CARBON AND WATER FLUXES IN A DRAINED COASTAL CLEARCUT AND A PINE PLANTATION IN EASTERN NORTH CAROLINA

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ABSTRACT

The effects of clear-cutting and cultivating for timber on ecosystem carbon and water fluxes were evaluated by comparative measurements of two drained coastal wetland systems in the North Carolina coastal plain. Measurements were conducted from January through September, 2005 in a recent clearcut (CC) of native hardwoods and a loblolly pine (*Pinus taeda*) plantation (LP) that represent a chronosequence after replacing native coastal hardwood species with fast-growing commercial species. Each of the study sites is an independent ditched block representing a complete watershed and has long-term hydrological record. Results suggest that evapotranspiration (ET) rates for both stands were similar, except during the early summer (April to June) when ET was significantly ($p < 0.01$) higher in LP. Despite the fact that the plant photosynthetic contribution in the CC was a small fraction of the LP; there was only a 20% difference in ET rates between the stands. Moreover, we observed a significant ($p<0.01$) negative relationship between ET and carbon flux (Fc) in LP, but a weak relationship in the CC stand. The LP was storing carbon whereas the CC was a source of carbon on a daily basis. We reason that photosynthesis is the dominant process in the LP stand whereas decomposition is the dominate process in the CC stand, which can explain observed ET and Fc relationship between the two stands. The study will continue in 2006 and 2007 to contrast water and carbon balances at multiple temporal scales between the two stands.

KEYWORDS: clearcut, carbon flux, eddy-covariance, evapotranspiration, latent and sensible heat, and loblolly pine plantation

INTRODUCTION

Large areas of forested wetlands have been drained for over 300 years in the costal plains of North Carolina where forestry practices were responsible for over half of the total wetland alteration and loss (Richardson, 1991; Campbell and Hughes, 1991). Ditching is an essential silvicultural practice to increase soil aeration conditions for seedling establishment and forest machine operations in a wet soil environment (Campbell and Hughes, 1991). Intensive forest management practices involving drainage, fertilization, and agrichemical applications have greatly increased forest productivity in this region. For example, a mature loblolly pine (*Pinus taeda*) stands may have net primary productivity in excess of 2500 g m^{-2} y^{-1}, which is more than twice that of a non-managed stand (Sun et al., 2000a; Albaugh et al., 1998). Environmental concerns of this practice have been mostly focused on how drainage affect onsite and offsite flow and nutrient loading to adjacent estuaries (Amatya et al., 1998; Amatya and Skaggs, 2001; Chescheir et al., 2003). In the past three decades, hydrologic and water quality effects of forest management in the coastal regions have been well studied with field investigation and simulation models (Amatya et al., 1998; Amatya and Skaggs, 2001; Chescheir et al., 2003). It is now known that forest practices may not necessarily alter the flow regimes and water quality. Moreover, forestry has the least impact on water quality when comparing to other land uses (e.g. agriculture).

Less is known about how forest management practices affect soil quality including the long-term storage of soil organic matter (SOM) and nutrients (Trettin and Jurgensen, 2003). Reforestation has been widely regarded as one way to slow down global warming because forests can sequester large amount of carbon dioxide (CO_2; Fan et al., 1998). However, little is known about the overall role of plantations in the coastal plain geographic regions in absorbing CO_2. Ecosystem-scale carbon flux studies using the eddy covariance method suggested that southern pine plantations are strong carbon sinks (Clark et al., 1999; 2004), yet those lands with high groundwater tables could be significant sources of greenhouse gases under various climatic (e.g., drought) and management conditions (e.g., harvesting; Castro et al., 2000; Sun et al.-this volume). Other studies based on biogeochemical computer models (e.g., Wetland-DNDC) suggested that hydrology was a major control of net ecosystem exchange (NEE) in wetland ecosystems (Li et al., 2003; Sun et al., 2006-this volume). Clearly, water flux was closely coupled with the carbon (C) flux in wet environment. Compared to upland ecosystems where water is often a limiting 'stress' factor, the shallow groundwater table is a 'switch' of the anaerobic-aerobic biogeochemical processes in wetland ecosystems. The groundwater table level reflects the balance between precipitation input and evapotranspiration (ET) output in a wetland ecosystem. Obviously, quantifying the ET process at multiple scales is essential to understand the ground water table fluctuation and its control on the biogeochemical processes including carbon and nutrient cycles.

Additionally, it is well known that ET is closely related to plant photosynthesis at the stomata level Therefore, it is likely that ET is related to forest productivity at the ecosystem and regional scales. ET is the second largest component of the water balance of forested wetland ecosystem. On average, more than 65% of total precipitation returns to the atmosphere in drained forested lands on the coastal plains of North Carolina (Amatya and Skaggs, 2001; Amatya et al.(a), this volume). A number of authors have documented the effects of forest management on watershed hydrology through the influence of the ET rates controlled by alterations of forest biomass and species compositions, and the energy balances at multiple temporal scales. The hydrologic responses to disturbances were found to vary greatly across the physiographic gradient due to differences in climate and land topography. Harvesting during a dry spring on the pine floodplains in Florida, for example, caused a large rise in the water table presumably due to reductions in forest ET rate (Sun et al., 2000; Bliss and Comerford, 2001). But this rise became non-significant when comparing to the non-cut site in the second growing season. It was suspected that ecosystem ET recovered to the pre-harvesting level rather quickly in wetland ecosystems (Sun et al., 2000b; Bliss and Comerford, 2001). Amatya et al. (b; this volume) also observed the greater rise in water table on the harvested watershed during the drier seasons than the wet periods. Unfortunately, direct measurements of ET for harvested and unharvested sites simultaneously have been rare. Past hydrologic studies on the coastal plains estimated ET either by mathematical models or by the watershed water balance approach (Amatya et al., 1996; Amatya and Skaggs, 2001; Amatya et al. (a; this volume).

The goal of this study was to assess the causal relationships between management and environmental controls of biosphere-atmosphere exchange of carbon and water. Specifically, the objectives were to report: 1) overall experimental design and installation of the eddy flux

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covariance systems for a 12-year old loblolly pine plantation and a recent clearcut stands, and 2) preliminary results on ecosystem carbon, energy, and water fluxes on hourly and seasonal scales.

MATERIALS AND METHODS

Study Site

The study sites were located at the Parker Tract Watershed in Washington County in the North Carolina (N 35° 48' by W 76°39') Coastal Plain (Figure 1). The Parker Tract encompasses 4000 ha of forested land that contains various chronosequences of loblolly pine plantations and native hardwoods managed by the Weyerhaeuser Company and drains into Albemarle Sound, NC. The topography is flat and drained with ditches about 90 to 100 m apart. These organic soils are classified as a Loamy, mixed, dysic, thermic Terric Haplosaprists. Mean annual temperature is 15.5°C, and mean annual precipitation is 1295 mm. The growing season is typically 195 days.

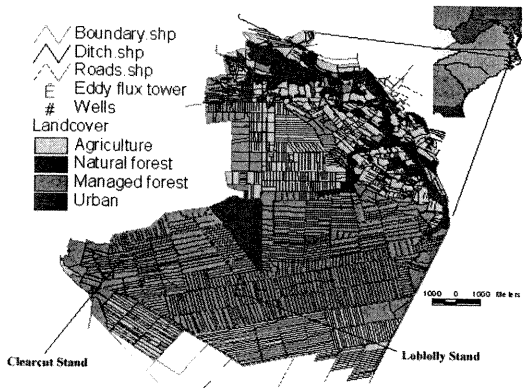

Figure 1. Location map of the Parker Tract in Washington County, NC

Our site consists of a recent clearcut (CC) of a mature native hardwood (75 yrs old) stand that was bedded and planted with loblolly pine seedling and a fifth rotation young loblolly pine plantation (LP). The CC is 70 ha, whereas the LP is 120 ha in size. At the CC site, we arranged 13 plots in a grid formation that are 175-m apart. The 13 plots from the LP were arranged 350-m apart.

Table 1. Study site characterization for a clearcut and loblolly plantation of costal North Carolina. Mean ± SE.

Stand Characterization	Recent Clearcut	Young Loblolly
Stand Establishment	2004	1992
Stand Height (m)	0.23± (0.06)	10± (1)
Basal Area (m^2 ha^{-1})	--	24.9 ± (1.5)
Leaf Area Index (m^2 m^{-2})	0	3.0 ± (0.1)
Litter Fall (g m^{-2})	--	163 ± (32)
Forest Floor Biomass (g m^{-2})	23± (8)	860 ± (88)

The center plot of the two stands is 4-km apart. Each circular plot was 154 m^2 and used in stand description (Table 1). Leaf area index (LAI) was measured at the center of each plot with a LAI-2000 Plant Canopy Analyzer (LI-Cor, Lincoln, NE), litter fall was measured in 5 of the 13 plots using three litter traps (0.33 m^2) installed 1-m above the ground in each plot, and forest floor biomass was collected with 0.25 m^2 sampling frames. We did not measure litter fall in the recent clearcut.

While the CC stand was planted with loblolly pine seedlings, this area is covered with emerging wetland plants and shrubs that reach a maximum height of 2.5 m. The weedy groundcover is dense and primarily composed of *Eupatorium capillofolium* (dog fennel) and *Smilax rotundifolia* (greenbrier). The stand also contains several large slash piles of course woody debris (CWD). The LP stand has no groundcover or understory, except *Acer rubrum* (red maple) re-growth along the ditches.

Eddy Covariance & Micrometerological Measurements

Net ecosystem exchange has been measured continuously at the two study sites since November 2004 using the eddy-covariance method. The towers were positioned in the center of each stand, allowing a homogeneous fetch of at least 50 sensor heights. The eddy-covariance system consists of a LI-7500 open-path infrared gas analyzer (IRGA; Li-Cor, Lincoln, NE), a CSAT3 3-dimensional sonic anemometer (Campbell Scientific, Logan, UT), and a CR5000 data logger (Campbell Scientific, Logan, UT). Air temperature (T_a) and relative humidity (RH) were measured with HMP45AC humidity and temperature probe (Vaisala, Finland), net radiation (R_n) with CNR-1 radiometer (Kipp & Zonen, NJ, USA) and precipitation with TE525 tipping bucket rain gauge (Texas Electronics, Dallas, TX).

Soil Respiration

Soil respiration (R_s) was measured with EGM-4 (PP Systems, Hertfordshire, UK) portable infra-red gas analyzers with matching soil respiration chambers (SRC-1). R_{soil} was measured 8 times from March to September, 2005. In all, we measured R_s 368 times distributed over 8 plots (4 in CC and 4 in LP stands). To minimize the influence of precipitation on R_s, respiration was measured at least 48 hours after a major rain event (wetting of soil). During measurements, soil temperature (T_{soil}) was recorded at a depth of 5 cm within 10 cm of the collar center. Moisture content (MC) was measured within 30 cm of the collar center to a depth of 10 cm using a time domain reflectometer (TDR100; Campbell Scientific, Inc., Logan, UT). Within a sampling time and plot, readings of R_{soil}, T_{soil} and MC were averaged across the 6 collars.

Data Analysis

The 30-minute mean fluxes of latent heat (LE) and sensible heat (HS) were computed as the covariance of vertical wind speed and the concentration of water vapor and temperature, respectively. Spikes greater than six standard deviations were removed from the raw data series (10 Hz), temperature was corrected for humidity and pressure, and wind coordinates were rotated according to planar fit method (Wilczak et al., 2001). The fluxes were corrected for fluctuations in air density using the Webb-Pearman-Leuning expression (Webb et al., 1980; Paw et al., 2000; Massman & Lee, 2002). Vapor pressure deficit (VPD) was calculated as the difference of saturated vapor pressure and actual vapor pressure (e_a). Actual vapor pressure was estimated from measured vapor density (g m^{-3}). Evapotranspiration (ET) at a half-hour scale was converted from LE (W m^{-2}) to (mm 0.5 h^{-1}) by dividing LE with latent heat of vaporization.

Values were then summed on a daily basis to yield daily ET mm day^{-1}. Data used for analysis were screened for out-of-range data (-10 to 500 W m^{-2} for LE, -15 to 50 °C for Ta and -300 to 700 W m^{-2} for HS). A repeated measure ANOVA was preformed to determine differences in variables between the two forested stands on hourly or monthly timescales. Differences between means were preformed using Tukey's post-hoc test. Significance for all statistical analyses was accepted at $\alpha = 0.05$.

The dependence of R_s on T_{soil} was estimated with a first-order exponential model:

$$R_s = R_{ref} * e^{(\ln(Q_{10})/10)*T_{soil}}$$

where R_s is measured soil respiration rate, R_{ref} is base soil respiration, normalized to 0°C, Q_{10} is temperature sensitivity of R_s (change in R_s per increase in T_s by 10°C), and T_s is the measured soil temperature. The R_{ref} and Q_{10} were estimated with non-linear least squares regression.

Results and Discussion

Climate

We observed that T_a, RH, and VPD changed the most between March and April for both of the stands (Figure 2). During this time period, monthly means of T_a exhibited the greatest change (i.e., a 33% increase), whereas monthly mean RH was the lowest and VPD doubled between these months (Figure 2). This time period was characterized by the start of the growing season with visible signs of plant growth. After the increase in spring, T_a and RH gradually increased with time, whereas VPD remained fairly consistent throughout the growing season. T_a was slightly higher in CC than in the LP stand. RH was significantly higher for most of the growing season and VPD was significantly ($P < 0.01$) higher in the CC in July than in the LP stand. However, this trend was reversed in September.

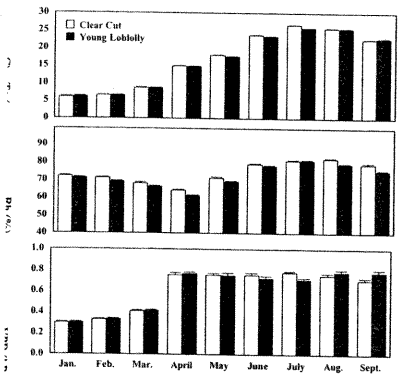

Figure 2. Monthly mean of air temperature (Ta), Relative humidity (RH), and vapor pressure deficit (VPD) for a recent clearcut and young loblolly pine plantation in costal North Carolina.

Energy Balance

Figure 2 shows that monthly means of Rn, LE, HS and ground heat (G) were similar between stands. While Rn steadily increased from January to August and started to decline in September, LE for LP started to decline in August whereas CC declined in September (Figure 3). HS in the LP stand peaked in April; HS in the CC stand reached its monthly mean maximum in May. G was the highest in June for both stands and the lowest in January.

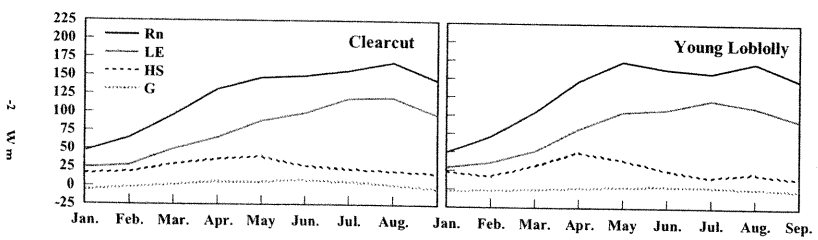

Figure 3. Monthly means of net radiation (Rn), latent heat (LE), sensible heat (HS), and ground heat (G) for a recent clearcut and young loblolly pine plantation in costal North Carolina.

Both of the stands displayed similar patterns of hourly means of R_n, LE, and HS (Figure 4). The patterns observed were typically where R_n, LE, and HS were highest at noon and the lowest at midnight. While the amount of R_n and LE are similar between stands, the LP stand generally had higher HS than the CC stand.

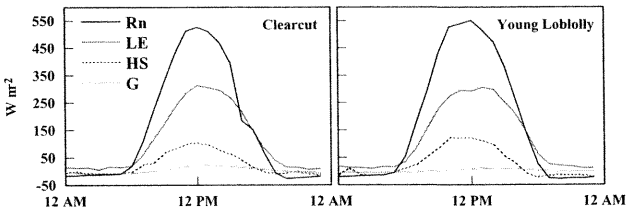

Figure 4. Hourly means of net radiation (R_n), latent heat (LE), sensible heat (HS), and ground heat (G) for a recent clearcut (CC) and young loblolly pine (LP) plantation in coastal North Carolina. Hourly means are compiled from May to September.

We observed that monthly means of R_n were similar ($P > 0.05$) for both sites and within months. Latent heat was similar for all months between sites, except in April where LE was significantly ($P < 0.01$) higher (i.e., 24%) on the LP than on the CC stand. HS was generally higher on the LP stand, but we observed no significant difference in monthly means. G was significantly higher on the clearcut stand than on the LP stand from April to August and was typically lower than the LP stand in the winter months. In September, heat from the ground was transferring upwards (i.e. negative G) in the CC stand, whereas in the LP stand heat was still transferring downwards as shown by a positive G value.

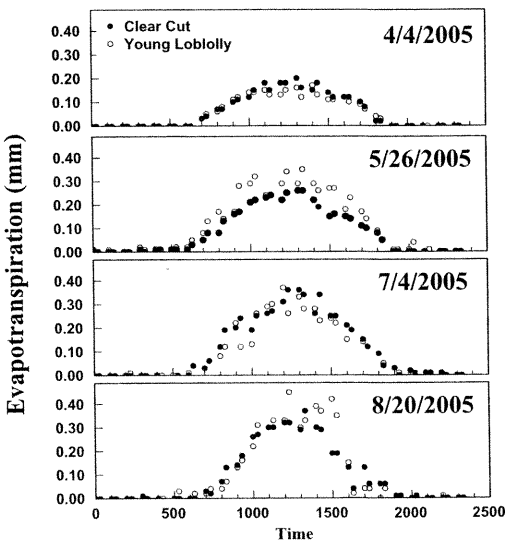

Figure 5. Daily thirty-minute means of evapotranspiration (ET mm/half hour) for four selective date that represent a typical sunny day for a recent clearcut (CC) and young loblolly pine (LP) plantation in coastal North Carolina.

Water Balance

Daily Variation of Evapotranspiration

The daily thirty-minute means of ET for four typical sunny days throughout the growing season suggest ET rates on both stands had a similar pattern on a daily basis (Figure 5). ET was higher for the young loblolly pine stand in early and late summer (sample dates May 26th and August 20th), whereas in mid-summer (July 4th) and spring (April 4th) the differences between sites were minimal. Overall, the sites differed little in ET throughout the study period, although LP had consistently higher ET in April and June (Table 2).

Table 2. Monthly mean precipitation (P; mm day^{-1}), mean evapotranspiration (ET; mm day^{-1}), and the ET/P ratio for a recent clearcut and young loblolly pine plantation in coastal North Carolina.

		Recent Clearcut		Young Loblolly	
Month	P	ET	ET/P	ET	ET/P
Jan.	1.0	0.8	0.8	1.0	1.0
Feb.	1.3	0.9	0.7	1.2	0.9
March	2.0	1.7	0.8	1.7	0.8
April	2.3	2.3	1.0	2.8	1.2
May	1.1	2.9	2.7	3.6	3.3
June	3.5	3.3	0.9	3.7	1.1
July	3.7	4.2	1.1	4.1	1.1
August	2.6	4.1	1.6	3.8	1.5
Sept.	0.2	3.2	14.1	3.2	14.1

Evapotranspiration/Precipitation Ratio

ET was significantly higher on the LP stand than on the CC from April to June (Table 2). Before April ET was slightly higher ($p > 0.05$), but after June ET was slightly lower on the LP stand than on the CC. P was similar between the stands and because of their close proximity (4 km) we averaged the P across the two stands.

The high ET/P ratio indicates that water was most limiting in May and September. In May, the CC stand released 2.7 times more water through ET than it received in precipitation, whereas the LP released 3.3 times as much. As expected, the LP would have a greater demand for water than CC from a higher photosynthetic capacity. It was likely the extremely high ET/P ratio in September is misleading because the sensors were removed for 4 days in September due to high winds from Hurricane Ophelia. During this time, a large amount of rain fell on this site; however, we had no record of the amount.

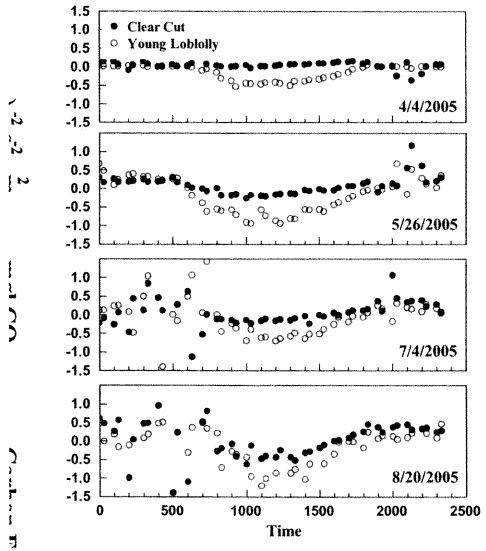

Figure 6. Daily 30 min means of C efflux (μmol CO_2 m^{-2} s^{-1}) for four dates that represent a typical sunny day for a clearcut (CC) and loblolly pine (LP) plantation in coastal North Carolina.

Carbon Fluxes and Water Use

Daily Variation of Carbon Efflux

The LP stand absorbed more CO_2 than the CC (Figure 6). These results were consistent throughout the growing season and expected because the LP had greater standing biomass (Table 1). During the growing season the LP stand typically stored more C than it released into the atmosphere on a daily basis, whereas the CC stand stored minimal amounts of C during the day, with nighttime respiration losses exceeding daytime gains.

We attributed the large C losses in the CC stand to low LAI and low photosynthetic capacity (Table 1). In addition, we hypothesized that C efflux from decomposition was higher in the CC than in the LP stand due to greater fresh litter input from the clearcut. For example, we observed from April to September ($n = 16$) R_s rates averaging 6.8 ± 1.5 (μmol CO_2 m^{-2} s^{-1}; ± SE), which was double than the 3.1 ± 0.5 (μmol CO_2 m^{-2} s^{-1}) measured in the LP stand. The higher soil C efflux could be caused by CC soil being typically 2°C warmer than that on the LP (18.7 vs. 16.6 °C), which was likely from more light penetrating the ground from an open canopy and minimal groundcover (Table 1). The warmer soils, however, did not cause drier soils because soil MC was similar ($p > 0.10$) between stands, which were 53% ± 15% (mean±SE) MC from April to September. Interestingly, the temperature sensitivity (Q_{10} value) of R_{soil} between CC and LP was similar at 2.43, which suggested these soils functioned in a similar manner (Zogg et al., 1997).

Evapotranspiration and Carbon Flux

We observed a significant negative relationship between ET and C flux for LP stands on our four selective dates (Table 3). In other words, as ET increased, the LP stand stored more C on a daily basis. The ecosystem water use efficiency (i.e., slope of the regression) indicated more water is needed in the LP than the CC to assimilate the same amount of C. ET also correlated well with the C flux on the three other sample days (Table 3). In CC, however, the relationship between ET and Fc was weak (Table 3). The difference between sites could be partially explained by the strong

correlation between ET and photosynthesis (Li et al., 2003; Sun et al., 2006-this volume). C flux in the LP stand was more dominated by photosynthesis when compared to the CC stand where decomposition plays a larger role in C flux. This was evident by the fact the CC is a recently disturbed stand where moist, organic soils were warmed due to the open canopy. While ET is a good global estimator of decomposition (Swift et al., 1979), this relationship appears fairly weak on small temporal and spatial scales. As loblolly aboveground biomass increases in the CC stands, we can expect the relationship between ET and C efflux to become stronger as assimilation/productivity increases.

Table 3. The relationship between ET and C efflux for four selective dates for a recent clearcut (CC) and young loblolly pine plantation (LP) in costal North Carolina.

	Clearcut			Young Loblolly		
Date	Slope	r^2	p-value	Slope	r^2	p-value
Apr-05	0.21	0.02	0.35	-3.09	0.92	<0.01
May-05	-1.88	0.49	<0.01	-3.50	0.83	<0.01
Jul-05	-0.58	0.02	0.28	-2.16	0.20	<0.01
Aug-05	-2.82	0.22	<0.01	-3.25	0.68	<0.01

CONCLUSIONS

The eddy covariance method provided a new approach to examine how ecosystem ET changed with time under different stages of the loblolly pine regeneration. Our study represented the few cases where ET was measured directly at fine temporal scale. The results from this study suggested that ET between a recent clearcut and young loblolly pine plantation were only different early in the growing season (i.e. April to June). Despite the fact the clearcut site has a small tree biomass; we did not observe a difference in ET between the two stands that reflects this difference. The similarity of total ecosystem ET between the two watersheds suggests ET and hydrology at the clear-cut stand recover to pre-harvesting conditions rather quickly in wetlands. However, the C fluxes between these two stands were vastly different. The LP stand, acting as a sink, stores C on a daily basis whereas the CC is a source of C. This was apparent by the R_{soil} rates in the CC that were around twice as high as the LP stand, probably due to the recent disturbance, increased substrate and warmer soil. Therefore, the land conversion from native hardwoods to loblolly pine plantation will likely will reduce soil organic matter, however, it remains unclear how much and how long the CC will lose soil C. Can the high R_{soil} rates in the CC be sustained or is this just a brief response to land conversion?

We plan to continue monitoring the carbon and water fluxes through 2006. A treatment (thinning and fertilization) was planned in 2007 for the 13-year old loblolly pine stand should provide us with an opportunity to study how change of forest nutrition and partial biomass removal affect the water and carbon balances.

Acknowledgements

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