium aquilinum</i>
Broom sedge	<i>Andropogon</i> spp.
Devil's walkingstick	<i>Aralia spinosa</i>
Dogfennel	<i>Eupatorium capillifolium</i> (Lam.) Small
Fox grape	<i>Vitis labrusca</i>
Large galberry	<i>Ilex coriacea</i> (Pursh) Chapm.
Netted chainfern	<i>Woodwardia areolata</i> (L.) T. Moore
Panicum	<i>Panicum repens</i>
Poison ivy	<i>Toxicodendron radicans</i>
Pokeweed	<i>Phytolacca americana</i>
Red maple	<i>Acer rubrum</i>
Redbay	<i>Persea borbonia</i>
Sedge	<i>Carex</i> spp.
Shrubby blackberry	<i>Rubus fruticosus</i> L.
Smooth sumac	<i>Rhus glabra</i>
Sweetgum	<i>Liquidambar styraciflua</i>
Virginia creeper	<i>Parthenocissus quinquefolia</i>

plant species was recorded using a 3 m tape measure (or, in some cases, a metric ruler). For the vegetation sampling, a 189 L (50 gal) plastic bag was weighed using a field spring balance. From the interior of each subplot, all vegetation was clipped (including any pine if it fell within the sampling frame) at the soil surface, placed within the plastic bag, and mixed. The bag was then weighed again using the field spring balance, recorded, and labeled with respect to the plot and subplot identifiers. Two subsamples, each approximately one handful in size, were removed from the well mixed bag and placed into separate zip-lock plastic bags (either 5 cm × 5 cm or 7 cm × 7 cm) and labeled with the date, time, plot number, and subplot number. One sample was then marked “dry biomass” while the other was marked “specific leaf area” (SLA) for future laboratory analysis. Approximately 10 g of dry ice was added to each subsample bag to prevent the leaves from wilting prior to placement in a plastic 30 L cooler for return to the lab for further analyses. Leaf biomass from the six subplots was pooled and assumed representative of the plot.

LABORATORY PROCEDURES

In the lab, leaf cut-outs representative of the major species (i.e., bracken fern, dogfennel, shrubby blackberry, panicum, pokeweed, Virginia creeper, red maple, and redbay; table 2) collected from the site were made, at the start of the study, using thin cardstock. The area of each cutout was determined using perimeter-area calculations to be used for calibration procedures. In the morning following each sampling date, 10 to 15 green leaves were removed from the “specific leaf area” subsample for each plot for determination of SLA. These leaves were individually placed on the surface of a LI-COR 3000 electronic photometer (camera) to determine projected leaf area. Each leaf was then weighed and recorded, oven dried at 65 °C for 24 h, and then reweighed to obtain leaf dry biomass (g). The plot-average SLA (measured as cm² mg⁻¹; reported as cm² g⁻¹) was estimated as the average SLA for all leaf subsamples.

The subsample labeled “dry biomass” was weighed, oven dried at 65 °C for 24 h, and then reweighed to obtain an estimate of the wet weight to dry weight ratio. This ratio estimate

was used to convert the field-weighted plot samples to a dry weight basis. The clip plot estimate of leaf area index (LAI_{CLIP}) was then obtained by multiplying the species-average estimate of SLA and the total leaf dry biomass estimate for each of three plots for each watershed.

LI-COR LAI 2000 ESTIMATES AND CORRECTIONS

We used a LI-COR LAI 2000 Plant Canopy Analyzer (PCA) to estimate the vegetation area index (hereafter considered an estimate of the LAI) on each of the 18 randomly assigned 1 m² subplots, for each watershed, from May to October on three to four week intervals over three growing seasons (1996 to 1998). Point estimates were averaged over the six subplots to obtain a plot-average estimate. This resulted in three separate estimates of projected LAI (LAI_{PCA}) for each watershed. A separate sensor unit located at a micrometeorological station collected simultaneous above-canopy readings. The PCA was calibrated at the start of each sampling date as defined in the user manual. On sunny days, PCA samples were collected early in the morning for each subplot for each watershed. On diffuse sky days, estimates were taken prior to vegetation clipping (for watershed D2).

The LAI_{PCA} estimates were continued for an additional six years (until 2004) beyond the clip plot vegetation sampling. This enabled us to create LAI estimates following silvicultural treatments for young and mature loblolly pine stands.

SIMULATED LAI

We used the forest process model SECRETS-3PG (Sampson et al., 2006) to simulate loblolly pine LAI (LAI_{SIM}) for watershed D2. Because the LAI_{PCA} estimates inherently included the LAI of the developing pine stand, the difference between LAI_{PCA} and LAI_{SIM} would enable us to differentiate between the LAI of emergent vegetation (grasses, forbs, and shrubs) and that of the planted loblolly pine.

The SECRETS-3PG hybrid model combines the process model SECRETS (Sampson and Ceulemans, 2000) and the process-based model Physiological Principles for Predicting Growth (3-PG) (Landsberg and Waring, 1997). The SECRETS model is a biogeochemical process model that simulates carbon and water pools and fluxes. The 3-PG model is a simplified forest growth model written to simulate biometrically accurate stand-level properties that are useful to foresters. These include LAI, stem volume, and quadratic mean diameter of a stand, to name a few. The SECRETS-3PG hybrid model uses the biomass allocation algorithms from 3-PG and the associated physiological process equations and the daily carbon outputs from SECRETS to partition carbon, and thus biomass, on a monthly basis. The model has previously demonstrated close correspondence between measured and simulated estimates of loblolly pine LAI (Sampson et al., 2006). See Sampson et al. (2006) for more details.

Daily climate data were necessary to run the model. The daily meteorological data include: shortwave radiation, minimum and maximum ambient air temperature, minimum and maximum relative humidity, and precipitation. Soil temperature was estimated from air temperature and day of year. Hourly photosynthetically active radiation (PAR) was calculated from daily shortwave radiation assuming that hourly PAR is normally distributed over the daylight period. We obtained climate data up to August 2005 from a weather station

located in the middle of watershed D2. This station recorded continuous data on air temperature, relative humidity, solar and net radiation, wind speed, and soil temperature on a half-hourly basis. Data after August 2005 were obtained from a nearby weather station located in Vanceboro, North Carolina.

Model parameterization for seedling to maturity simulations requires only three parameters: (1) mean seedling weight and height at the time of planting, (2) planting density, and (3) seedling survival rate after one year. These data were made available to us from Weyerhaeuser Company (Cliff Tyson, personal communication, 2006). We used empirical estimates of stand quadratic mean diameter to compare with simulated estimates for model validation.

STATISTICAL ANALYSES

We used general linear models (PROC GLM) (SAS, 1999) to test for significance of month, year, and month \times year interaction on leaf moisture content and on specific leaf area. All tests were evaluated at the 0.05 probability level.

We also used SAS (SAS, 1999) to examine the relationship between the direct (LAI_{CLIP}) and indirect (LAI_{PCA}) estimates of LAI. Based on previous work (Sampson and Allen, 1995), it was thought that the PCA measurements, as a direct comparison, would be lower than the clip plot estimates of LAI and, further, that the relationship would be curvilinear. However, our earlier work never considered the potential effects of emergent vegetation LAI (i.e., herbaceous and arborescent broad-leaved species) on the PCA estimates. Thus, for these analyses, we examined linear and curvilinear regression procedures; we used simple linear regression (general linear models in SAS) (no intercept option) and a first-degree inverse polynomial (Sit and Poulin-Costello, 1994). We used three criteria, in descending order of importance, to converge on an appropriate model: (1) regression residuals, (2) F tests, and (3) coefficient of determination values. In this case, the PCA measurements were used as the independent variable in the model, with the dependent variable being the vegetation clip plot estimates of LAI. The resulting regression equation was used to correct for bias in the PCA estimates of LAI.

RESULTS AND DISCUSSION

Leaf moisture content varied temporally, ranging from a low of 58% in October 1997 to a high of 72.5% in July of the same year (table 3). Measurement year ($p < 0.7418$) and month ($p < 0.2047$) were not statistically significant, but the month \times year interaction was ($p < 0.0001$). In general, leaf

Table 3. Mean (and one standard error of the mean) leaf moisture content (percent) over a three-year period for clipped plots in watershed D2.

Month	Year		
	1996	1997	1998
April	NA ^[a]	NA	65.37 (1.14)
May	NA	68.53 (1.24)	69.93 (1.35)
June	63.80 (1.37)	67.50 (0.97)	63.40 (0.91)
July	72.45 (0.62)	69.49 (1.36)	66.14 (0.91)
August	64.00 (0.83)	69.56 (1.09)	66.57 (0.75)
September	NA	63.00 (1.01)	NA
October	58.31 (1.21)	59.82 (0.95)	66.43 (0.51)

^[a] NA = not applicable (data not available).

Table 4. Mean (and one standard error of the mean) specific leaf area (cm² g⁻¹) for clipped plots in watershed D2.

Month	Year		
	1996	1997	1998
April	NA ^[a]	NA	162.41 (7.88)
May	120.38 (10.51)	162.25 (5.3)	166.30 (5.20)
June	126.85 (6.32)	150.29 (7.51)	154.07 (8.17)
July	123.52 (5.85)	157.07 (5.52)	126.32 (3.55)
August	138.78 (4.12)	163.65 (6.04)	152.42 (7.28)
September	NA	135.93 (3.84)	NA
October	118.27 (4.47)	112.89 (4.82)	152.11 (7.25)

^[a] NA = not applicable (data not available).

moisture content decreased over the course of the year, although exceptions to this trend could be observed. Our estimates were similar to, or moderately lower than, those found by Meziane and Shipley (1999) for 22 herbaceous species.

Specific leaf area (SLA; cm² g⁻¹) ranged considerably over the three years of vegetation clip plot analyses. Average SLA varied from a low of 112 cm² g⁻¹ in October 1997 to a high of about 166 cm² g⁻¹ in May of the following year (table 4). No clear trend in mean SLA could be discerned, although SLA was generally lowest in autumn of each year (except for 1998). Measurement year, month, and the year \times month interaction were all significant ($p < 0.0001$) factors in the linear models analysis. Our estimates of SLA were at the lower end of those found by Hunt and Cornelissen (1997) for herbaceous species but well within the range found by Woodward (1983).

LAI_{CLIP} ranged from zero to almost 11 m² m⁻² (project area basis) over the three-year sampling period (fig. 2). Corresponding LAI_{PCA} estimates ranged from zero to almost 6 m² m⁻². Simple linear regression indicated that the PCA underestimated LAI_{CLIP} by about 44% on average ($r^2 = 0.53$, $p < 0.0001$, $N = 193$). Residual analyses of the linear and first-degree inverse polynomial regressions demonstrated that simple linear regression was sufficient to describe the relationship between the two methods; the first-degree inverse polynomial did not improve the prediction capability ($r^2 = 0.53$, $p < 0.0001$, $N = 193$), and the residuals from that model did not demonstrate improvement over the linear regression

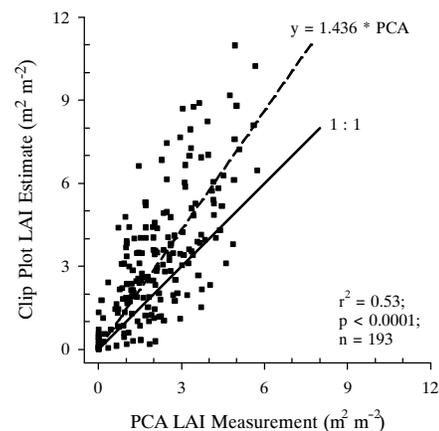


Figure 2. Relationship between vegetation clip plot estimates of LAI (m² m⁻² projected area basis) and LAI estimated using the LI-COR LAI 2000 plant canopy analyzer (PCA) post-harvest for watershed D2, Carteret County, North Carolina. Vegetation sampling and PCA measurements were taken monthly, beginning in 1996, for three growing seasons following the 1995 harvest.

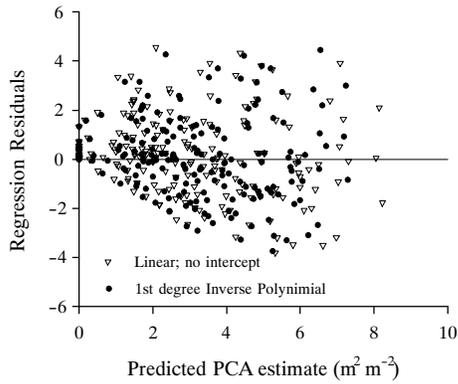


Figure 3. Regression residuals for the relationship between vegetation clip plot estimates of LAI ($\text{m}^2 \text{m}^{-2}$ projected area basis) and LAI estimated using the LI-COR LAI 2000 plant canopy analyzer (PCA) post-harvest for watershed D2, Carteret County, North Carolina. Simple linear (open triangles) and first-degree inverse polynomial (filled circles) regression models were examined.

residuals (fig. 3). These data suggest that the relationship between the PCA estimates of LAI and those obtained from the vegetation clip plots was linear.

From previous work (Sampson and Allen, 1995) and published literature (Gower and Norman, 1991), we were fairly certain that the PCA would underestimate LAI_{CLIP} . However, we were surprised when the analyses supported a linear relationship between the PCA estimates and LAI_{CLIP} . The PCA has been demonstrated to underestimate LAI, but the relationship is often curvilinear when compared to direct approaches (destructive sampling, litter trap methods, etc.) (Smith et al., 1993; Fassnacht et al., 1994; Stenberg et al., 1994; Sampson and Allen, 1995). However, a downward bias in the LAI estimates from the PCA is most often associated with pine or hardwood forests; underestimation of LAI by the PCA has been attributed to self-shading and foliage clumping, or to the influence of stems and branches on the PCA estimate (i.e., vegetation area index) (e.g., Smolander and Stenberg, 1996).

Welles and Coehen (1996) and Bréda (2003) reviewed the performance of various ground-based approaches to indirectly estimate LAI. Welles and Coehen (1996) examined the performance of the PCA in relation to five alternate, indirect methods to estimate LAI for forest, shrub, and row crop species. Although favorable and unfavorable results were reported, no reference to herbaceous species was found. Similarly, Bréda (2003) did not discuss the performance of the PCA for herbaceous and arborescent species. We were unable to find studies comparable to ours for appropriate comparisons.

Stand measurements of dominant height (m) and diameter at breast height (DBH, m) began in 2005 for watershed D2. We compared the dormant (end-of-year) season estimates of quadratic mean diameter (D_q) from the empirical data to the simulated estimates for similar dates (fig. 4). We observed a favorable correspondence between measured and simulated D_q over the measurement period. However, simulated D_q for years 10 and 11 following harvest underpredicted the empirical estimates; the step increase in measured D_q in year 10 may be attributed to changes in stand density that were not well represented in the modeling analyses. Regardless, the 3-PG model is considered biometrically accurate (Landsberg and

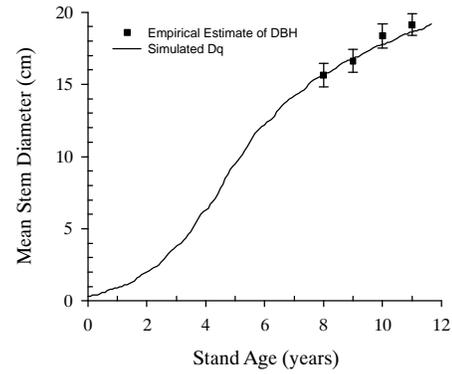


Figure 4. Relationship between empirical (filled squares) and simulated (solid line) estimates of quadratic mean diameter (D_q) for a Coastal Plain Loblolly pine stand for watershed D2, Carteret County, North Carolina. Error bars denote two standard deviations of the mean.

Waring, 1997); these first principal equations are based on the strong biometric coupling between diameter and individual tree LAI (accurate representation of one suggests accurate representation of the other). Accordingly, we are reasonably confident in our LAI_{SIM} (e.g., Sampson et al., 2006).

We applied the correction factor from the clip plot regression to eight years of post-harvest LAI_{PCA} measurements. These estimates then represented herbaceous and arborescent vegetation in addition to LAI of the planted loblolly pine. Projected LAI increased from about $2 \text{m}^2 \text{m}^{-2}$ at the start of the study to a maximum of about $8 \text{m}^2 \text{m}^{-2}$ by the seventh year (fig. 5a). Decreased site LAI for 1996 and, consequently, reduced maximum LAI for 1997 could be attributed to the destructive effects on LAI by Hurricane Fran that came ashore in September 1996. Annual fluctuations in LAI were appar-

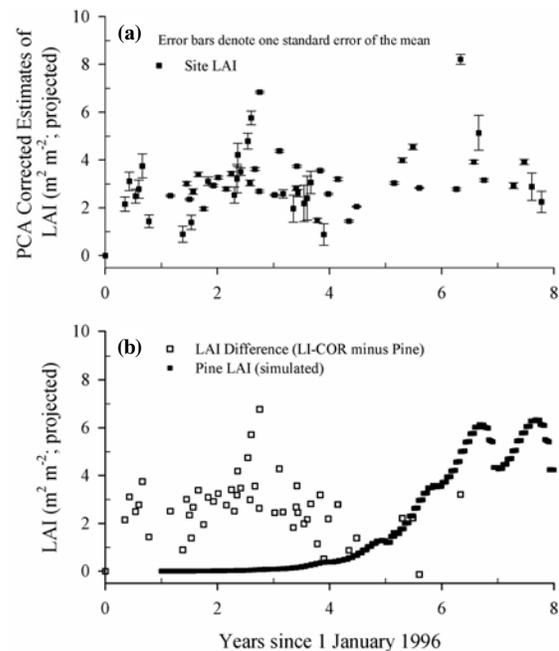


Figure 5. (a) Corrected estimates of LAI ($\text{m}^2 \text{m}^{-2}$ projected area basis) from the LI-COR LAI 2000 plant canopy analyzer (PCA) for pine and emergent vegetation, and (b) simulated LAI for loblolly pine (*Pinus taeda* L.) seedlings using the SECRETS-3PG model (Sampson et al., 2006) (filled squares) and the difference between the corrected PCA estimates of LAI and that simulated (open squares).

ent and corresponded to the yearly leaf-on and leaf-off of arborescent hardwoods, but also to the annual, biannual, and perennial species present on the site (fig. 5a). The pattern also reflects the seasonal and developmental changes in pine LAI over the same period simulated using the SECRETS-3PG model.

Model estimates of LAI_{SIM} enabled us to differentiate between pine LAI and that of competing vegetation (fig. 5b). In this case, these data suggest that pine did not dominate the site, as evaluated using LAI as the metric, until well into the fourth year after planting (i.e., the pine was planted in 1997). By the sixth year, simulated LAI was very high but almost comparable to that found by Samuelson et al. (2004) for similar-aged fertilized stands and to that found by Sword Sayer et al. (2004) for slightly older fertilized stands that exhibited similar diameters. Although our simulated estimates of quadratic mean diameter were similar to those measured, the high estimates of LAI for the age and diameter simulated suggests that we may have slightly overestimated the projected LAI for pine in this stand.

In a 15-year regional study, Miller et al. (2003) examined species dominance for three treatments for loblolly pine plantations: no control, vegetation control of herbaceous species, and control of herbaceous and woody plants. Herbaceous cover, expressed as a percentage, was roughly 80% of total canopy cover for up to seven years post-planting. Not until age 15 in their study did pine coverage represent 70% or more of the total canopy cover across three levels of hardwood dominance. Of course, estimates of LAI and that of canopy cover (on a percentage basis) provide different information. Whether one versus the other best addresses the competitive status of a species warrants further attention (and a more rigorous protocol).

Of course, emergent vegetation would have a strong effect on site water balance. McCarthy and Skaggs (1992) simulated ET for pre- and post-harvest loblolly pine stands on the Coastal Plain of North Carolina. Using an annual maximum LAI trajectory of 1 m² m⁻² post-harvest to roughly 6 m² m⁻² at peak stand LAI, their ET estimates were approximately 11% lower in the first year following the harvest than that estimated from a water balance analysis based on 1996 data from an artificially drained experimental watershed harvested in 1995 (i.e., Amatya et al., 2006). In their study Amatya et al. (2006) estimated ET as the difference between rainfall and drainage outflow. Underestimation of ET in the hydrologic simulations may thus be due to unaccounted-for ET by emergent vegetation observed on the site but not modeled by McCarthy and Skaggs (1992). Tian (2011) used DRAINMOD-Forest to estimate site water balance for the same site as Amatya et al. (2006). We suspect that annual outflow of the harvested watershed may have been overpredicted by Tian (2011) because of unaccounted-for ET losses from understory LAI, especially in relatively dry years. The physically based LAI module in DRAINMOD-Forest predicted only 7% lower ET than that estimated from a water balance approach by McCarthy et al. (1992) for a planted pine stand in a dry year (1997) 1.5 years following harvest. Our results demonstrate that post-harvest emergent vegetation, when unchecked, can represent a dominate fraction of stand LAI early in rotation and, subsequently, competes vigorously with planted loblolly pine for growing space and, undoubtedly, site resources (e.g., nutrients and water) well into the sixth year post-planting.

Anecdotal evidence from other studies provides support for our findings. Sun et al. (2010) studied ET rates from clear-felled/planted and mid-rotation pine stands in eastern North Carolina. They did not measure LAI of the emergent vegetation at their site, which was planted in 2004 two years after a harvest, but they reported a dense weedy ground cover, with annual plants and shrubs reaching a height of 2.5 m by the end of their study period (2007) when the pine trees were just three years old. Gholz and Clark (2002) reported that LAI could increase dramatically up to 3.0 m² m⁻² within the first few years following a harvest of pine flatwoods that were similar to the stands examined in our study. In another study Sun et al. (1998b) assumed that 60% of the total maximum LAI for a 5-year-old pine forest could be attributed to volunteer vegetation in their long-term modeling of the hydrologic response in stand development following harvest of a pine flatwood site in northern Florida. Our results on LAI of emergent vegetation and on young pine, although somewhat limited, may be useful for estimating the post-harvest ET contributed by emerging vegetation until the planted pine trees catch up with increased ET rates.

Notwithstanding, there are several protocol assumptions that may have influenced our LAI results. First, we did not rigorously record the species of our clip plots. We recognize that temporal changes in species composition likely occurred between the start of the study and our last clip plot field campaign. Thus, species changes over time could have influenced our PCA correction factor. We therefore examined the parameter estimates in the regression between “measured” LAI and the PCA estimates for each year. When evaluated separately, the slope parameter estimates were not significantly different among years (table 5); however, the intercept parameters were significantly different. We suggest that the combined model was likely appropriate. Second, the PCA sensor height was maintained at a similar height throughout the study. Changes in height of the species found in the clip plots over time could influence our PCA estimate of LAI and likely lead to a reduced estimate of LAI overtime for the clipped plots. Finally, species composition of the emergent vegetation would influence our PCA estimates and the quantity of light reaching the soil surface. It appears that even low-stature plants exhibit differential underestimation in LAI by the PCA (e.g., Wells and Norman, 1991).

The species composition and changes in the species richness over time influence the amount of light reaching the forest floor by determining canopy light extinction. Coefficients of light extinction (*k*) vary by species (e.g., Aubin et al., 2000; Bréda, 2003), which results in species differences in the photon flux density (PPFD) absorbed. It has been demonstrated that broad-leafed plants have, in general, greater *k* values (greater efficiency in light capture) than narrow-leaved (needled) plants (Bréda, 2003). In addition, taller species can

Table 5. Slope and intercept estimates for 1996 through 1998 in the regression between direct (clip plot techniques) and indirect (LI-COR LAI-2000 Plant Canopy Analyzer) estimates of LAI (m² m⁻²; projected) for watershed D2.

Parameter Estimate	Year		
	1996 (N = 94)	1997 (N = 35)	1998 (N = 61)
Intercept	0.933	0.3376	-0.432
Standard error	0.30488	0.2750	0.6209
Slope	1.269	1.26	1.427
Standard error	0.1406	0.2248	0.1830

generally intercept greater incident PPF than subordinate species, but subordinate species have greater efficiency in capturing PPF due to a greater leaf area ratio (the ratio of leaf area to aboveground biomass) (Tadaki and Werger, 1995). Consequently, the species composition and the associated structure of the vertical leaf profile would strongly influence light interception above the forest floor, thereby influencing the radiation load at the soil surface and, thus, soil evaporation (and species-combined transpiration).

CONCLUSIONS

We compared direct and indirect estimates of LAI for emergent vegetation in a post-harvest loblolly pine plantation in eastern North Carolina that underwent mechanical site preparation prior to replanting with loblolly pine seedlings. We also simulated LAI of loblolly pine using a biometrically accurate biogeochemical forest process model to examine site differentiation in LAI during early stand development. Estimates of LAI from the LI-COR LAI-2000 plant canopy analyzer (PCA) consistently underestimated those obtained from clip plot techniques. A simple linear correction factor was found. Based on the correction, the PCA underestimated LAI by approximately 44% (when no intercept was specified).

LAI differences between simulated LAI and that estimated using the PCA for emergent vegetation suggest that the pine did not dominate the stand LAI until four to five years post-planting. Moreover, our results demonstrate that post-harvest emergent vegetation, when unchecked, competes rigorously with planted loblolly pine for growing space and, undoubtedly, site resources well into the fourth to seventh year after planting.

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