



## Energy and water balance of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA

G. Sun<sup>a,\*</sup>, A. Noormets<sup>b</sup>, M.J. Gavazzi<sup>a</sup>, S.G. McNulty<sup>a</sup>, J. Chen<sup>c</sup>, J.-C. Domec<sup>b</sup>, J.S. King<sup>b</sup>, D.M. Amatya<sup>d</sup>, R.W. Skaggs<sup>e</sup>

<sup>a</sup> Southern Global Change Program, Southern Research Station, USDA Forest Service, 920 Main Campus Dr., Suite 300, Venture II, Raleigh, NC 27606, United States

<sup>b</sup> Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, United States

<sup>c</sup> Department of Earth, Ecological, and Environmental Sciences, University of Toledo, Toledo, OH 43606, United States

<sup>d</sup> Center for Forested Wetlands Research, USDA Forest Service, 3734 Highway 402, Cordesville, SC 29434, United States

<sup>e</sup> Department of Biological and Agricultural Engineering, North Carolina State University, Raleigh, NC, United States

### ARTICLE INFO

#### Article history:

Received 21 March 2009

Received in revised form 4 September 2009

Accepted 9 September 2009

#### Keywords:

Energy balance  
Evapotranspiration  
Forest albedo  
Forest hydrology  
Loblolly pine  
Water balance

### ABSTRACT

During 2005–2007, we used the eddy covariance and associated hydrometric methods to construct energy and water budgets along a chronosequence of loblolly pine (*Pinus taeda*) plantations that included a mid-rotation stand (LP) (i.e., 13–15 years old) and a recently established stand on a clearcut site (CC) (i.e., 4–6 years old) in Eastern North Carolina. Our central objective was to quantify the differences in both energy and water balances between the two contrasting stands and understand the underlining mechanisms of environmental controls. We found that the LP site received about 20% more net radiation ( $R_n$ ) due to its lower averaged albedo ( $\alpha$ ) of 0.25, compared with that at the CC ( $\alpha = 0.34$ ). The mean monthly averaged Bowen ratios ( $\beta$ ) at the LP site were  $0.89 \pm 0.7$ , significantly ( $p = 0.02$ ) lower than at the CC site ( $1.45 \pm 1.2$ ). Higher net radiation resulted in a 28% higher ( $p = 0.02$ ) latent heat flux (LE) for ecosystem evapotranspiration at the LP site, but there was no difference in sensible heat flux ( $H$ ) between the two contrasting sites. The annual total evapotranspiration (ET) at the LP site and CC site was estimated as 1011–1226 and 755–855 mm year<sup>-1</sup>, respectively. The differences in ET rates between the two contrasting sites occurred mostly during the non-growing seasons and/or dry periods, and they were small during peak growing seasons or wet periods. Higher net radiation and biomass in LP were believed to be responsible to the higher ET. The monthly ET/Grass Reference ET ratios differed significantly across site and season. The annual ET/P ratio for the LP and CC were estimated as 0.70–1.13 and 0.60–0.88, respectively, indicating higher runoff production from the CC site than the LP site. This study implied that reforestation practices reduced surface albedos and thus increased available energy, but they did not necessarily increase energy for warming the atmosphere in the coastal plain region where soil water was generally not limited. This study showed the highly variable response of energy and water balances to forest management due to climatic variability.

Published by Elsevier B.V.

### 1. Introduction

Loblolly pine (*Pinus taeda* L.) is a common species in the southern United States and pine plantations are a major economic component in the region (Schultz, 1997; Fox et al., 2004). The productivity of loblolly pine plantations increased greatly during the past decades due to advances in tree genetic improvement and intensive silviculture practices that often involve water management such as drainage (Amatya et al., 1996), bedding, and applications of fertilization and herbicides (Albaugh et al., 2004). The impacts of intensive forest managements and land conversions on ecosystem services including energy partitioning

(Gholz and Clark, 2002; Powell et al., 2005), water quantity and quality (Sun et al., 2004), forest productivity, and carbon sequestration (McNulty et al., 1996; Johnsen et al., 2001; Clark et al., 2004; Powell et al., 2008; Noormets et al., 2009) are of great interest to both scientists and policy makers.

Energy, water, and carbon cycles in forest ecosystems are tightly coupled through the evapotranspiration (ET) processes (Wilson and Baldocchi, 2000; Law et al., 2002; Noormets et al., 2006) (Fig. 1). Although land managers are more interested in water and carbon balances, quantifying forest energy balance offers insights to how management affects the forest microclimate and the feedbacks of land use change to climate change at a regional scale (Gholz and Clark, 2002; Powell et al., 2005; Restrepo and Arain, 2005; Jackson et al., 2005; Pielke et al., 2007; Liu et al., 2008). Uncertainty about the combined consequences of afforestation or deforestation on regional climate and greenhouse gas

\* Corresponding author. Tel.: +1 919 515 9498; fax: +1 919 5132978.

E-mail addresses: [Ge\\_Sun@ncsu.edu](mailto:Ge_Sun@ncsu.edu), [gesun@fs.fed.us](mailto:gesun@fs.fed.us) (G. Sun).

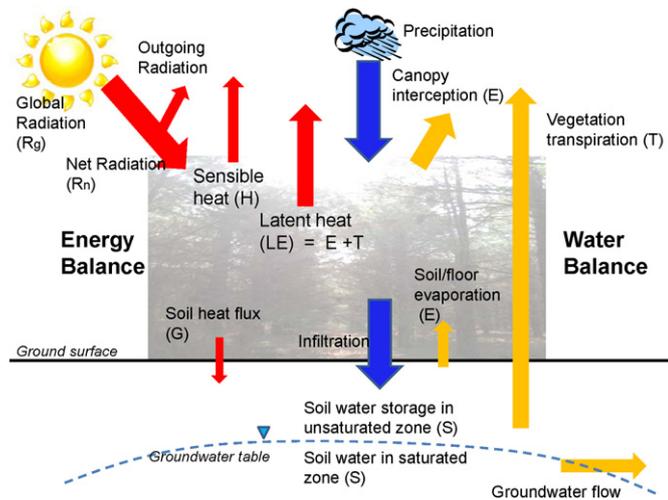


Fig. 1. A sketch to show the coupling of energy and water cycles in a drained loblolly pine forest.

emissions indicates the need for more research on the physical and biological effects of forest management in the mid-latitude region (Bala et al., 2007; Juang et al., 2007).

ET is a major component of the water balance of forested watersheds in the Southeastern U.S., consuming about 50–90% of the incident precipitation (Gholz and Clark, 2002; Sun et al., 2002; Lu et al., 2003; Ford et al., 2007). Changes in land use/land cover and climate impact the regional hydrological cycle (DeWalle et al., 2000; Sun et al., 2008a), climate (Liu et al., 2008), and ecosystem functions directly through altering the evapotranspiration processes. Evapotranspiration is also linked to ecosystem productivity (Law et al., 2002) and biodiversity (Currie, 1991), and ET is the only variable that directly links hydrologic and biological processes in most ecosystem models (McNulty et al., 1994; Hanson et al., 2003). The functional recovery of the hydrology of afforested or reforested watersheds depends on the recovery of ET, but the processes are not well understood due to the dynamic and complex nature of the ET processes (van Dijk and Keenan, 2008; Sun et al., 2008a).

In spite of the importance of forest ET, direct measurements of ET at the landscape scale have become possible only in the past decade (Wilson and Baldocchi, 2000; Gholz and Clark, 2002;

Powell et al., 2005; Stoy et al., 2006). Watershed-scale ET is usually estimated as the residual of precipitation, runoff, and change in soil water storage. This water balance method is limited to estimating long-term average (i.e., annual) when the change in water storage is negligible and other fluxes can be measured accurately (Wilson et al., 2001; Ford et al., 2007). The sapflow-based techniques to estimate ecosystem-level ET is limited to uniform stands that have few tree species with minor ET from understory plants (Wullschlegel et al., 1998; Ewers et al., 2002; Ford et al., 2007). The most common practice to estimate short-term forest ET and runoff is employing the widely used Penman-Monteith equation (McCarthy et al., 1992) or empirical ET models driven by readily available meteorological variables (Amatya et al., 1995; Amatya and Skaggs, 2001; Lu et al., 2003; Harder et al., 2007; Sun et al., 2008b; Zhou et al., 2008; Amatya and Trettin, 2007). The eddy covariance method has gained popularity for simultaneously measuring both ET and CO<sub>2</sub> fluxes with high temporal scale due to performance improvements and reduced costs of fast-response monitoring sensors in recent years. A complete comparison among the pros and cons of major ET estimation methods is found in Wilson et al. (2001) and Shuttleworth (2008).

As part of the United States-China Carbon Consortium (USCCC) (Sun et al., 2009), this study focuses on the carbon and water fluxes from plantation forests characteristic of drained forested wetlands in the coastal plain of North Carolina, USA. The specific objectives of this paper were to: (1) contrast the key energy and water fluxes between two loblolly pine stands under two management statuses and age and (2) explore the environmental controls on the energy and water balances at multiple temporal scales.

2. Methods

2.1. Site description

The study site (35°48'N, 76°40'W) is located in the Albemarle Sound drainage area near the city of Plymouth within the outer coastal plain mixed forest province of North Carolina in the Southeastern U.S. (Noormets et al., 2009) (Fig. 2). Locally called the Parker Tract, this site has been managed by the forestry industry for timber production. The area is dominated by loblolly pine plantations with various ages and native hardwood forests. The near flat area has poorly drained soils with a ground elevation less

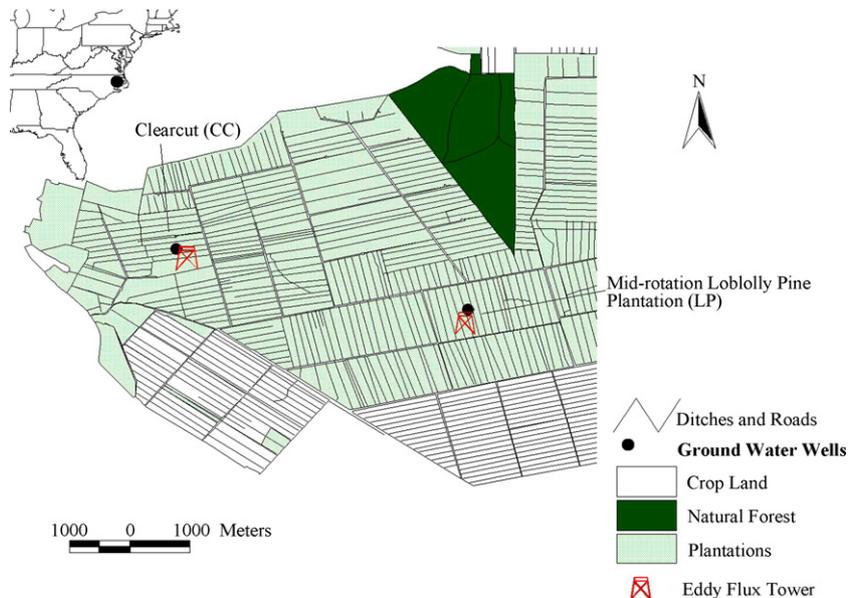


Fig. 2. Research site location and instrumentations.

than 8 m above the sea level. The area has been drained with a network of field ditches (90–100 cm deep; 80–100 m spacing) and canals that divide the watershed into a mosaic of regularly shaped fields and blocks of fields. The long-term (1945–2008) average annual precipitation was  $1320 \pm 211$  mm and was evenly distributed. The annual mean temperature was  $15.5$  °C, with a high average monthly temperature occurring in July ( $26.6$  °C), and an average monthly low occurring in January ( $6.4$  °C). The growing season averaged about 195 days.

Within the Parker Track, two blocks were selected to represent an age chronosequence of loblolly plantations (Fig. 2). The first block (CC) has an area of 70 ha. It was originally a native hardwoods forest, but was harvested using a clearcut method in 2002. Two-year-old loblolly pine seedlings were planted in 2004 at a  $1.5 \text{ m} \times 6 \text{ m}$  spacing and had a density of  $1040 \pm 127$  trees  $\text{ha}^{-1}$ . This block was covered with annual plants and shrubs that reached a height of 2.5 m in 2006. The dense weedy groundcover was primarily composed of *Eupatorium capillofolium* (dog fennel) and *Smilax rotundifolia* (greenbrier). The soil is classified as the Cape Fear Series (i.e., fine, mixed, semiactive Typic Umbraquult). Diggs (2004) described the soil as being dark sandy loam in the top 25 cm with 5–15% organic matter, sandy clay loam from a depth of 25–60 cm, sandy loam at 60–75 cm depth, and gray sandy clay from a depth of 75–155 cm. Soil porosity was estimated to be 0.68, 0.5, 0.4 for soil layer 0–25, 25–75, and 75–100 cm, respectively. The maximum hydraulic conductivity of the top layer was  $700 \text{ cm h}^{-1}$ , but decreased to  $40 \text{ cm h}^{-1}$  at the 70 cm depth. Leaf area was not measured at this site, but we observed a dense weedy cover during the study period (2005–2007). According to Gholz and Clark (2002) leaf area could increase dramatically up to  $3.0 \text{ m}^2 \text{ m}^{-2}$  within the first few years at a clearcut pine flatwoods, similar to this study site.

The second loblolly pine plantation site (LP) was located about 3 km from CC (Fig. 2). The LP block was a 90 ha, mid-rotation loblolly pine stand established in 1992 after clearcutting the previous mature pine plantation. Planting spacing was  $1.5 \text{ m} \times 4.5 \text{ m}$ . In 2005, the measured basal area was approximately  $25 \text{ m}^2 \text{ ha}^{-1}$ , and the tree density was about 1660 trees  $\text{ha}^{-1}$ . The averaged canopy height was 11.9 m (2005), 12.8 m (2006) and 14.1 m (2007). The maximum projected leaf area index (LAI) in early fall was  $3.9 \text{ m}^2 \text{ m}^{-2}$  (2005),  $4.0 \text{ m}^2 \text{ m}^{-2}$  (2006) and  $4.4 \text{ m}^2 \text{ m}^{-2}$  (2007). In winter season (January–March), LAI decreased to 2.4–2.8  $\text{m}^2 \text{ m}^{-2}$ , mostly due to leaf fall of subdominant and understory *Acer rubrum* (red maple) and *S. rotundifolia* (greenbrier). The organic soil at this site was classified as the Belhaven Series histosol (i.e., loamy mixed dysic thermic Terric Haplosaprists). The soil is a very dark brown to black, with a high organic matter content in the top 50 cm, and dark grayish brown sandy loam at 50–85 cm depth. A sandy clay loam layer exists from 85 to 200 cm, and a gray loamy sand was common below the 200 cm depth. The maximum hydraulic conductivity of the top layer was  $700 \text{ cm h}^{-1}$ , but decreased to about  $10 \text{ cm h}^{-1}$  at the 70 cm depth. Soil porosity values were estimated as 0.72, 0.40, 0.36, 0.45 for the layers of 0–45 cm, 45–75, 85–150, and 150–250 cm, respectively (Diggs, 2004; Grace et al., 2006a,b). Drainable porosity varied from 0.05 in the deep soil layers (>100 cm) to 0.2 in the shallow layers (<40 cm).

In the fall of 2004, a walk-up scaffold and a radio towers were erected at the center of LP and CC blocks, respectively, and both towers were instrumented to measure water and carbon fluxes and micrometeorology. The LP and CC towers had a fetch of about 1000 and 300 m, respectively.

## 2.2. Flux measurements for $H$ , $LE$ , and $G$

Following the AmeriFlux protocols, latent heat ( $LE$ ), and sensible heat ( $H$ ) flux measurements were made 23 and 10 m above the forest floor at LP and CC, respectively (Noormets et al.,

2009). The open-path eddy covariance system consists of an infrared gas analyzer (IRGA, Model LI-7500, LI-COR, Lincoln, NE, USA), a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Instrument-CSI, Logan, UT, USA), and a CR5000 data logger (CSI). Air temperature was derived from sound speed measured by the sonic anemometer and was also obtained using a thermocouple, that was used for estimating  $H$ . A relative humidity and air temperature sensor (model HMP-45C; Vaisala Oyj, Helsinki, Finland) was also installed at the same height as the IRGA to check vapor density. The 30-min mean fluxes for  $H$  and  $LE$  were computed as the covariance of vertical wind speed, air temperature, and the concentration of water using the EC\_Processor software package (<http://research.eeescience.utoledo.edu/lees/ECP/ECP.html>). The algorithm uses the formulation of Leuning (2004) in the planar fit coordinate system (Wilczak et al., 2001), which was calculated from the entire year's mean wind data. The turbulent fluxes were adjusted for fluctuations in air density (Webb et al., 1980). Sonic air temperatures were corrected for changes in humidity and pressure (Schotanus et al., 1983). We corrected the 30-min fluxes for the warming of IRGA using the method developed by Burba et al. (2008).

For each site, soil heat flux ( $G$ ) was measured at three locations using heat flux plates (model HFT3, CSI, Logan, UT, USA) buried 5 cm below the ground surface. Data were recorded at a 30-min interval along with other micrometeorological variables described later. The average of the three plate measured values were used for energy balance calculations.

## 2.3. Micrometeorological measurements

Micrometeorological variables measured on each tower included air temperature, photosynthetically active radiation (PAR) (model LI-190, Licor), downward and upward shortwave and longwave radiation (model CNR-1, Kipp and Zonen, Delft, Netherlands). Net radiation ( $R_n$ ) was derived by summing up the net shortwave and long wave radiation measurements using all four measured radiation components. Precipitation was measured continuously by two tipping bucket type of rain gages (TE-525, CSI; Onset® Data Logging Rain Gauge, Onset Computer Corporation, USA), and one backup using manual rain gages (Forestry Suppliers Inc., USA).

Soil temperature ( $T_s$ ) was measured at 5 and 20 cm with CS107 (CSI) temperature probes. The top 30-cm averaged volumetric soil moisture content was measured continuously using a vertically inserted CS616 (CSI) time domain reflectometer (TDR). Beginning on 10th May of 2007, the soil moisture profile at 10, 20, 30, 40, 50, 60, 80, 120 cm depths was measured using Sentek EnviroSCAN sensors (Sentek Sensor Technologies, Stepney, Australia) at a separate location at the LP site. Next to the flux each tower, a shallow groundwater well was installed to monitor the water table fluctuations at an hourly basis. The ground water table loggers were based on ultrasonic and water pressure mechanisms (Infinites USA, Port Orange, FL, USA). Soil moisture content profile and water table level data were used to estimate the annual and monthly change in soil water storage at the LP site.

## 2.4. Energy balance equation

We adopted the following simplified equation to examine energy balances of a loblolly pine plantation forest (Gholz and Clark, 2002). We neglect changes in energy storage and in energy used by photosynthesis at the monthly time scale:

$$R_n = H + LE + G \quad (1)$$

where  $R_n$  is net radiation flux at the interface between forest canopy and the atmosphere.  $R_n$  represents the absorbed total

energy by the ecosystem this is redistributed into of  $H$ ,  $LE$ , and  $G$ . The ratio of  $H$  and  $R_n$  is called Bowen ratio,  $\beta = H/LE$ . Albedo is defined as the ratio of outgoing and incident shortwave radiation.

## 2.5. The water balance equation

The water balance for the study site is expressed as

$$P = ET + Q + \Delta S \quad (2)$$

where  $P$  is precipitation (mm),  $ET$  is ecosystem evapotranspiration (mm) that includes canopy interception or wet canopy evaporation and plant transpiration (i.e., dry canopy transpiration);  $Q$  is drainage (i.e., shallow groundwater flowing out the watershed) (mm); and  $\Delta S$  represents the change in water storage (mm) in both the unsaturated and saturated soil zones (Fig. 1).

The total 30-min  $ET$  ( $\text{mm } 30\text{-min}^{-1}$ ) was converted from latent heat flux,  $LE$  ( $\text{W m}^{-2}$ ) in Eq. (1), by the formula:  $ET = LE \times (0.01800/44000) \times 3600 \times 0.5$ . The measured eddy fluxes are interpreted as representing the total ecosystem evapotranspiration ( $ET$ ) that includes both plant transpiration and evaporation from soil and plant surfaces.

We used the following equation to calculate monthly or annual  $\Delta S$  when only soil moisture ( $\theta_{30}$ ) for the top 30 cm was measured before 20 May 2007.

$$\Delta S = \Delta\theta_{30} \times 300 + \Delta WT \times \theta_d \quad (3)$$

where  $\Delta WT$  is the change in water table depth (mm) and  $\theta_d$  is the soil drainable porosity ( $\theta_d$ ). After 20 May 2007, soil moisture content at multiple layers was measured, so the following formula was used to estimate  $\Delta S$ :

$$\Delta S = \left( \sum_{i=1}^n \theta_i D_i(t+1) + D_s(t+1) \times \theta_s \right) - \left( \sum_{i=1}^m \theta_i D_i(t) + D_s(t) \times \theta_s \right) \quad (4)$$

where  $\theta_i$  is the soil moisture content at layer  $i$  that varies from  $m$  to  $n$  depending on the water table level from 1 month (year)  $t$  to next month (year)  $t+1$ .  $D_i$  is the soil thickness interval (mm) corresponding to layer  $i$ .  $D_s$  is the saturated soil thickness (mm) above an arbitrary reference level and  $\theta_s$  is the saturated soil moisture content or soil porosity.

### 2.5.1. Throughfall and stemflow measurements

A total of ten manual rain gages used as throughfall collectors were randomly installed between the trees on the planting beds and in the middle of two adjacent beds in the vicinity of the flux tower at the LP site. Data were collected at a biweekly time interval. The interception rates were calculated as the difference between gross rainfall recorded by the rain gage on the tower and that measured as throughfall divided by the gross rainfall. Stemflow measurements were made on two trees for a few storm events in 2005 to estimate the proportion of rainfall and not captured by the throughfall collectors.

### 2.5.2. Grass reference evapotranspiration ( $ET_o$ )

The FAO Penman-Monteith equation or often called the FAO-56 grass reference  $ET$  method (Allen et al., 1994) estimates the actual  $ET$  of a hypothetical well-watered grass that has a 0.12 m canopy height, a leaf area of 4.8, a bulk surface resistance of  $70 \text{ s m}^{-1}$ , and albedo of 0.23. Since actual  $ET$  generally correlates closely with  $ET_o$ , we used  $ET_o$  to gapfill missing  $ET$  data at the half-hour scale. Using half-hour meteorological data, half-hour  $ET_o$  (mm) was estimated and summed to derive daily and monthly  $ET$ . The albedo at the CC site was very close to the 'reference grass' (see Section 3).

Therefore, we assumed that the CC site represented the 'reference grass' condition defined by the FAO-56 method.

### 2.5.3. Data quality control and gapfilling of missing 30-min $ET$

Data quality was judged by atmospheric stability and flux stationarity during periods of well-developed turbulence as reported previously (Noormets et al., 2008). Following the quality screening, the remaining data coverage was 42% (2005), 47% (2006) and 49% (2007), with gaps caused primarily by periods of dew and precipitation, and poorly developed turbulence ( $u^* = 0.20$  at LP,  $u^* = 0.1$  at CC, determined for each site, data not shown). The latter often co-occurred with very stable or very unstable atmospheric conditions. Obvious outliers were removed on a year and site basis. For example, data points with  $LE > 800 \text{ W m}^{-2}$  or  $LE < -200 \text{ W m}^{-2}$  and  $H > 500 \text{ W m}^{-2}$  or  $H < -200 \text{ W m}^{-2}$  were removed. The 30-min  $ET$  data sets were gap-filled using the established monthly  $ET - ET_o$  regression models developed from existing data. If  $ET_o$  is not available, gaps were filled with regression relationships between  $ET$  and  $R_n$  by month. When all meteorological variables are missing, linear interpolation method was used. When large gaps occurred such as half of the 48 data points were missing, that date was considered to produce "no data". Similarly, if a third of the data points in a month were missing or invalid, then this month was considered as having "no data". Potential estimation errors in  $LE$  during rainfall events when sensors are wet were also addressed in the EC Processor (Meiresonne et al., 2003).

We recognize the energy imbalance problem for all eddy covariance measurements. The available energy ( $R_n + G$ ) is generally higher than turbulence fluxes ( $LE + H$ ). Several reasons have been identified: (1) missing data due to either equipment failure, or a lack of air turbulence needed to meet the designed accuracy of IRGA (Wilson et al., 2002). Wilson et al. (2002) documented that a lack of closure, with 20% the energy is missing was not uncommon in the FLUXNET. (2) Heterogeneity of landscape (Foken, 2008). (3) Measurement errors in net radiation and soil heat flux (Restrepo and Arain, 2005).

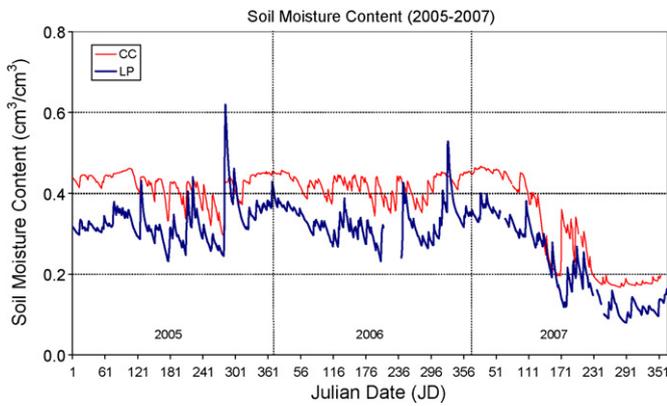
Data quality control on the half-hour eddy flux data were performed in the EC processor that was implemented using the SAS software. The SAS procedure, 'Proc Mixed', that considers the influence of time on the variances of a variable examined, was used to test the differences of the means of key observed energy and micrometeorological variables between the LP and CC sites.

## 3. Results

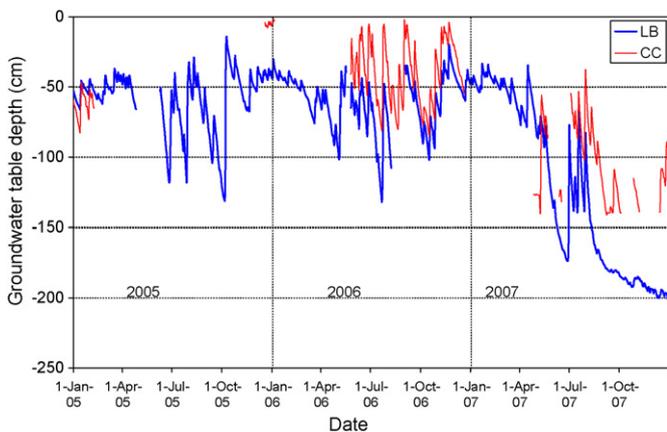
### 3.1. Micrometeorology

The year 2006 had an annual total precipitation of 1272 mm, slightly lower than the long-term average (1320 mm) measured 8-km North at the Plymouth Weather Station in Washington County by NOAA (<http://www.nc-climate.ncsu.edu/>). However, 2005 was much wetter ( $P = 1467$  mm) than the average due to higher than normal rainfall in the fall, and 2007 was an extremely dry year ( $P = 892$  mm or 68% of long-term average). The severe dry summer, fall, and winter resulted in extremely dry hydrologic conditions as indicated by the low soil moisture (Fig. 3) and low groundwater table (Fig. 4).

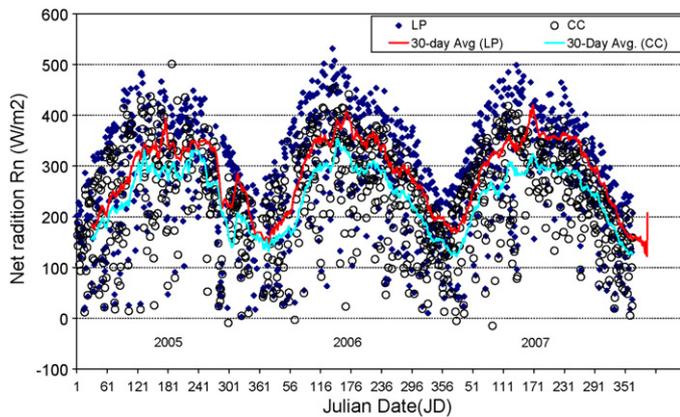
The 3-year averaged daily  $R_n$  at LP was significantly ( $p < 0.01$ ) higher than CC by about 20% (Fig. 5).  $R_n$  was linearly correlated with incoming global radiation input at the half-hour time interval (Table 1). The mean albedos ( $\alpha$ ) were 0.25 and 0.16 for CC and LP, respectively. The mean albedos at both sites had little inter-annual variations (Table 1), but they had large intra-annual variability, reflecting the changes of plant phenology and surface characteristics of vegetation covers (e.g., LAI). Site albedos reached the



**Fig. 3.** A comparison of daily soil moisture content dynamics measured at a 20-cm depth between a mid-rotation loblolly pine and a clearcut site (CC) during 2005–2007.



**Fig. 4.** A comparison of daily groundwater table depth measured at the mid-rotation (LP) and a clearcut site (CC) during 2005–2007.



**Fig. 5.** Daily average net radiation measured at a mid-rotation loblolly pine site (LP) was significantly higher than clearcut site (CC) during 2005–2007. Note: The daily average was calculated using filtered, but not gap-filled 30-min net radiation data.

minimums around end of July and the maximums around the end of December.

There were no significant differences in air temperature that was measured above vegetation canopies between the two sites ( $p = 0.26$ ). Overall, there were no significant differences in average soil temperatures between sites for both depths ( $p > 0.05$ ). However, during 2006, soil temperature of both depths at CC was significantly higher than at LP ( $p < 0.05$ ). In contrast, soil temperature at the 20-cm depth was significantly higher at LP than at CC in 2007.

The daily wind speed at LP ( $2.11 \pm 0.77$  m/s) was significantly ( $p < 0.01$ ) higher than at the CC site ( $1.97 \pm 0.86$  m/s) with seasonal highs during winter and spring months, and lows during the summer and fall months. The difference was partially due to the fact that the sensor at LP was installed at a much higher level (35 m) at LP than at the CC site (8 m).

### 3.2. Energy balances

#### 3.2.1. Energy closure at a half-hour scale

The sum of latent and sensible heat,  $LE + H$ , was linearly correlated with available energy,  $R_n - G$  (Table 2) at the 30-min time scale. The averaged energy balance closures at the 30-min scale were 89 and 96% for the LP and CC sites, respectively. These values were considered rather high when compared to other sites within the eddy flux network (Wilson et al., 2002) and thus the energy balance measurements were regarded as being reliable to examine energy partitions among all energy fluxes.

#### 3.2.2. Energy balance

Annual mean net radiation ( $R_n$ ) flux was significantly ( $p = 0.003$ ) higher at the LP site ( $286 \pm 113$  W m<sup>-2</sup>) than the CC site ( $238 \pm 100$  W m<sup>-2</sup>), ranging from 14% in May to 30% higher in November (Fig. 5; Tables 2 and 3). Similarly, the annual mean of LE ( $143 \pm 69$  W m<sup>-2</sup>) at LP was significantly ( $p = 0.017$ ) higher than at CC ( $105 \pm 64$  W m<sup>-2</sup>) (Figs. 6 and 7a). The LE was significantly correlated with  $R_n$  with a mean  $r^2$  of 0.64 and 0.66 for the LP and CC site, respectively (Table 2). Those regression models suggest that, on average, over the 3 years about 52% (48–53%) of  $R_n$  was converted to LE at the LP site. Surprisingly, this annual-scale ratio for the CC site was similar to the LP site (47–57%).

Overall, monthly LE at the LP site was about 28% higher than the CC site (Figs. 6 and 7a). However, there were no significant differences in sensible heat ( $H$ ) between the two sites ( $p = 0.9$ ) (Figs. 6 and 7b). The annual means of  $H$  at the two sites were almost identical, about 88 W m<sup>-2</sup>, or 31 and 37% of  $R_n$  at LP and CC sites, respectively.

The annual mean Bowen ratios  $\beta$  ( $H/LE$ ) values ( $0.89 \pm 0.7$ ) at the LP sites were significantly ( $p = 0.02$ ) lower than at the CC sites ( $1.45 \pm 1.2$ ). However,  $\beta$  values at both sites were almost identical during the growing season from May to September. The differences between the two sites were largest during the non-growing seasons or during the severe drought period during September–October 2007 (Table 3).

Averaged soil heat flux was rather small for both sites at the monthly scale, with negatives during roughly October–February and small positives in the spring and summer months (Fig. 6;

**Table 1**  
Relationships between half-hour net radiation ( $R_n$ ) and incidence global radiation ( $R_g$ ) for two loblolly pine plantations.

Site	2005	2006	2007
Mid-rotation (LP)	$R_n = -37.92 + 0.84R_g$ $r^2 = 0.98$	$R_n = -40.41 + 0.85R_g$ $r^2 = 0.98$	$R_n = -42.88 + 0.84R_g$ $r^2 = 0.98$
Clearcut (CC)	$R_n = -37.38 + 0.75R_g$ $r^2 = 0.97$	$R_n = -37.27 + 0.74R_g$ $r^2 = 0.97$	$R_n = -39.84 + 0.75R_g$ $r^2 = 0.98$

**Table 2**  
Energy closure and relationships between half-hour net radiation ( $R_n$ ), sensible heat ( $H$ ), latent heat (LE), soil heat flux ( $G$ ) for two loblolly pine sites.

Site	2005	2006	2007	Season	
Mid-rotation (LP)	$[H + LE] = -18.22 + 0.89(R_n - G)$ $r^2 = 0.87$	$[H + LE] = -26.62 + 0.90(R_n - G)$ $r^2 = 0.89$	$[H + LE] = -20.67 + 0.88(R_n - G)$ $r^2 = 0.88$	All year	
	$LE = -6.29 + 0.54R_n$ $r^2 = 0.62$	$LE = -3.8 + 0.53R_n$ $r^2 = 0.65$	$LE = 0.66 + 0.48R_n$ $r^2 = 0.62$	Growing (May–October)	
	$H = -10.5 + 0.33R_n$ $r^2 = 0.49$	$H = -21.67 + 0.36R_n$ $r^2 = 0.59$	$H = -20.13 + 0.39R_n$ $r^2 = 0.64$		
	$LE = 6.69 + 0.61R_n$ $r^2 = 0.75$	$LE = 5.8 + 0.62R_n$ $r^2 = 0.77$	$LE = 9.86 + 0.53R_n$ $r^2 = 0.71$		
	$H = -22.89 + 0.27R_n$ $r^2 = 0.61$	$H = -27.74 + 0.27R_n$ $r^2 = 0.65$	$H = -25.12 + 0.35R_n$ $r^2 = 0.67$	Dormant (November–April)	
	$LE = 7.95 + 0.30R_n$ $r^2 = 0.43$	$LE = 7.55 + 0.35R_n$ $r^2 = 0.51$	$LE = 15.19 + 0.29R_n$ $r^2 = 0.45$		
	$H = -24.52 + 0.57R_n$ $r^2 = 0.76$	$H = -35.07 + 0.54R_n$ $r^2 = 0.78$	$H = -34.04 + 0.55R_n$ $r^2 = 0.77$		
	Clearcut (CC)	$[H + LE] = -17.51 + 0.88(R_n - G)$ $r^2 = 0.84$	$[H + LE] = -24.95 + 1.0(R_n - G)$ $r^2 = 0.88$	$[H + LE] = -24.9 + 1.0(R_n - G)$ $r^2 = 0.90$	All year
		$LE = -16.38 + 0.56R_n$ $r^2 = 0.69$	$LE = -21.59 + 0.57R_n$ $r^2 = 0.68$	$LE = -17.62 + 0.47R_n$ $r^2 = 0.61$	Growing (May–October)
$H = -0.90 + 0.29R_n$ $r^2 = 0.58$		$H = -0.39 + 0.34R_n$ $r^2 = 0.56$	$H = -3.62 + 0.46R_n$ $r^2 = 0.68$		
$LE = -3.5 + 0.61R_n$ $r^2 = 0.77$		$LE = -8.05 + 0.64R_n$ $r^2 = 0.80$	$LE = -6.05 + 0.52R_n$ $r^2 = 0.70$		
$H = -9.91 + 0.25R_n$ $r^2 = 0.67$		$H = -12.22 + 0.28R_n$ $r^2 = 0.65$	$H = -14.23 + 0.41R_n$ $r^2 = 0.72$	Dormant (November–April)	
$LE = -14.49 + 0.38R_n$ $r^2 = 0.61$		$LE = -13.04 + 0.32R_n$ $r^2 = 0.57$	$LE = -11.71 + 0.29R_n$ $r^2 = 0.48$		
$H = -2.63 + 0.43R_n$ $r^2 = 0.74$		$H = -7.07 + 0.54R_n$ $r^2 = 0.81$	$H = -10.49 + 0.64R_n$ $r^2 = 0.87$		

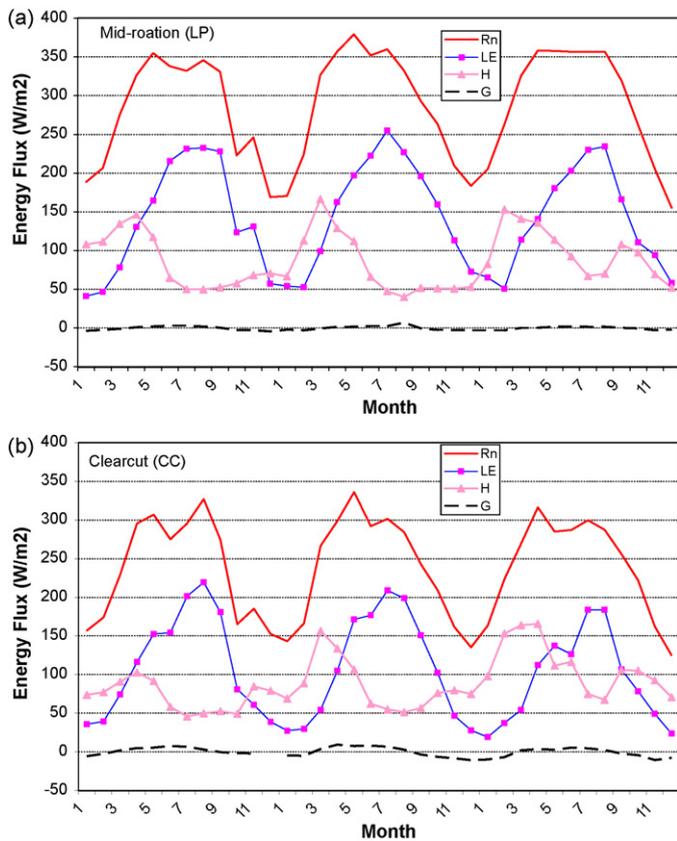
Table 3). The CC site had much higher values at all three measured depths than the LP site. The maximum values of 30-min mid-day  $G$  at a 10-cm depth could reach as high as  $200 \text{ W m}^{-2}$  in March 2006, but values at the LP site rarely exceeded  $30 \text{ W m}^{-2}$ . Similarly,  $G$  values could drop to  $-70 \text{ W m}^{-2}$  during early morning hours at the CC site while values at the LP site were rarely lower than  $-10 \text{ W m}^{-2}$ . Overall,  $G$  was a minor component of the overall energy balances in the growing season at both sites.

### 3.2.3. Temporal variability and drought effects on the energy balances

Energy partitioning showed a clear seasonal and inter-annual variability at both sites (Tables 2 and 3; Fig. 6). The mean  $LE/R_n$  ratio was 0.45 and 0.36 at the LP and CC sites, respectively in the dry year 2007. These values were much lower than in other 2 years, about 0.50 and 0.43 at the LP and CC sites, respectively. Consequently, the  $H/R_n$  ratios in 2007 were higher, 0.35 and 0.48, compared to 0.31 and 0.36 during 2005–2006 for the LP and

**Table 3**  
Three-year (2005–2007) averaged monthly energy balances for two loblolly pine sites.

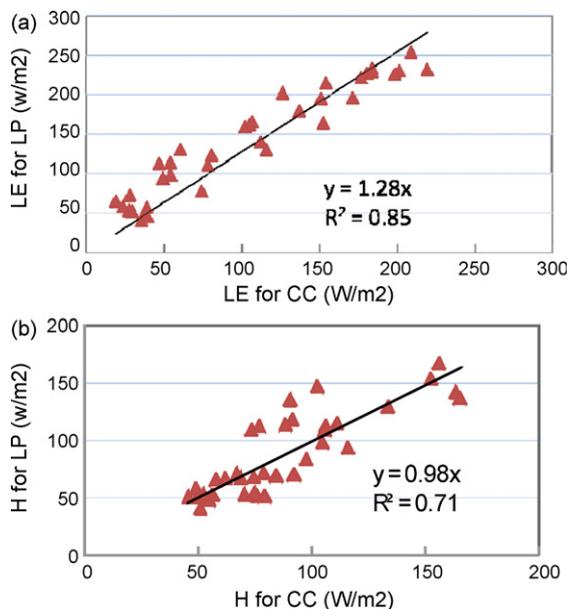
Site	Month	$R_n$	$LE/R_n$	$H/R_n$	$G/R_n$	(Other fluxes + error)/ $R_n$	Bowen ratio ( $H/LE$ )
Clearcut site (CC)	Jan	154	0.18	0.52	-0.04	0.35	3.25
	Feb	188	0.19	0.55	-0.03	0.28	3.02
	Mar	255	0.24	0.53	0.01	0.22	2.38
	Apr	304	0.37	0.44	0.02	0.17	1.21
	May	309	0.50	0.34	0.02	0.15	0.68
	Jun	285	0.54	0.28	0.02	0.16	0.55
	Jul	299	0.66	0.20	0.02	0.12	0.30
	Aug	300	0.67	0.19	0.01	0.13	0.28
	Sep	258	0.57	0.28	-0.01	0.16	0.55
	Oct	199	0.44	0.38	-0.02	0.20	0.90
	Nov	170	0.31	0.51	-0.04	0.23	1.66
	Dec	138	0.22	0.55	-0.07	0.28	2.57
Mid-rotation site (LP)	Jan	188	0.29	0.46	-0.01	0.27	1.70
	Feb	231	0.22	0.54	-0.01	0.25	2.51
	Mar	309	0.31	0.48	0.00	0.21	1.54
	Apr	347	0.42	0.40	0.00	0.18	0.96
	May	364	0.50	0.32	0.01	0.18	0.64
	Jun	349	0.61	0.21	0.01	0.17	0.35
	Jul	350	0.68	0.16	0.01	0.15	0.23
	Aug	345	0.67	0.15	0.01	0.16	0.23
	Sep	315	0.63	0.22	0.00	0.15	0.38
	Oct	249	0.53	0.28	-0.01	0.20	0.56
	Nov	220	0.51	0.29	-0.01	0.21	0.57
	Dec	169	0.37	0.35	-0.02	0.30	0.95



**Fig. 6.** Monthly mean values of net radiation  $R_n$ , sensible heat ( $H$ ), latent heat ( $LE$ ), and soil heat flux during 2005–2007 at: (a) a mid-rotation loblolly pine (LP), and (b) a clearcut site (CC) site. Note: The monthly values were calculated using filtered, but not gap-filled 30-min data.

CC sites, respectively. It appears that the effects of the 2007 drought on  $LE$  and  $H$  were most pronounced at the CC site.

The  $\beta$  values were the lowest in August, but highest during February–March (Table 3). The mean  $\beta$  values were  $0.54 \pm 0.23$  and



**Fig. 7.** A comparison of measured monthly latent heat ( $LE$ ) (a) and sensible heat ( $H$ ) (b) between a mid-rotation loblolly pine (LP) and a clearcut (CC) sites during 2005–2007.

$0.40 \pm 0.17$  for the growing season (May–October) at CC and LP, respectively. They were much larger during the dormant season (November–April),  $2.34 \pm 0.79$  and  $1.26 \pm 0.71$  for the CC and LP sites, respectively.

During the growing season,  $LE$  dominated the energy balances, reaching the maximum of  $235 \text{ W m}^{-2}$  in July at the CC site (Fig. 6) and in August ( $235 \text{ W m}^{-2}$ ) at the LP site (Fig. 6). The differences in  $LE$  between the LP and CC sites were larger in 2007 than in other time periods. The droughts in the summer and fall of 2007 resulted in a much lower  $LE$ , and only about 52% of  $R_n$ . The average  $H/R_n$  ratio during the growing season was approximately 0.27 during 2005–2006 for both sites, but it was much higher during 2007, 0.35 and 0.41 for the LP and CC sites, respectively.

In contrast to the growing season,  $H$  dominated the energy balances in the dormant season at both sites, accounting for about 55% of  $R_n$  (Table 2; Fig. 7). Generally,  $H$  exceeded  $LE$  in the dormant season that started in October and ended in April at the CC site, but starting 2 months later in December and ended in April at the LP site (Fig. 6). At the CC site, droughts during the dormant season of 2007 elevated  $H/R_n$  up to 0.64, much higher than in 2005 (0.43) or in 2006 (0.54). However, droughts in 2007 did not impact the relations between  $H$  and  $R_n$  or  $LE$  and  $R_n$  at the LP site (Table 2).

### 3.3. Water balances

#### 3.3.1. Canopy Interception and stemflow

Throughfall measurements at the LP site during 2005–2006 showed that interception rates varied from 11.0 to 17.3% in the winter seasons to 13.0–32.0% in the spring, 10.2% in the summer, and about 12% in the fall. Calculated canopy interception rates at the biweekly time interval varied from zero to as high as 86%. Stemflow was estimated to be negligible by representing less than 1% of precipitation.

#### 3.3.2. Change in soil water storage ( $\Delta S$ ): Soil moisture, and groundwater table level

Both ground water table level (WT) and soil moisture content ( $\theta$ ) indicated that the CC site was wetter than the LP site (Figs. 3 and 4). In fact, the soil profile at the CC site was periodically saturated ( $\theta = 0.46$ ) during winter and fall or after storms in the summer, while it rarely reached saturation ( $\theta = 0.61$ ) at the LP site. The extreme drought during August–December of 2007 resulted in exceptionally dry soil condition with  $\theta$  dropping below 18% at both sites and the water table depths retreated deeper than 1.5 and 2.0 m at the CC and LP site, respectively.

#### 3.3.3. Evapotranspiration (ET)

The overall daily ET rates at the CC site ( $2.35 \pm 1.40 \text{ mm day}^{-1}$ ) were significantly ( $p < 0.001$ ) lower than at the LP site ( $3.00 \pm 1.50 \text{ mm day}^{-1}$ ) (Fig. 8). The largest ET differences were found during dry periods in 2006 and 2007, and the differences became smaller during wet periods, such as the entire year of 2005, or during the peak of the growing season in 2006 when soil moisture was not limiting (Fig. 9). The ET rates at the CC site were occasionally higher than from the LP site (Fig. 9) when the CC surface soil was close to saturation.

The mean  $ET/ET_0$  ratio for the LP site was  $1.13 \pm 0.21$ , significantly ( $p = 0.02$ ) higher than at the CC site (mean =  $0.83 \pm 0.18$ ) (Fig. 10). At the LP site, the  $ET/ET_0$  ratios were lowest in February ( $0.78 \pm 0.18$ ) and highest ( $1.48 \pm 0.37$ ) in November. The mean  $ET/ET_0$  ratios at the CC site were at the lowest ( $0.56 \pm 0.21$ ) in March and highest ( $1.06 \pm 0.08$ ) in August (Fig. 10). The annual  $ET/ET_0$  ratios at the Amatya et al. (2006) site varied from 0.7 to 1.3, comparing closely to this study (1.0–1.13).

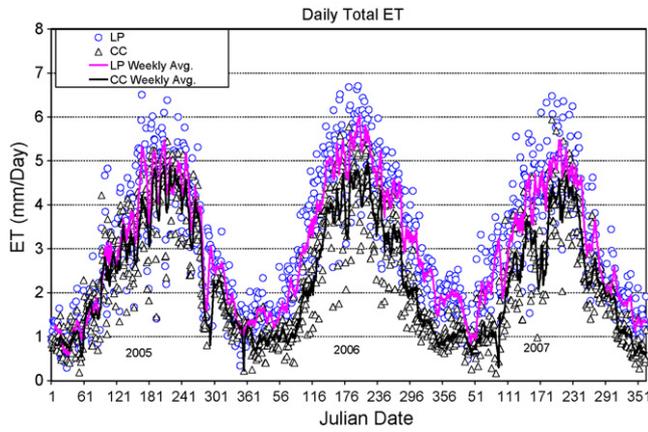


Fig. 8. A comparison of daily evapotranspiration rates measured by the eddy covariance method at the mid-rotation and a clearcut site during 2005–2007.

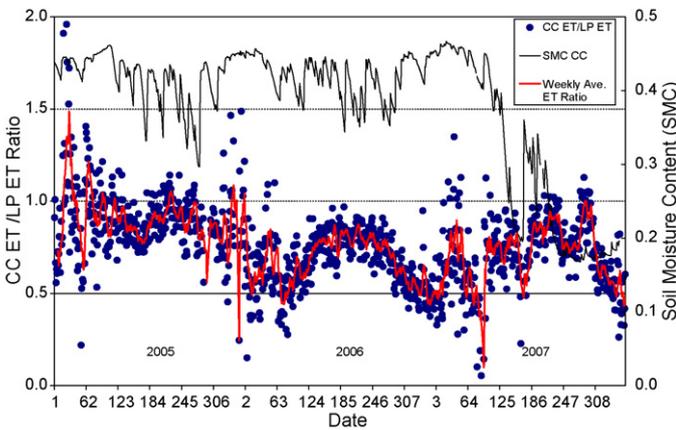


Fig. 9. Ratios of daily evapotranspiration rate of clearcut site and the mid-rotation site during 2005–2007 suggest relative differences were more pronounced during dormant season or dry periods.

Monthly ET at the LP site was significantly correlated with  $ET_0$  ( $p < 0.001$ ), measured LAI ( $p = 0.03$ ), and  $P$  ( $p = 0.06$ ), suggesting both biological and climatic control on actual water loss in pine forests. The regression model (adj  $R^2 = 0.86$ ) had the form:

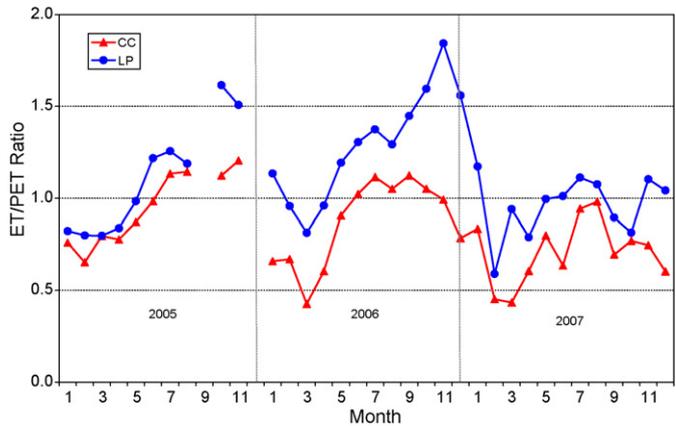


Fig. 10. Monthly evapotranspiration/grass reference evapotranspiration ratio for clearcut site (CC) and the mid-rotation (LP) sites during 2005–2007, indicating that monthly ET rates at LP were much higher than grass reference ET during the summer, and fall due to higher leaf area.

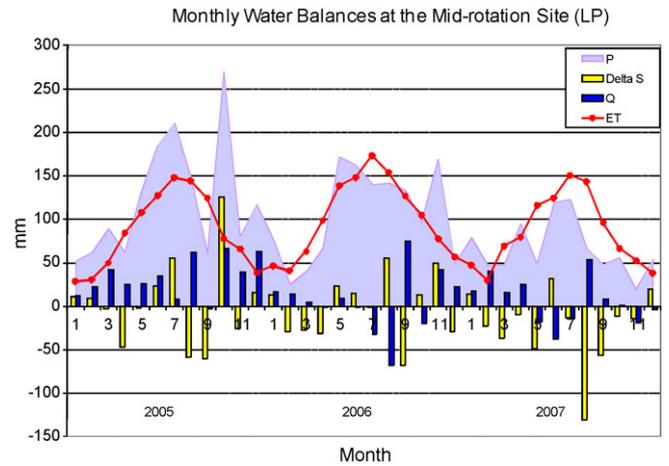


Fig. 11. Monthly precipitation PPT, evapotranspiration ET, change in soil water storage  $\Delta S$ , and estimated drainage ( $Q$ ) at the mid-rotation (LP) site during 2005–2007.

$ET = -50.1 + 0.759 ET_0 + 0.112 P + 18.52 LAI$ . We could not derive this type of regression model for the CC site since we did not measure LAI, but a similar analysis without LAI suggested that monthly ET was also closely ( $p < 0.001$ ) related to  $ET_0$  and  $P$ .

3.3.4. Drainage rates at monthly and annual-scale

The groundwater table datalogger failure prevented us from deriving a complete water balance for the CC site. Monthly water balance for the LP site was presented in Fig. 11 in which  $Q$  was calculated using the water balance equation, and other variables were measured. In spite of the significant decrease in precipitation during the severe drought in 2007, monthly ET rates were relatively stable (Fig. 11). Therefore, the drainage rates ( $Q$ ) and fluctuations of  $\theta$  and WT (i.e.,  $\Delta S$ ) were dictated by  $P$  patterns.

Clearly, large estimation errors for drainage ( $Q$ ) existed for some months, such as July–August of 2006 and June–August 2007, when  $Q$  was calculated as being negative. In general, large errors occurred when the water table had a large change, suggesting that uncertainty existed in estimating change in soil water storage at the watershed and landscape scale. When combining the adjacent 2 months, the estimation errors could be minimized.

Annual water budgets indicated that the total ET at the LP site ( $1087 \pm 121$  mm) was 16–40% higher than at the CC site ( $838 \pm 72$  mm) (Table 4). Compared to 2005 and 2006, the severe drought of 2007 resulted in a 14% and 10% reduction in ET at the CC and LP site, respectively. The CC site had about 70% higher drainage than that at the LP site.

Table 4 Annual water balances for a clearcut (CC) and a mid-rotation plantation (LP) forests.

Site	Year	P (mm)	ET (mm)	$\Delta S$	Estimated drainage (mm)	ET/P	$ET_0$ (mm)	ET/ $ET_0$
CC	2005	1467	885	54	528	0.60	885	1.00
	2006	1447	874	-44	617	0.60	969	0.90
	2007	907	755	-164	316	0.83	1024	0.74
	Average	1274	838	-51	393	0.66	959	0.87
LP	2005	1467	1024	9	434	0.70	1069	1.16
	2006	1355	1226	-5	134	0.91	1137	1.27
	2007	892	1011	-240	121	1.13	1178	0.99
	Average	1238	1087	-79	230	0.88	1128	1.13

**Table 5**  
Albedo values for selected forests ecosystems.

Forest types	Reported albedo ( $\alpha$ ) values	Reference
Loblolly pine plantation (16 years old, North Carolina)	0.25 0.22 (growing season) 0.29 (dormant season)	This study
Loblolly pine plantation (4 years old), coastal North Carolina	0.34 0.31 (growing season) 0.38 (dormant season)	
Loblolly pine plantation, 4 years old, North Carolina	0.25–0.31	Amatya et al. (2000)
Grass surface, North Carolina	0.35	Amatya et al. (2000)
Loblolly pine plantation, 25 year old, Piedmont North Carolina	0.10	Juang et al. (2007)
Mature hardwoods, piedmont North Carolina	0.15	Juang et al. (2007)
Grass-cover old field	0.20	Juang et al. (2007)
Slash pine plantation, clearcut, Florida	0.26	Gholz and Clark (2002)
Slash pine plantation, 10 years old, Florida	0.18	
Slash pine plantation, mid-rotation, Florida	0.18	
Eastern white pine ( <i>Pinus strobus</i> L), 65 years old, Canada	0.12 (growing season)	Restrepo and Arain (2005)
Aspens	0.15 (growing season)	Betts and Ball (1997)
Jack pine and spruce	0.08 (growing season)	
Rain forests	0.12 $\pm$ 0.05	Pinker et al. (1980)

## 4. Discussion

### 4.1. Energy balance

#### 4.1.1. Albedo and net radiation

The large differences in net radiation between the two sites were mainly due to the differences in albedo of the land surfaces. Albedo varied greatly during the year reflecting the changes of radiation property and land surface reflectance characteristics that were influenced by both 'greenness' and wetness of land surfaces. The seasonal contrasts of albedo values between LP and CC sites corresponded to the dynamics of plant growth patterns: the LP was a conifer plantation with needles being present and transpiring water year-round, but most herbaceous and deciduous woody plants at CC lost leaves in the dormant season. Averaged albedo values for the CC ( $\alpha = 0.34$ ) and LP sites ( $\alpha = 0.25$ ) were comparable to reported values for the coastal plain forests, but were much higher than those for other type of forests in the Southeastern U.S. and boreal forests (Table 5). The differences have significance to parameterize climate models for addressing the current debates regarding positive effects of afforestation global warming through reducing land surface albedo (Betts, 2000; Gibbard et al., 2005).

#### 4.1.2. Seasonal variability of distribution of LE and H

The exchange of dominance of the energy balances by LE and H corresponded to leaf area dynamics. During the growing season, LE was greater than H and the opposite was true during the dormant season. This alteration pattern was not found at a slash pine plantation site in Florida (Gholz and Clark, 2002) where H rarely exceeded LE. Bowen ratio ( $0.49 \pm 0.32$ ) of the mid-rotation forest at the Florida site was somewhat higher than our summer observations ( $0.40 \pm 0.17$ ), but much lower than in the winter,  $0.75 \pm 0.49$  in Florida vs.  $1.26 \pm 0.71$  at this site. In contrast, H dominated the energy balance of a pine forest growing under a temperate climate with a Bowen ratio greater than 1.0 during the growing season and ranging from  $-0.86$  in November to as high as 33.3 in February (Restrepo and Arain, 2005). Arain et al. (2003) reported that the Bowen ratios for a boreal black spruce forest were about 3.5, 1.7 and 5.2 in the spring, summer and winter seasons, respectively.

The climatic variability such as precipitation variations is a major control to the partitioning of net radiation. For example, during the wet year of 2005, the differences in LE and Bowen ratio ( $\beta$ ) were small between the two sites. However, H was much higher in the fall of 2006 and 2007 (i.e., higher Bowen ratio) than other 2 years. In comparison, Gholz and Clark (2002) found that full saturation at a clearcut site greatly increased soil evaporation and

reduced Bowen ratio in the growing season ( $\beta = 0.35 \pm 0.19$ ), which was much lower than those ( $\beta = 0.54 \pm 0.23$ ) found at the CC site in this study. Overall, we found that the growing season  $\beta$  values for both the LP and CC sites were lower than reported values for most forest ecosystems, and they are similar to tropical rainforests (Ref. Chapin et al., 2002; page 76).

#### 4.1.3. Differences in energy balances between the CC and LP sites

Two major reasons may have contributed the higher LE values at the LP site than the CC site. First,  $R_n$  was higher at the LP site due to its lower surface albedo. Second, the LP site had a higher leaf area, and thus likely had higher canopy rainfall interception and plant transpiration rates.

However, contrary to studies on forests in Northern latitude (Arain et al., 2003; Restrepo and Arain, 2005; Amiro et al., 2006a,b; Sun et al., 2008b) where disturbances had a large effect on H and H/LE, our study showed that H at the CC site was very similar to that at the LP site over the 3 years. This finding was similar to the results in Gholz and Clark (2002) who compared a clearcut and mature plantations during a rather wet period.

Our study suggested that both forest management and climatic variability affect energy partitioning. Forest management had more notable effects on energy partitioning during dry periods for a water-unlimited system. The short-term study by Gholz and Clark (2002) suggested that energy partitioning was more sensitive to environmental fluctuations than management activities. Apparently, the conclusion was biased toward a much wetter environment than this study had. Our study demonstrated how soil moisture regime affected ecosystem response to land management. Amiro et al. (2006a,b) also suggested soil moisture status is a major controlling factor on energy partitioning in disturbed ecosystems.

### 4.2. Water balances

#### 4.2.1. Variability of annual ET among ecosystems and management regimes

The annual variability of ET was clearly much smaller compared to other hydrologic components as observed in other ecosystems (Chapin et al., 2002; Amatya et al., 2006; Stoy et al., 2006). The reduction of total ET of 114 mm or 10% in 2007 from the two previous years at the LP site could be most likely due to reduction of canopy interception (71 mm) and ground surface evaporation if we assume an interception rate of 15%, a conservative estimate. However, the relatively larger reduction in ET, 175 mm or 20% at the CC site could not be explained by reduction in rainfall

**Table 6**

A comparison of annual measured evapotranspiration in major forest ecosystems in Southeastern United States. Values in parentheses represent range.

Ecosystems	Evapotranspiration (mm/year)	Precipitation (P)	ET/P	References
Loblolly pine plantation (LP) 16 years old, North Carolina	1087 (1011–1226)	1238	0.88	This study
Loblolly pine plantation (CC), 4 years old, coastal North Carolina	838 (755–885)	1274	0.66	This study
Loblolly pine plantation, 4 years old, Parker Track, North Carolina	895 (702–1078)	1152	0.78 (0.73–0.94)	Diggs (2004)
Loblolly pine plantation, 15 years old, Parker Track, North Carolina	988, 938 (after thinning 1/3 of basal area)	1098	0.9	Grace et al. (2006a,b)
Loblolly pine plantation, 14–30 years old, Parker Track, North Carolina	997 (763–1792)	1538 (947–1346)	0.65	Amatya et al. (2006)
Loblolly pine plantation (PP), 25 years old, Piedmont North Carolina	658 (560–740)	1092 (930–1350)	0.60	Stoy et al. (2006)
Mature deciduous hardwoods (HW), Duke Forest, Piedmont North Carolina	573 (460–640)		0.52	Stoy et al. (2006)
Grass-cover old field (OL), Duke Forest, Piedmont North Carolina	508 (360–650)		0.46	Stoy et al. (2006)
Slash pine ( <i>Pinus taeda</i> L.) plantation, clearcut, Florida	958 (869–1048)	959 (869–1048)	0.85 (0.84–0.86)	Gholz and Clark (2002)
Slash pine ( <i>Pinus taeda</i> L.) plantation, 10 years old, Florida	1058 (994–1122)	1062 (877–1247)	1.0 (0.9–1.1)	Gholz and Clark (2002)
Slash pine ( <i>Pinus taeda</i> L.) plantation, full-rotation, Florida	1193 (1102–1284)	1289 (887–1014)	0.93 (0.92–0.93)	Gholz and Clark (2002)
Slash pine ( <i>Pinus taeda</i> L.) plantation, full-rotation, Florida (extreme drought years)	754 (676–832)	883 (811–956)	0.85	Powell et al. (2005)
Pine flatwoods, Bradford Forest, Florida	1077	1261	0.87	Sun et al. (2002)
Deciduous hardwoods, Coweeta, North Carolina	779	1730	0.47	Sun et al. (2002)
Mixed Pine and hardwoods, Santee Exp. Forest, South Carolina	1133	1382	0.82	Lu et al. (2003)
White pine ( <i>Pinus strobus</i> L.), Coweeta, North Carolina	1291	2241	0.58	Ford et al. (2007)
Deciduous hardwoods, Oak Ridge, Tennessee	567 (537–611)	1372 (1245–1682)	0.41	Wilson and Baldocchi (2000)
Deciduous hardwoods, Oak Ridge, Walker Branch watershed, Tennessee	575	1244	0.45	Updated data from Lu et al. (2003); Hanson et al. (2003)

interception alone, but reduction in transpiration of plants that had shallow roots and reduced plant hydraulic conductivity could have been the major cause (Domec et al., 2009).

The annual ET values reported from this study are comparable to other studies for the lower coastal plains whose ET rates are on the high end among Southeastern forests (Table 6). These differences in ET and ET/P ratios can be explained by available energy (Lu et al., 2003; Stoy et al., 2006), precipitation distribution and topography (Sun et al., 2002), and forest canopy interception capacity associated tree species and leaf area (Swank and Douglass, 1974). The combination of shallow groundwater and high available energy resulted in high ET, and low drainage along the Atlantic coastal plain.

#### 4.2.2. Monthly scale water balance

Developing annual watershed water balance using measured P, ET, and estimated change in soil water storage ( $\Delta S$ ) appeared to be feasible and accurate in most cases but was problematic for some months, such as July–August in 2006, and June 2007 (Fig. 11) in this study. In those cases, it was likely that  $\Delta S$  values were over-estimated. We also suspected that drainage might be over-estimated in September 2006 and August 2007. In those cases,  $\Delta S$  was likely underestimated. All these 3 months experienced large either positive or negative changes in groundwater table depth (Fig. 4). Another source of error may be that our measurements of soil moisture and water table depth were limited to only one spot and they were not sufficient to represent the true monthly  $\Delta S$  at the landscape scale when its magnitude was large.

## 5. Conclusions

This 3-year study suggested that clearcutting a native forested wetlands and subsequent reforestation could significantly alter

radiation input and latent heat flux for evapotranspiration, but caused little change in sensible heat, the energy source for heating the atmosphere. Therefore, our study supports the notion that atmospheric warming due to reforestation is not likely (Juang et al., 2007) and effects may be negligible in the mid-latitude region (Betts, 2000).

In general, clearcutting a forest reduced available energy for ET, thus it elevated drainage and groundwater table level significantly. However, the hydrologic effects of forest conversion are mostly pronounced during dry periods and dormant seasons when the changes in land surface prosperities are greatest. We concluded that ET from the drained pine plantations was mostly controlled by energy availability.

Severe droughts can have significant effects on surface soil moisture and plant water use (i.e., latent heat) and plant growth. We conclude that soil water conditions should be considered in evaluating the effects of afforestation/deforestation on albedo and ecosystem energy and water balances at large-scales. This is perhaps particularly important for wetland ecosystems that have a rather dynamic hydrology and the impacts of droughts on ecological processes are more consequential than upland ecosystems (Sun et al., 2002; Domec et al., 2009; Noormets et al., 2009).

## Acknowledgements

This study was supported by the USDA Forest Service Southern Global Change Program cooperative agreements 03-CA-11330147-073 and 04-CA-11330147-238, and in part by DOE-NICCR award 08-SC-NICCR-1072. The Weyerhaeuser Company is gratefully acknowledged for facilitating access to the study site and offering logistical assistance. Sara Strickland, Johnny Boggs, and Emrys Treasure assisted with field data collection. This study is partially supported by the US-China Carbon Consortium (USCCC).

## References

- Albaugh, T.J., Allen, H.L., Dougherty, P.M., Johnson, K.H., 2004. Long-term growth responses of loblolly pine to optimal nutrient and water resource availability. *Forest Ecology and Management* 192 (3–A), 19.
- Allen, R.G., Smith, M., Pereira, L.S., Perrier, A., 1994. An update for the calculation of reference evapotranspiration. *ICID Bulletin* 43, 35–92.
- Amatya, D.M., Skaggs, R.W., Gregory, J.D., 1995. Comparison of methods for estimating REF-ET. *ASCE Journal of Irrigation and Drainage Engineering* 121 (6), 427–435.
- Amatya, D.M., Skaggs, R.W., Gregory, J.D., 1996. Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina coastal plain. *Journal of Hydrology* 181, 211–232.
- Amatya, D.M., Skaggs, R.W., Cheschie, G.W., Fernandez, G.P., 2000. Solar and net radiation for estimating potential evaporation from three vegetation canopies. Presentation at the 2000 ASAE Annual International Meeting, Paper No: 002135.
- Amatya, D.M., Skaggs, R.W., 2001. Hydrologic modeling of pine plantations on poorly drained soils. *Forest Science* 47, 103–114.
- Amatya, D.M., Skaggs, R.W., Gilliam, J.W., 2006. Hydrology and water quality of a drained loblolly pine plantation in coastal North Carolina. In: Williams, Thomas, (Eds.), *Hydrology and Management of Forested Wetlands: Proceedings of the International Conference*. St. Joseph, MI: American Society of Agricultural and Biological Engineers, pp. 218–230.
- Amatya, D.M., Trettin, C.C., 2007. Annual evapotranspiration of a forested wetland watershed, SC. ASABE Paper No. 07222. St. Joseph, Mich.: ASABE. In: 2007 ASABE Annual International Meeting, 17–20 June. 16 p.
- Amiro, B.D., Barr, A.G., Black, T.A., Iwashita, H., Kljun, N., McCaughey, J.H., Morgenstern, K., Murayama, S., Nesic, Z., Orchansky, A.L., Saigusa, N., 2006a. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology* 136, 237–251.
- Amiro, B.D., Orchansky, A.L., Barr, A.G., Black, T.A., Chambers, S.D., Chapin III, F.S., Goulden, M.L., Litvak, M., Liu, H.P., McCaughey, J.H., McMillan, A., Randerson, J.T., 2006b. The effect of post-fire stand age on the boreal forest energy balance. *Agricultural and Forest Meteorology* 140, 41–50.
- Arain, M.A., Black, T.A., Barr, A.G., Griffis, T.J., Morgenstern, K., Nesic, Z., 2003. Year-round observations of the energy and water vapour fluxes above a boreal black spruce forest. *Hydrological Processes* 17, 3581–3600.
- Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C., Mirin, A., 2007. Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academic Sciences United States America* 104, 6550.
- Betts, A.K., Ball, J.H., 1997. Albedo over the boreal forest. *Journal of Geophysical Research* 102 (D24) 28, 901–909.
- Betts, R.A., 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* 408 (9), 187–190.
- Burba, G.G., McDermitt, D.K., Grelle, A., Anderson, D.J., Xu, L., 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO<sub>2</sub> flux from open-path gas analyzers. *Global Change Biology* 14, 1854–1876.
- Chapin, F.S., Maston, P.A., Mooney, H.A., 2002. *Principles of Terrestrial Ecosystem Ecology*. Springer-Verlag, New York.
- Clark, K.L., Gholz, H.L., Castro, M.S., 2004. Carbon dynamics along a chronosequence of slash pine plantations in North Florida. *Ecological Applications* 14 (4), 1154–1171.
- Currie, D.J., 1991. Energy and large-scale patterns of animal and plant species richness. *The American Naturalist* 137 (1), 27–49.
- DeWalle, D.R., Swistock, B.R., Johnson, T.E., McGuire, K.J., 2000. Potential effects of climate change and urbanization on mean annual streamflow in the United States. *Water Resources Research* 36 (9), 2655–2664.
- Diggs, J.A., 2004. Simulation of nitrogen and hydrology loading of forested fields in Eastern North Carolina using DRAINMOD-N 11. M.S. Thesis, North Carolina State University, Raleigh, NC, 155 p.
- Domec, J.-C., Noormets, A., King, J.S., Sun, G., McNulty, S.G., Gavazzi, M.J., Boggs, J.L., Treasure, E.A., 2009. Decoupling the influence of leaf and root hydraulic conductances on stomatal conductance and its sensitivity to vapor pressure deficit as soil dries in a drained loblolly pine plantation. *Plant, Cell & Environment*, doi:10.1111/j.1365-3040.2009.01981.x.
- Ewers, B.E., Mackay, D.S., Gower, S.T., Ahl, D.E., Burrows, S.N., Samanta, S., 2002. Tree species effects on stand transpiration in Northern Wisconsin. *Water Resources Research* 38 (7), doi:10.1029/2001WR000830.
- Ford, C.R., Hubbard, R.M., Kloepfel, B.D., Vose, J.M., 2007. A comparison of sap flux-based evapotranspiration estimates with catchment-scale water balance. *Agricultural and Forest Meteorology* 145, 176–185.
- Foken, T., 2008. The energy balance closure problem: an overview. *Ecological Applications* 18 (6), 1351–1367.
- Fox, T.R., Jokela, E.J., Allen, H.L., 2004. The evolution of pine plantation silviculture in the Southern United States. In: Rauscher, H.M., Johnson, K. (Eds.), *Southern Forest Science: Past, Present, and Future*. Gen. Tech. Rep. SRS-75, Asheville, NC, U.S. Department of Agriculture, Forest Service, Southern Research Station, (Chapter 8), pp. 63–82.
- Gholz, H.L., Clark, K.L., 2002. Energy exchange across a chronosequence of slash pine forests in Florida. *Agricultural and Forest Meteorology* 112, 87–102.
- Gibbard, S., Caldeira, K., Bala, G., Phillips, T.J., Wickett, M., 2005. Climate effects of global land cover change. *Geographical Research Letters* 32, L23705, doi:10.1029/2005GL024550.
- Grace III, J.M., Skaggs, R.W., Cheschie, G.M., 2006a. Hydrologic and water quality effects of thinning loblolly pine. *Transactions of the American Society of Agricultural and Biological Engineers* 49 (3), 645–654.
- Grace III, M.J., Skaggs, R.W., Cassel, D.K., 2006b. Soil physical changes associated with forest harvesting operations on an organic soil. *Soil Science Society of America Journal* 70, 503–509.
- Hanson, P.J., Amthor, J.S., Wullschlegel, S.D., Wilson, K.B., Grant, R.F., Hartley, A., Hui, D., Hunt Jr., E.R., Johnson, D.W., Kimball, J., King, A.W., Luo, Y., McNulty, S.G., Sun, G., Thornton, P.E., Wang, S., Williams, M., Cushman, R.M., 2003. Carbon and water cycle simulations for an upland oak forest from 1993 to 2000 using 13 stand-level models: inter-model comparisons and evaluations against independent measurements. *Ecological Monographs* 74, 443–489.
- Harder, S.V., Amatya, D.M., Callahan, T.J., Trettin, C.C., Hakkila, J., 2007. Hydrology and water budget for a forested Atlantic coastal plain watershed, South Carolina. *Journal of the American Water Resources Association* 43, 563–575.
- Jackson, R.B., Jobbagy, E.G., Avissar, R., et al., 2005. Trading water for carbon with biological carbon sequestration. *Science* (1944–1947).
- Johnson, K.H., Wear, D.N., Oren, R., Teskey, R.O., Sanchez, F., Will, R.E., Butnor, J., Markewitz, D., Richter, D., Rials, T., Allen, H.L., Seiler, J., Ellsworth, D., Maier, C., Katul, G., Dougherty, P.M., 2001. Carbon sequestration and southern pine forests. *Journal of Forestry* 99 (4), 14–21.
- Juang, J.-Y., Katul, G.G., Siqueira, M.B.S., Stoy, P.C., Novick, K.A., 2007. Separating the effects of albedo from eco-physiological changes on surface temperature along a successional chronosequence in the Southeastern US. *Geophysical Research Letters* 34 (L21408), doi:10.1029/2007GL031296.
- Law, B.E., Falge, E., Gu, L., Baldocchi, D.D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A.J., Falk, M., Fuentes, J.D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I.A., Jarvis, P., Jensen, N.O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw, K.T., Thorgerisson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. *Agricultural and Forest Meteorology* 113, 97–120.
- Leuning, R., 2004. Measurements of trace gas fluxes in the atmosphere using eddy covariance: WPL corrections revisited. In: Lee, X., Massman, W.J., Law, B.E. (Eds.), *Handbook of Micrometeorology. A Guide to Surface Flux Measurement and Analysis*. Kluwer Academic Publishers, Boston, pp. 119–132.
- Liu, Y., Stanturf, J., Lu, H., 2008. Modeling the potential of the Northern China forest shelterbelt in improving hydroclimate conditions. *Journal of the American Water Resources Association* 44 (5), 1176–1192.
- Lu, J., Sun, G., Amatya, D.M., McNulty, S.G., 2003. Modeling actual evapotranspiration from forested watersheds across the Southeastern United States. *Journal of American Water Resources Association* 39, 887–896.
- McCarthy, E.J., Flewelling, J.W., Skaggs, R.W., 1992. Hydrologic Model for Drained Forested Watershed. *ASCE Journal of Irrigation and Drainage Engineering* 118, 1242–1255.
- McNulty, S.G., Vose, J.M., Swank, W.T., Aber, J.D., Federer, C.A., 1994. Regional scale forest ecosystem modeling: database development, model predictions and validation using a geographic information system. *Climate Research* 4, 223–231.
- McNulty, S.G., Vose, J.M., Swank, W.T., 1996. Loblolly pine hydrology and productivity across the Southern United States. *Forest Ecology and Management* 86, 241–251.
- Meiresonne, L., Sampson, D.A., Kowalski, A.S., Janssens, I.A., Nadezhkina, N., Cermak, J., Van Slycken, J., Ceulemans, R., 2003. Water flux estimates from a Belgian Scots pine stand: a comparison of different approaches. *Journal of Hydrology* 270, 230–252.
- Noormets, A., Ewers, B., Sun, G., Mackay, S., Zheng, D., McNulty, S.G., Chen, J., 2006. Water and carbon cycles in heterogeneous landscapes: an ecosystem perspective. In: Chen, J., Saunders, S.C., Brosofske, K.D., Crow, T.R. (Eds.), *Linking Ecology to Landscape Hierarchies*. Nova Publishing, Carbondale, IL, USA, pp. 89–123.
- Noormets, A., McNulty, S.G., DeForest, J.L., Sun, G., Li, Q., Chen, J., 2008. Drought during canopy development has lasting effect on annual carbon balance in a deciduous temperate forest. *New Phytologist* 179, 818–828.
- Noormets, A., McNulty, S.G., Gavazzi, M.J., Sun, G., Domec, J.C., King, J., Chen, J., 2009. Response of carbon fluxes to drought in a coastal plain loblolly pine forest. *Global Change Biology*, doi:10.1111/j.1365-2486.2009.01928.x.
- Pielke, R.A., Adegoke, J., Beltrán-Przekurat, A., Hiemstra, C.A., Lin, J., Nair, U.S., Niyogi, D., Nobis, T.E., 2007. An overview of regional land-use and land-cover impacts on rainfall. 2007. *Tellus B* 59 (3), 587–601.
- Pinker, R.T., Thompson, O.E., Eck, T.F., 1980. The albedo of a tropical evergreen forest. *Quarterly Journal of the Royal Meteorological Society* 106 (449), 551–558.
- Powell, T.L., Starr, G., Clark, K.L., Martin, T.A., Gholz, H.L., 2005. Ecosystem and understory water and energy exchange for a mature, naturally regenerated pine flatwoods forest in North Florida. *Canadian Journal of Forest Research* 35 (7), 1568–1580.
- Powell, T.L., Gholz, H.L., Clark, K.L., Starr, G., Cropper Jr., W.P., Martin, T.A., 2008. Carbon exchange of a mature naturally regenerated pine forest in North Florida. *Global Change Biology*, doi:10.1111/j.1365-2486.2008.01675.x.
- Restrepo, N.C., Arain, M.A., 2005. Energy and water exchanges from a temperate pine plantation forest. *Hydrological Processes* 19, 27–49.
- Schotanus, P., Nieuwstadt, F.T.M., de Bruin, H.A.R., 1983. Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes. *Boundary-Layer Meteorology* 26, 81–93.
- Schultz, R.P., 1997. *Loblolly Pine—The Ecology and Culture of Loblolly Pine (Pinus taeta L.)*. Agricultural Handbook 713. U.S. Department of Agriculture Forest Service, Washington, DC.
- Shuttleworth, W.J., 2008. Evapotranspiration measurement methods. *Southwest Hydrology* 7, 22–23.

- Stoy, P., Katul, G.G., Siqueira, M.B.S., Juang, J.Y., Novick, K.A., McCarthy, H.R., Oishi, A.C., Uebelherr, J.M., Kim, H.-S., Oren, R., 2006. Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US. *Global Change Biology* 12, 2115–2135.
- Sun, G., McNulty, S.G., Amatya, D.M., Skaggs, R.W., Swift, L.W., Shepard, J.P., Riekerk, H., 2002. A comparison of the hydrology of the coastal forested wetlands/pine flatwoods and the mountainous uplands in the southern US. *Journal of Hydrology* 263, 92–104.
- Sun, G., Riedel, M., Jackson, R., Kolka, R., Amatya, D., Shepard, J., 2004. Influences of management of Southern forests on water quantity and quality. In: Rauscher, H.M., Johnsen, K. (Eds.), *Southern Forest Science: Past, Present, and Future*. Gen. Tech. Rep. SRS-75. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, (Chapter 19), pp. 195–234.
- Sun, G., McNulty, S.G., Moore Myers, J.A., Cohen, E.C., 2008a. Impacts of multiple stresses on water demand and supply across the Southeastern United States. *Journal of American Water Resources Association* 44 (6), 1441–1457.
- Sun, G., Noormets, A., Chen, J., McNulty, S.G., 2008b. Evapotranspiration estimates from eddy covariance towers and hydrologic modeling in managed forests in Northern Wisconsin, USA. *Agricultural and Forest Meteorology* 148, 257–267.
- Sun, G., Sun, O.J., Zhou, G., 2009. Water and carbon dynamics in selected ecosystems in China (Editorial). *Agricultural and Forest Meteorology*, doi:10.1016/j.agrformet.2009.06.008.
- Swank, W.T., Douglass, J.E., 1974. Streamflow greatly reduced by converting hardwoods to pine. *Science* 185, 857–859.
- van Dijk, A.I.J.M., Keenan, R.J., 2008. Planted forests and water in perspective. *Forest Ecology and Management* 251, 1–7.
- Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapor transfer. *Quarterly Journal of the Royal Meteorological Society* 106, 85–106.
- Wilczak, J.M., Oncley, S.P., Stage, S.A., 2001. Sonic anemometer tilt correction algorithms. *Boundary-Layer Meteorology* 99, 127–150.
- Wilson, K.B., Baldocchi, D.D., 2000. Seasonal and inter-annual variability of energy fluxes over a broadleaved temperate deciduous forest in North America. *Agricultural and Forest Meteorology* 100, 1–18.
- Wilson, K.B., Hanson, P.J., Mulholland, P.J., Baldocchi, D.D., Wullschleger, S.D., 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agricultural and Forest Meteorology* 106, 153–168.
- Wilson, K.B., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. *Agricultural and Forest Meteorology* 113, 223–243.
- Wullschleger, S.D., Meinzer, F.C., Vertessy, R.A., 1998. A review of whole-plant water use studies in trees. *Tree Physiology* 18, 499–512.
- Zhou, G., Sun, G., Wang, X., Zhou, C., McNulty, S.G., Vose, J.M., Amatya, D.M., 2008. Estimating forest ecosystem evapotranspiration at multiple temporal scales with a dimension analysis approach. *Journal of American Water Resources Association* 44 (1), 208–221.