ABSTRACT

ZIETLOW, DAVID ROBERT GIBBON. Energy and Water Balance of Wetland Use Change in the Lower North Carolina Coastal Plain. (Under the direction of Drs. Asko Noormets and John King).

The conversion of native ecosystems to managed ones changes many of their structural and functional properties that can influence environmental conditions across a broader landscape. For example, the cultivation of commercial timber plantations in the coastal plain of SE-US, that were previously occupied by forested wetlands, alters the hydrology, species composition and surface reflectance that could affect energy partitioning at the ecosystem scale, and influence atmospheric properties more broadly. The current study used the eddy covariance method to examine energy partitioning and water cycles across a gradient of Land Use Change (LUC) from a naturally forested wetland to a ditched and drained, intensively managed forestry plantation in the lower North Carolina (N.C.) Coastal Plain. Nineteen site years of data were measured over an 8 year (2005-2012) period across a chronosequence of 3 ecosystems representing a naturally forested wetland stage (NS), a ditched and drained early rotation Loblolly (3–10 year old trees) plantation transition stage (TS), and a ditched and drained mid-late rotation Loblolly (15–22 year old trees, 4th rotation) plantation stage (PS). The effect of the LUC on energy fluxes and their partitioning was partly confounded by interannual variability at individual sites, as the 8-year measurement period included the thinning of the PS stand and a 2.5 year drought that affected the TS more than the PS. However, the LUC gradient sampled affected all energy fluxes, energy partitioning and energy balance closure (EBC), with the greatest absolute effect and interannual variation in the flux of latent energy (LE). While the underlying change in the LUC gradient was altered hydrology (through intensive draining), the temporal dynamics of the post-disturbance recovery was attributed to changes in canopy structure and canopy reflectance. The recovery dynamics of the energy fluxes appeared to consist of two phases – the first phase of 7–8 years was associated with the clearing of land, and the establishment of the pine plantation, when net radiation (Rn), sensible heat (Hs), and LE were at a minimum, and the ground heat flux (G) was at maximum across the study years. Rn, Hs and G appeared to stabilize by the end of the first phase, but LE continued to increase. The second phase of 8–15 years was associated with canopy closure when LE maximized and then decreased to the more stable values of the PS. The NS and PS stands had slightly different Rn, Hs and LE, and given the hydrologic and structural differences, the ‘recovery’ following the LUC should be viewed only as time required for the stabilization of the measured fluxes, and not a recovery to the pre-LUC conditions. Results from this study indicate that LUC in the Lower Coastal Plain affects both short and long term energy and water cycles, drought tolerance, and

potential feedbacks to regional climates that should be considered in future land management decisions.

Energy and Water Balance of Wetland Use Change in the Lower North Carolina Coastal Plain

by
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DEDICATION

This is dedicated to the quest for understanding how the massive human population may co-exist on this planet with natural environments and wild things, and to the concept that this is the best use of the incredible talent and resources that drive this quest.

BIOGRAPHY

The author is from the mountains of North Carolina. He received a BA in physics from Bard College in New York. He has accepted a position at the Coweeta Hydrologic Laboratory in Franklin, NC.

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1. Introduction

Wetlands are a unique and important ecosystem type in our landscape providing both ecological and socioeconomic services (Messina and Connor, 1998). Wetlands are beneficial for water quality (Chescheir et al. 2003), carbon storage (Trettin and Jurgensen, 2003), buffering against storm surges, and are predicted to play an important role during times of changing climate (Gedney et al., 2004). Wetlands also provide vital habitat for both species endemic to wetlands such as the Venus flytrap (*Dionaea muscipula)*, and other biota such as the Red Wolf (*Canis rufus*) and Cougar (*Puma concolor*), which only survive in modern eastern USA within the seclusion of wetlands. In North Carolina (N.C.), 70% of rare and endangered flora and fauna are dependent on wetlands (Fretwell et al., 1996).

Historically, many of the services provided by wetlands were not well recognized, and their value was interpreted primarily based on their agricultural potential. Settlers, commercial interests, and governments agreed that wetlands should be drained and reclaimed for other purposes (Dahl and Allord, 1996). In the conterminous United States it is estimated that over half of the 221 million acres of wetlands that existed in the 1700s have been drained since the 1780s (Dahl, 1990). North Carolina was a location of early European colonization, and has had pressure on its wetlands since the 1600s (Dahl and Allord, 1996). North Carolina is home to two of the 11 major wetland areas in the United States, the Great Dismal Swamp and the Albemarle Pamlico Peninsula (Dahl, T.E. 1991 unpublished data, US Fish and Wildlife Service), and has had a significant extent of land use change in the past few centuries. Large scale efforts involving construction of canals beginning in the 1780s have resulted in 42% of the original 11 million acres of wetlands in North Carolina being drained by the mid-1980s (Dahl, 1990). Washington County is located in North Carolina's Coastal Plain where 95% of the state's wetlands are found, and is an example of these drainage efforts. The county, which was previously 85% wetlands, has had two thirds of its original 186,000 acres of wetlands drained (Dahl and Allord, 1996). While the decisions to alter these lands have produced specific benefits to agriculture ,forestry and settlement, the resulting repercussions of the extensive land use change (LUC) were not considered, or understood.

The obvious disadvantages of draining wetlands have become acknowledged, and have caused a reversal of public policy beginning in the 1970s. More complex aspects, including biogeochemical cycling and ecosystem services, are yet to be fully understood (Dahl and Allord 1996). We are still in the process of understanding the significance of how LUC affects the water cycle (Vörösmarty and Sahagian, 2000),the energy balance (Schneider and Eugster, 2007), and how mobilization of the nutrients in the organic soil also leads to the mobilization of carbon (Trettin and Jurgensen, 2003, Gedney et al., 2004). Exaggerated by the extensive increase in human population during the past few centuries, the consequences of this LUC have become of great concern due to their compounding influence on Earth's climate and sustainability of natural resources and ecosystem services (Vörösmarty and Sahagian, 2000).

Energy is the driver for all ecosystem processes and investigations of the surface energy balance can reveal important impacts of LUC. Quantifying the energy balance can indicate the role of a particular land use conversion on water cycles, the local microclimate, and potentially regional circulation patterns affecting climate. Until the emergence of wide-spread use of eddy covariance technology and the ability to measure vertical movement of water vapor, evapotranspiration (ET) remained the most elusive component of the water balance, and was estimated as the residual between precipitation and streamflow (Sun et al., 2000, Amatya and Trettin, 2007, Harder et al., 2007, Rao et al., 2011). It has only been in the past 20 years that instantaneous measurements of ET have become possible, allowing a renewed look at the partitioning of energy in ecosystems. Studies show that ET accounts for about 50–90% of incident precipitation in the SE US (Sun et al., 2002, Gholtz and Clark, 2002, Chesheir et al., 2008).

Previous studies have modeled effects on the hydrologic cycle from the LUC of forest to agriculture (Kim et al., 2013, Mao and Cherkauer, 2010, Mirsha et al., 2010), evergreen forest to deciduous forest and grassland to agriculture (Mao and Cherkauer, 2010). Other studies have modeled effects on the energy balance from the LUC of forest to agriculture (Schneider and Eugster, 2007, Mao and Cherkauer, 2010). The effects on the energy balance of LUC from evergreen forest to deciduous forest have also been measured (Stoy et al., 2006); but, there is little information on the effects of draining wetlands (Schneider and Eugster, 2007), and no studies that measure or model changes to the energy balance from the LUC of natural forested wetlands to drained forestry plantations. This study fills an important void in our understanding of the effects of a historically common LUC. Because most flux of energy and water (ET) occurs during the growing season, and differences caused by LUC have been shown to be highest during this period (Schneider and Eugster, 2007, Mishra et al., 2010), this study will concentrate on results from the growing season. Results from this study indicate how LUC from a naturally forested wetland to an intensively managed pine plantation affects the energy balance, ET and the water cycle during the growing season.

This study utilized the eddy covariance method, and developed a quality assurance protocol for selecting accurate energy flux data to evaluate the magnitude and partitioning of energy and water fluxes and their controls at different stages of LUC in the Lower N.C. Coastal Plain. I investigated how the process of converting a naturally forested wetland to a ditched and drained, intensively managed forestry plantation affects (i) the partitioning of energy at the ecosystem level, (ii) evapotranspiration, and (iii) energy balance closure.

2. Background on the Energy Balance

Energy from the sun is the driver for almost all ecosystem functions. How this solar energy is absorbed and re-emitted by different land covers can be examined through the surface energy balance (Figure 1):

$$Rn - G = LE + Hs + S + B \qquad (1)$$

where Rn is net radiation, G is the heat flux into the ground, LE is the latent heat of evaporated water, Hs is the sensible heat, S is stored heat, and B is the biochemical energy used by living organisms. The portion of the sun's energy which remains after reflectance and is absorbed by the planet is the Rn. The portion of Rn that is not transferred into the ground is the available energy (A_E=Rn-G). Most of the A_E is re-emitted back into the atmosphere in the form of the turbulent fluxes (T_E) of LE and Hs (T_E=LE+Hs). A small fraction of the available energy is stored (S) in the mass of the land cover between the elevations of the ground heat sensor and the turbulent flux sensors above the canopy. A tiny fraction of the available energy is metabolized into biochemical energy (B) through photosynthesis and other biological reactions. Storage and biochemical energies are difficult to quantify, yet assumed to be small in magnitude and are typically omitted from energy balance calculators. With common instruments it is possible to measure the four primary fluxes of the energy balance (Figure 1) which are equated by

$$Rn - G = LE + Hs \qquad (2)$$

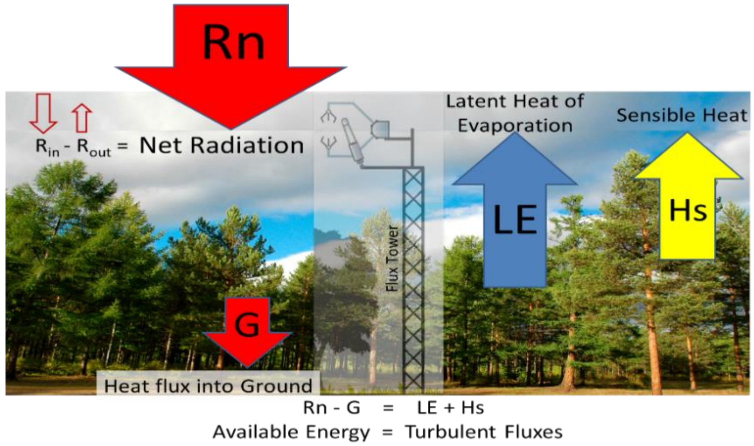


Figure 1. The four major energy fluxes at the ecosystem scale. The area of the solid arrows is proportional to the magnitude of the flux. The vertical locations of the arrow points, relative to the forest canopy, represent the approximate elevation of the sensors.

The common units for these fluxes are Watts per square meter (W/m^2). Measurements showing the turbulent fluxes (LE + Hs) to be consistently less than the available energy (Rn – G) became apparent in the 1980s (Foken and Oncley, 1995). The residual of this measurement imbalance, defined by

$$R_{EB}=Rn-G-LE-Hs \qquad (3)$$

(Stoy et al., 2013, Foken, 2008) is often on the order of 20% of the available energy (Leuning et al., 1982, Foken et al., 1997, Mauder et al., 2006). Energy Balance Closure (EBC) is a measure of the degree to which the turbulent fluxes add up to the available energy. EBC can be examined through the residual, or quantified with the Energy Balance Ratio (EBR) (Wilson et al., 2002), which cumulatively sums the fluxes over specified time periods.

$$EBR = \frac{\sum(LE+Hs)}{\sum(Rn-G)} \qquad (4)$$

EBR is a unitless parameter, and has also been referred to as C_{EB} (Stoy et al., 2013) or EBC (Foken et al., 2009). This study will use the EBR approach defined by Wilson et al. (2002) when examining closure at the 30 minute time scale. The most prevalent method of quantifying EBC, which was used throughout this study, is the slope of an Ordinary Least Squares (OLS) linear regression analysis (Figure 2) of the turbulent fluxes (LE +Hs) vs. the available energy (Rn – G) (Sun et al., 2010). A slope equal to one represents full closure; however, it is usually less when calculated with experimental data (Wilson et al., 2002).

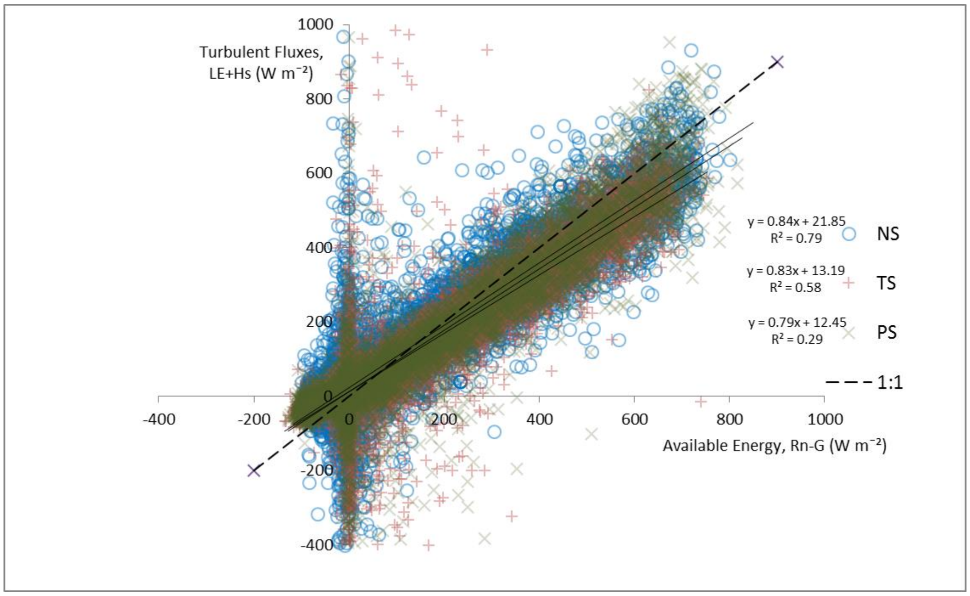


Figure 2. EBC calculated from an OLS linear regression analysis. Unfiltered 2009 data.

The lack of closure in the ecosystem scale energy balance measured with the eddy covariance method has been attributed to a range of factors including footprint mismatch of the sensors (Foken, 2008), thermal advection, time lags associated with large eddies, possible underestimation of turbulent fluxes, energy storage in vegetation and energy used in metabolic processes. Energy stored in the ecosystem may contribute to the imbalance, especially in ecosystems with standing water (Barr et al., 2013). Metabolic fluxes are generally considered negligible (<2% of Rn) and inconsequential given other measurement uncertainties (Hendricks Franssen et al., 2010). Energy storage in the aboveground biomass and partitioning to metabolic processes were not measured in the current study and have been omitted from the analysis.

Developing objective criteria to evaluate the quality of eddy covariance data is part of a growing body of scientific research which has been more focused on carbon fluxes and merits further investigation into energy fluxes. Because of the significance of the energy balance, its contribution to the water cycle, and its role as a quality checkpoint of carbon fluxes, a better understanding of the conditions which produce quality data is needed. To minimize the uncertainties associated with the eddy covariance method, I developed a quality assurance protocol to select quality energy flux data based on the EBC, which has been used as a measure of the accuracy of turbulent flux estimates (Aubinet et al., 2000, Baldocchi et al., 2000, Foken, 2004). Selecting and using quality data will increase the accuracy of energy flux comparisons between the sites and help specify the effects of LUC on the surface energy balance in the N.C. Coastal Plain.

3. Methods

3.1. Site configuration using space for time substitution

Three Ameriflux research sites were used to represent different historic stages of LUC in the lower N.C. Coastal Plain, the area that extends from the Atlantic ocean west to the Goldsboro area. The three sites characterize stages of LUC that may occur at a single site over multiple decades with the naturally forested wetland stage representing the "baseline conditions" of a wetland in the Lower Coastal Plain (Figure 3). A natural stage (NS), a transition stage (TS), and an established plantation stage (PS) were measured for multiple years simultaneously to assess their differences in energy fluxes and energy partitioning. The space-for-time substitution assumes that the sites were similar in their underlying properties and climate, which may have introduced an additional component of uncertainty to the analysis. For example, the TS site is located on a different soil series than NS and PS, and it has a higher site index than PS. However, these differences are considered small compared to the potential effects that the dramatic changes in canopy structure and site hydrology were likely to cause.

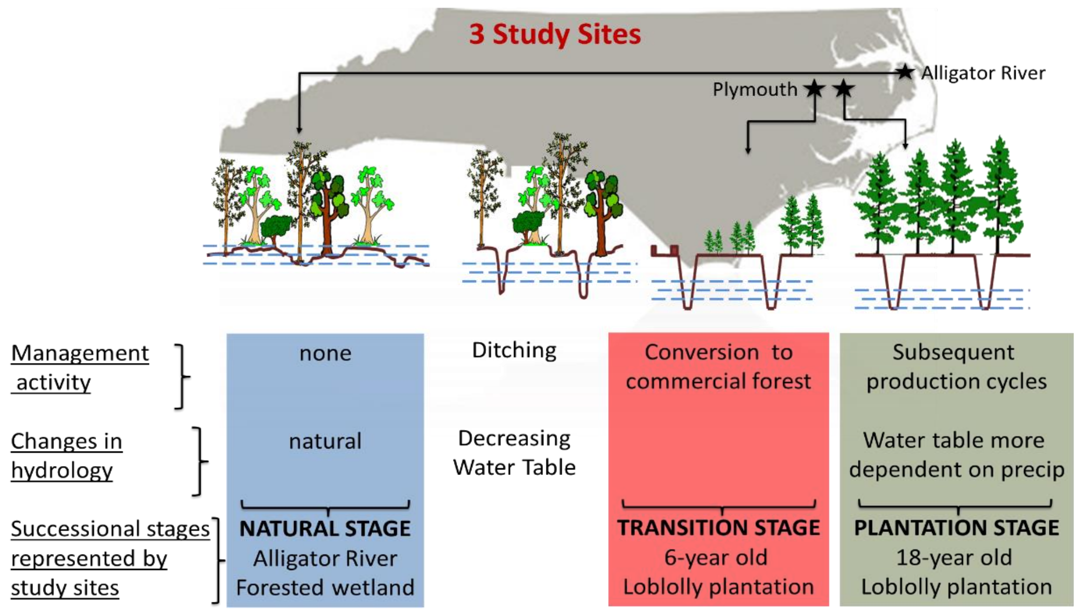


Figure 3 Successional Stages of Land Use Change (LUC) in the lower N.C. Coastal Plain. Three of the major stages (natural, transition, and plantation) are each represented by one of the three different study sites.

Natural Stage

The study site used to represent the NS was located in the Alligator River National Wildlife Refuge on the Albemarle-Pamlico peninsula of North Carolina (35°47′N, 75°54′W) and is a registered Ameriflux site. This peninsula differs from other coastlines in the south Atlantic region because of large low elevation areas, low flow, poorly drained soils and absence of large tide changes more common to coastal fringe wetlands. These features result in high accumulation rates of organic matter (1–3mm/yr) and a deeper organic layer than the adjacent mainland areas (Moorhead and Brinson, 1995). Climate records from a nearby airport (Manteo, NC) showed that the mean (1971–2000) annual precipitation was 1298 mm. Water Table Depth (WTD) was commonly between -10cm below and 15 cm above ground (Miao et al., 2013). The average annual temperature was 16.8°C with minimum and maximum monthly averages of 6.8°C in January and 26.5°C in July, respectively. The overstory was predominantly composed of swamp tupelo (*Nyssa biflora*), black gum (*Nyssa* *sylvatica*), and bald cypress (*Taxodium distichum*), with occasional red maple (*Acer rubrum*), white cedar (*Chamaecyparis thyoides*), Pocosin pine (*Pinus serotina*), and loblolly pine (*Pinus taeda*). The understory was predominantly fetterbush (*Lyonia lucida),* bitter gallberry (*Ilex galbra*), and red bay (*Persea borbonia*). Canopy height ranged from 15 to 20 m, with peak leaf area index (LAI) of 3.5 ± 0.3. Tree stand density was 2320 ± 800 stems ha^{-1}. Soils at this site were acidic with pH of 4.2–4.8 at surface horizons. Major soil types were poorly drained Pungo and Belhaven mucks.

Transition Stage and Plantation Stage

The sites used to represent the transition and plantation stages (35°48′N, 76°40′W) were located within 3 km of each other in Washington County, in the Albemarle Sound drainage area, within the Lower Coastal Plain mixed forest province of N.C. in the southeastern U.S. (Noormets et al., 2010). Locally called the Parker Tract, this site has been managed by the forestry industry for timber production since the early 20th century. The area is dominated by planted loblolly pine stands of various ages with plots of native bottomland hardwood forests interspersed. Soils were poorly drained with a ground elevation less than 5 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 roadside canals (150–200cm deep) that divide the watershed into a mosaic of regularly shaped fields and blocks of fields. The long-term (1971–2000) average annual precipitation is 1320 mm. The average annual temperature is 15.5°C, with minimum and maximum monthly averages of 6.4°C in January and 26.6°C in July, respectively. Near Plymouth, within the Parker Track, two sites were selected to represent a chronosequence of transition and plantation stages of LUC (Figure. 1).

The transition stage site (TS) had an area of 70 ha and is registered in FLUXNET. Part of the transition from the NS to the TS occurred when the stand was clearcut in 2002, and planted in 2004 with two-year-old loblolly pine seedlings at a 1.5 m x 6 m spacing and a density of 1040 trees ha^{-1}. Canopy height increased from 0.7 to 9.5m during the eight study years (2005-2012). Peak LAI was not measured during this study period but has been shown to increase up to 3.0 $m^2\ m^{-2}$ within the first few years at a clearcut pine flatwoods similar to this study site (Gholz and Clark, 2002). This site was covered with dense weedy groundcover primarily composed of dog fennel (*Eupatorium capillofolium*) and greenbrier (*Smilax rotundifolia*). The soil was 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. The common range of WTD is between 25 and >120 cm (measurement sensors did not extend below 120cm) below the ground surface.

The plantation stage site (PS) was located about 3 km from the TS (Fig. 1) and is registered in FLUXNET and Ameriflux databases as US-NC2. The PS block is a 90 ha, mid to late-rotation loblolly pine stand established in 1992 after clear cutting the previous mature pine plantation. Planting spacing was 1.5m x 4.5 m., and the tree density was about 1660 trees ha^{-1}. Canopy height increased from 12 to 18m over the eight study years, with peak leaf area index of 4.3 ± 0.2 (Measured in June 2009).

In winter season (January–March), LAI decreased mostly due to leaf fall of subdominant and understory red maple (*Acer rubrum*) and greenbrier (*Smilax rotundifolia*). The organic soil at this site was classified as the Belhaven Series histosol (i.e., loamy mixed dysic thermic Terric Haplosaprists). The soil was 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 existed from 85 to 200 cm, and a gray loamy sand was common below the 200 cm depth. The common range of WTD was between 25 and 190 cm below the ground surface.

3.2. Equipment

Net radiation above the canopy was measured with CNR1 4-component radiometer (Kipp & Zonen, Delft, Netherlands; KZ) at the TS and PS sites, and with NRLITE single component net radiometer (KZ) at the NS site. Soil surface heat flux was measured with three HFT1 soil heat flux plates (Radiation and Energy Balance Systems (REBS), Seattle, OR) at the TS and the PS, and with two HFP01 heat flux plates (KZ) at the NS. The readings of replicate sensors were averaged to account for spatial variability in soil surface heat flux. The turbulent fluxes of sensible and latent heat were measured with the eddy covariance method, using a CSAT3 3-dimensional sonic anemometer (Campbell Scientific, Logan UT) and an LI-7500 open-path infrared gas analyzer (IRGA) (Licor Inc., Lincoln, NE), and processed with the EC_Processor software package (Noormets et al., 2010, 2012). All fluxes were analyzed as 30-minute means. G was measured every 15 seconds and Rn, the water vapor density, air temperature and wind speed and direction were measured at 10 Hz. The data were recorded with Campbell Scientific CR 1000 data loggers.

3.3. Quality Control

Only quality data were selected to compare EBC and energy fluxes from the different sites. A filter was developed to select quality data, based on conditions of best EBC. Atmospheric, temporal, and site parameters were investigated for relationships with EBC and the conditions that produced the best EBC. Parameter thresholds that define conditions of best EBC were determined and utilized in the filter to select quality data. Parameters investigated included friction velocity calculated from measurements of temperature and wind velocity, atmospheric stability calculated with measurements of sensor height and temperature (Nordbo et al., 2012), the integral turbulence characteristic (ITC) (a measure of the consistency of turbulence across the 30 minute recording time), wind direction, and the time of day (TOD). Conditions when sensor accuracy was compromised and erroneous EBR values (both high and low) were produced, were excluded by the filter that defined and selected quality data through the conditions that consistently produced best EBC.

3.4. Statistical Analyses

Differences in (April-September) LE and EBC were determined among sites in individual years. Variances among different seasons and different years were not statistically evaluated. Statistical differences in growing season EBC slopes were evaluated using multiple regression models with indicator variables for sites. If an indicator variable was determined to be a significant model parameter, then that site had a statistically different EBC from the reference site for the growing season. Similarity in EBC between sites indicated the reliability of comparing eddy covariance results measured at different sites. Statistical differences in growing season LE were determined using a repeated measures analyses with a quadratic model and using the daily average of quality midday flux as the repeated measure. Results from these site comparison analyses indicated whether LUC from a naturally forested wetland to an intensively managed pine plantation affects LE and the water cycle during the growing season.

4. Results

4.1. Quality Control

Most parameters investigated for the filter revealed relationships with EBC which were both consistent and varied across sites and seasons. Both Wind direction and friction velocity showed relationships with EBC that varied between sites and seasons. The relationship between EBC and time of day was consistent across sites as well as stability which was also consistent seasons.

4.1.1. Time of Day

The Time of Day (TOD) has been determined to have a relationship with EBC in previous studies (Foken et al., 2009, Hendricks Franssen et al., 2010, Barr et al., 2013, Stoy et al., 2013) and in results from this study. Best closure occurred during the midday period with highest EBC occurring shortly after full development of the convective mixed layer and dropping off in the early afternoon (Figure 4). The QA filter selected only 4–5 hours of data from the midday period to compare sites.

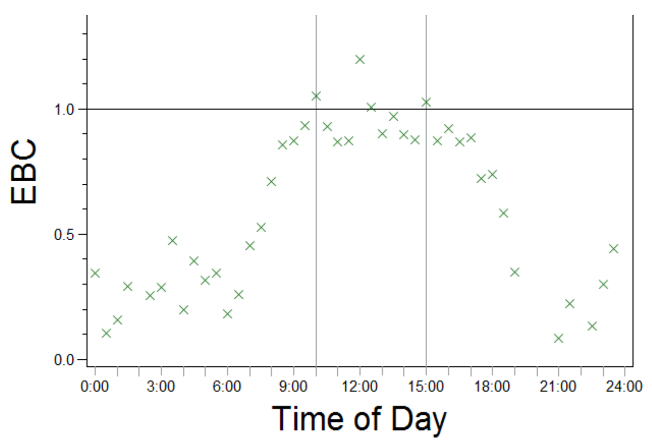
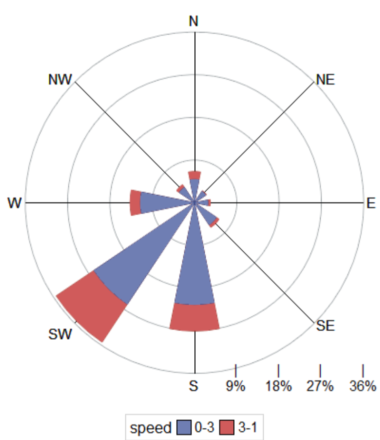


Figure 4. Daily EBC cycle at the PS, 2009.

4.1.2.Wind Direction

Landscape heterogeneity has been shown to affect EBC due to footprint mismatch of the available energy measurements and the large fetch of turbulent energy measurements (Stoy et al., 2013). The potential for this mismatch to be affected by wind direction was also evaluated in this study. Because the prevailing wind directions vary seasonally, we first defined the seasons by combining months with consistent wind patterns. Monthly wind roses indicated distinct seasonality in prevailing wind directions at all sites (Figure 5). Southwestern and southern winds prevailed during April-August and defined the summer season. Northwestern and northern winds prevailed from September through January and defined the winter season. February and March were classified as spring. Because the fall months of September, October and November did not have a distinctly different wind pattern than the winter months, these months were classified as winter. **No fall season was distinguished**. Throughout the investigation of quality eddy flux data and on to the results of EBC, the three seasons defined by different wind patterns (spring, summer and winter), were used to represent the whole year. These three seasons were used to examine data quality and develop the filter and should not be confused with the growing season (April-September), which was the period used to compare the individual energy fluxes.



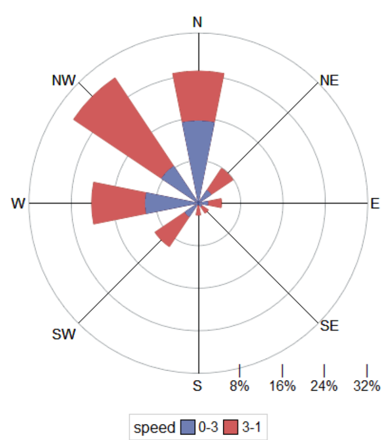


Figure 5. Wind roses showing summer (left) and winter (right) wind patterns. Speed in in m/s.

Common wind directions within a season were distinguished by examining graphs of 30 minute EBR vs. wind direction (Figure 6) specific to site and season and using high density data clouds to bin regularly occurring wind directions. From the results in Figure 6, Summer at the PS was binned into 3 major clouds. For each site and season, 3–4 bins were defined. Results indicate that EBC varied significantly by which way the wind was blowing (Figure 7), contrasting the finding of Oliphant et al. (2004). Using Google Earth, an attempt was made to correlate these results to landscape heterogeneity among the eddy flux footprints of the different wind directions. The temporal resolution of Google Earth was not specific enough to match the rotating landscapes of an intensive timber plantation. No qualifiable correlations were made between wind direction specific EBC and their eddy covariance footprints. A more intensive investigation, utilizing GIS technology, could lead to understanding why wind direction affects EBC. Wind direction was not utilized in the resultant filter to select quality data.

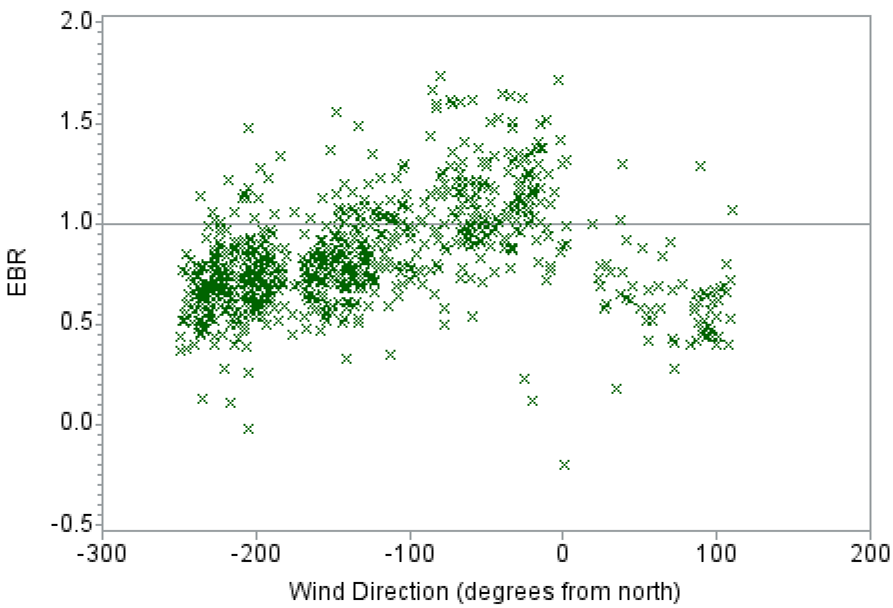


Figure 6. Midday thirty minute EBR values vs. wind direction during summer 2009 at the PS.

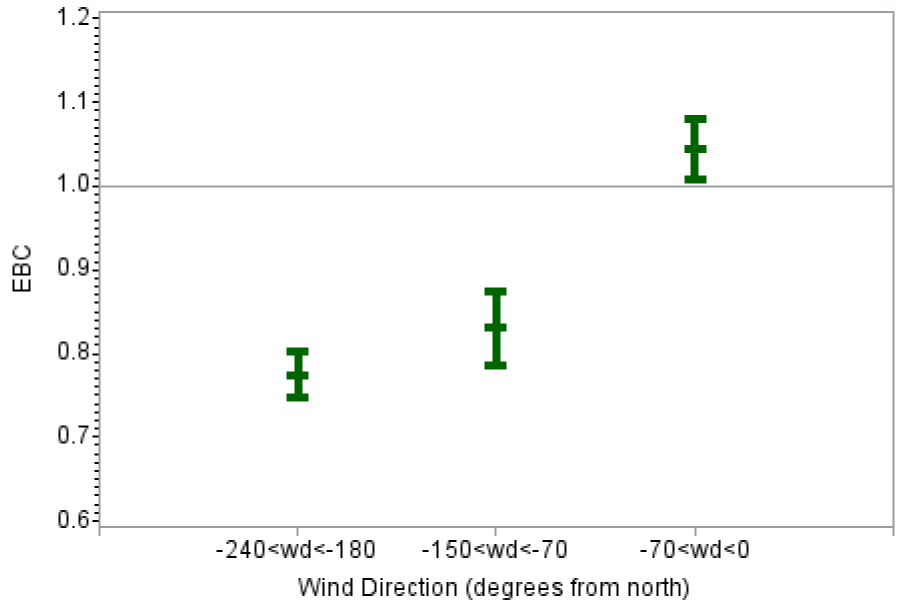


Figure 7. EBC with standard error of binned midday wind directions during summer 2009 at the PS.

4.1.3.Stability

Stability calculated from sensor height and temperature (Nordbo 2012), classifies Monin-Obukhov length into categories 1-6 where higher values represent stable conditions with poor vertical transport. The relationship between stability and EBC was evaluated by dividing the data by site and season. A drop off in EBC for high stabilities (4-6) was apparent for all sites and seasons (Figure 8a) indicating that low stabilities (1-3) represent high quality data. This was confirmed by plotting the actual regressions of low and high stabilities (Figure 8b) demonstrating the small fluxes during high stabilities. Because of the high error associated with smaller fluxes and the low EBC , the filter and resultant site comparisons were based on stability classes 1–3.

4.1.4.Friction Velocity

Friction Velocity, also called shear velocity, and often referred to as u*, is a method of characterizing the shear strength between layers of fluid with different velocities, in units of velocity (m/s). u* has been determined to have a relationship with EBR in other studies (Hendricks Franssen et al. 2010, Sto casy et al. 2013, Wilson et al. 2002). Results from this study show a non-linear relationship with a plateau and drop off (Figure 9a). The drop off point was determined and utilized in the filter to select quality data. In the specific case of friction velocity, the continuous variable was binned, and EBC was determined for binned values specific to site and season (Figure 9b). The drop off point was defined by the point where the ratio of binned EBC values to the average plateau value (EBC Ratio) became less than 0.95 when working from high to low values (Figure 9c). This drop off point, the u* threshold, was determined for all 60 individual site seasons considered in this study (Figure 9d). A minimum sample size of 5 observations was required to consider regression results of a specific binned u* value. Variance in minimum sample size (Observations>=5,10, & 20) had very little effect on resultant u*threshold values, causing a 0.025 m/s difference only for a summer value at LP. It is more common to determine critical u* values through night time respiration (Foken and Wachura, 1996) than through a relationship with EBC (Stoy et al. 2013, Hendricks Franssen et al. 2010) making this study unusual in the approach to critical u* values and unique with regard to the specificity of season.

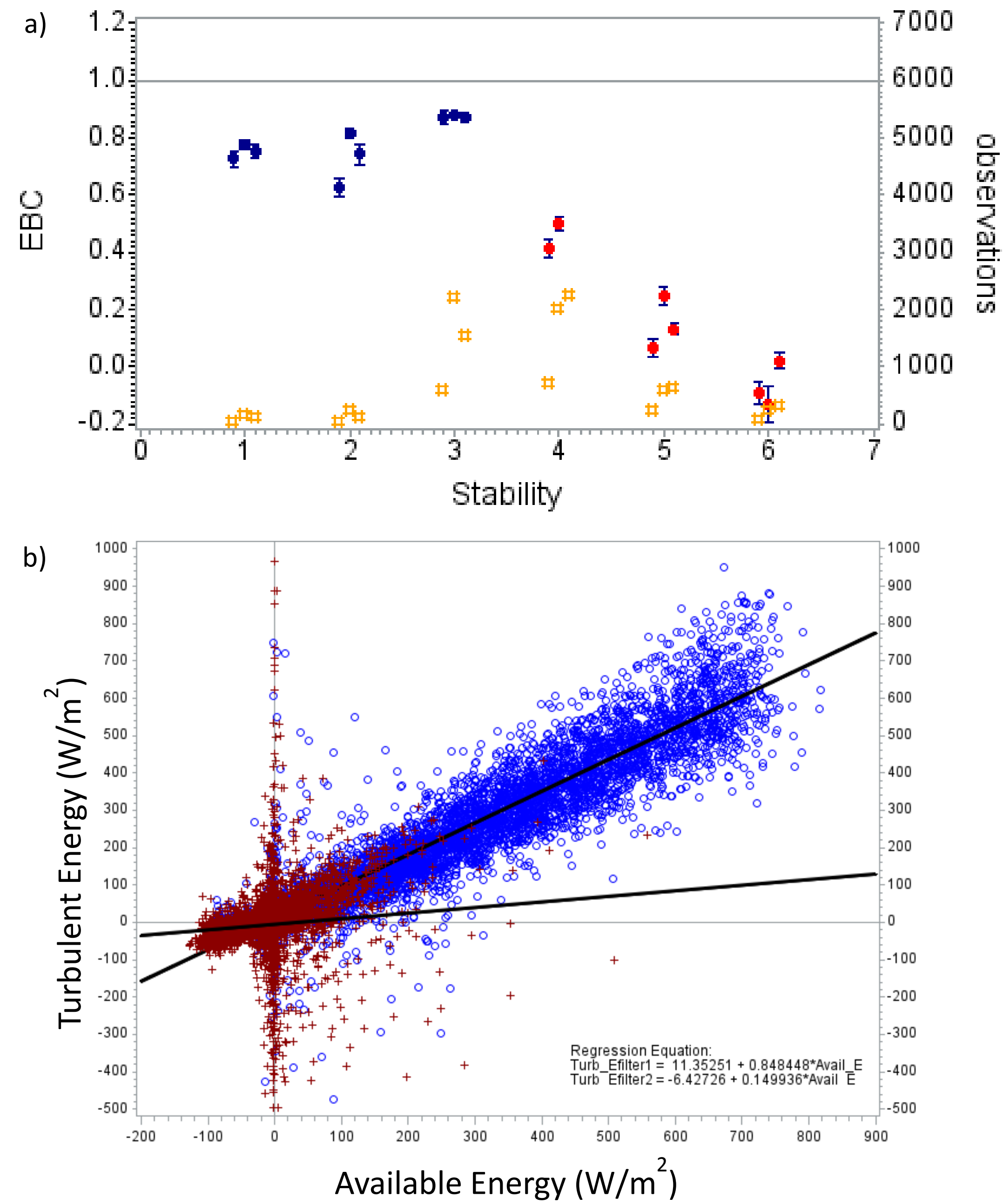


Figure 8. Stability classes vs. EBC (a) calculated from 30 minute values recorded from all 24 hours during 2009 at the PS site. Spring, summer, and winter seasons are represented from left to right in each of the clusters of 3 dots (low and high stabilities in blue and red dots respectively) with number of observations represented by number signs and the right vertical axis. EBC regressions of low (1-3, Blue) and high (4-6, Red) stabilities (b).

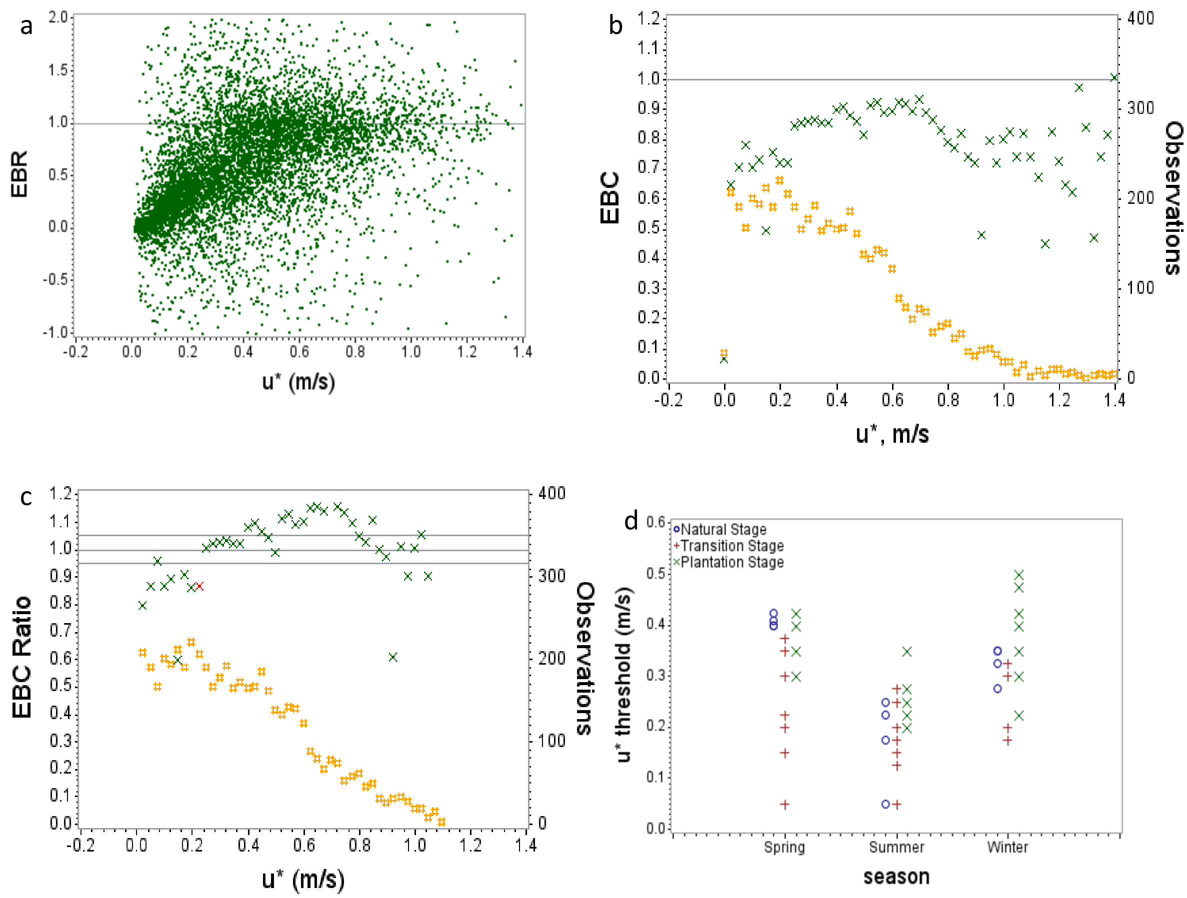


Figure 9. Thirty minute EBR vs u* from all 24 hours during 2011 at the PS (a). EBC of binned u* values (b), and EBC Ratio values with threshold value indicated with red x (c), from summer 2011 at PS. Hash marks represent number of 30 min observations included in a site and season specific u* bin. Resultant u* threshold values from all 60 site seasons (d).

4.1.5. Existing Filters common to Eddy Flux methodology

Established filters of Eddy flux methodology were also used. Included was a condition of the measure of cleanliness of the IRGA, the auto gain control (AGC, unitless), that was required to be less than 70 (agc<70). Observations were also required to have at least 17,000 of the of the 18,000 0.1 second measurements available in a 30 minute recording period (Records>17,000). There was no relationship evident between the ITC and EBC so the default condition established by Foken and Wachura (1996) was used (ITC<0.3).

4.1.6. Resultant Filter

The cumulative filter of the above conditions is comprised of 3 main categories, (1) newly developed conditions based on EBC, (2) range check and energy data availability, and (3) existing filters in eddy flux methodology.

(1) Stability ≤ 3, 10am<TOD<2pm, u*>u*threshold

(2) -40<G<60, -200<LE<800, -200<Hs<600, (abs (LE)<(abs (Rn)+200)

(3) AGC<70, Records>17000, ITC<0.3

The quality data selected by the cumulative filter represents 9.4% (19.4% excluding the TOD condition) of the original 300,000 observations recorded at the three sites between 2005 and 2012. For a more detailed explanation of the effects of the individual and cumulative conditions on the number of observations, refer to appendix B. Because the effects of the TOD condition are obvious, this condition was not utilized in Figure 10 which demonstrates the less predictable effects of the other filter conditions and their effectiveness in removing erratic data from days with precipitation (days 4 & 5), while selecting conditions on cloud free days (days 1–3) when differences in LE were most pronounced and Rn was similar.

The midday flux index (MFI) is the average of quality midday data, and was used as the basic unit to compare energy fluxes between the different sites. Comparing the energy fluxes with daily, monthly, or annual integrals would require extensive gap filling and incorporate model errors into the results. In order to avoid these errors only quality midday data were used. Because the stability and u* filters favor higher fluxes, the averages of quality data are likely to be higher than the actual averages and are more accurately referred to as an index. At least 5 of the 8 available 30 minute observations between 10am and 2 pm were required to calculate the MFI for a specific day. While this method does not lead to annual totals, it offers an accurate, novel metric with which to compare the sites.

4.2. Data

The G data from the PS site were missing for the first half of 2010 preventing EBC calculations. G data were generated from seasonally specific linear regression models using the nearby TS site for input. The models were developed using data from July 2010 through December 2011 ($0.85<R^2<0.89$). Considering the small magnitude of the ground heat flux, the error associated with the synthesized data is expected to have minimal effect on the accuracy of EBC calculations. For specifics on the G data and gap filling parameters refer to appendix A. The most significant gaps in these data occurred in 2008 and the winter of 2011–12 when the TS and PS towers were taken down by a tree and a storm respectively. While each of these gaps include part of the growing season, and may affect results from these individual seasons, the larger effects of LUC on energy partitioning are still apparent through the multi-year trends.

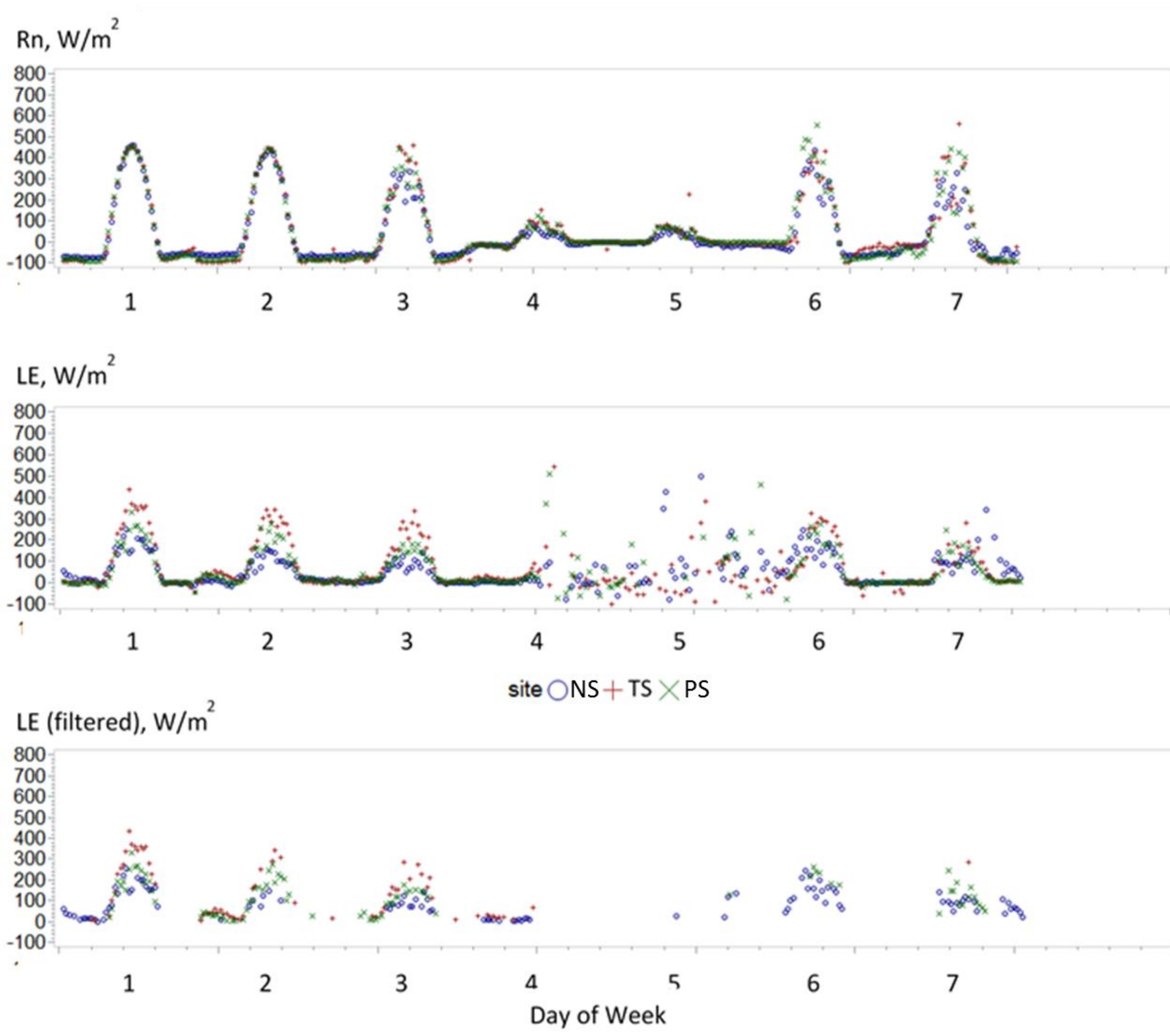


Figure 10. (Top down) Unfiltered Rn, unfiltered LE and filtered LE (lest the TOD condition) through week 44 (Oct.30-Nov.5), 2010.

4.3. EBC

There were consistent differences in EBC between sites and across seasons (Figure 11). Seasonally, EBC increased from spring to summer to winter seasons. There were significant differences between the sites, indicating that this LUC significantly affected EBC during the growing season (Figure 12). In general, EBC was highest at TS, and lower at NS and PS, which were generally similar.

4.4. Energy Partitioning and LE

All energy fluxes peaked during mid growing season, except for Hs which had peak values earlier in the spring (Figure 11). Because most flux of energy and water (LE) occurs during the growing season, and differences caused by LUC have been shown to be highest during this time (Schneider & Eugster, 2007, Mishra et al., 2010), this study will concentrate on results from the growing season.

Growing season averages of Rn (April-September, Figure 12) show that peak rates occurred in the PS in 2006 (15 years old). Growing season Rn at the PS was 5% greater than at the NS and 20% greater than values from early years (2005-2008) of the TS, when growing season Rn was at minimum values (460-475 W/m^2) among all study years. At 8 years (2010) and older, the TS showed similar Rn to the PS. Differences in Rn both between the sites and between years are, at least in part, attributable to changes in canopy structure, including the Leaf Area Index (LAI), the ratio of leaf area to ground area for a given ecosystem. The differences in LAI between the TS and PS are evident (Figure 13), but this data was not readily available for the NS.

There were significant differences in LE among the sites, indicating that this LUC significantly affected evapotranspiration during the growing season (Figure 12). Across the 3 years of data available from the NS, growing season LE varied , but was similar to the PS (Figure 12). During the early years at the TS, growing season LE was 20% smaller than at the PS, but became significantly greater (40%) after about 8 years of age (2010). There was a drought in 2007 and 2008 (Figure 14) when the difference in LE between the TS and PS was larger than in previous wet years. LE at the NS was similar to the TS in 2009 and 2010, but was significantly less than the TS during 2011. The NS was significantly less than the PS during 2009 and significantly higher during 2012. LE at the TS was significantly lower than the PS from 2005–2008 and significantly higher from 2009–2012.

Growing season averages of Hs were lowest during the early years of the TS (Figure 12). Like Rn, Hs levels at the TS became similar to the PS, and the NS, at 8 years of age (2010). Hs was most stable at the NS. Average growing season bowen ratios reflected trends in Hs and showed differences between the sites that were consistent through most of the site specific interannual variations. Bowen ratios were usually lowest at the TS and highest at the PS, except in the first year of the drought (2007) when the TS had the highest ratios. The trend in monthly bowen ratio (Figure 11), showed a tendency to decrease across the LUC and was especially apparent in the winter.

Differences in growing season averages of G were small considering the scale of the flux, but showed obvious differences among the sites (Figure 12). G was similar across most site seasons except for the early stages of the TS when G was highest. Like Rn and Hs, G levels at the TS became similar to the PS, at 8 years of age (2010).

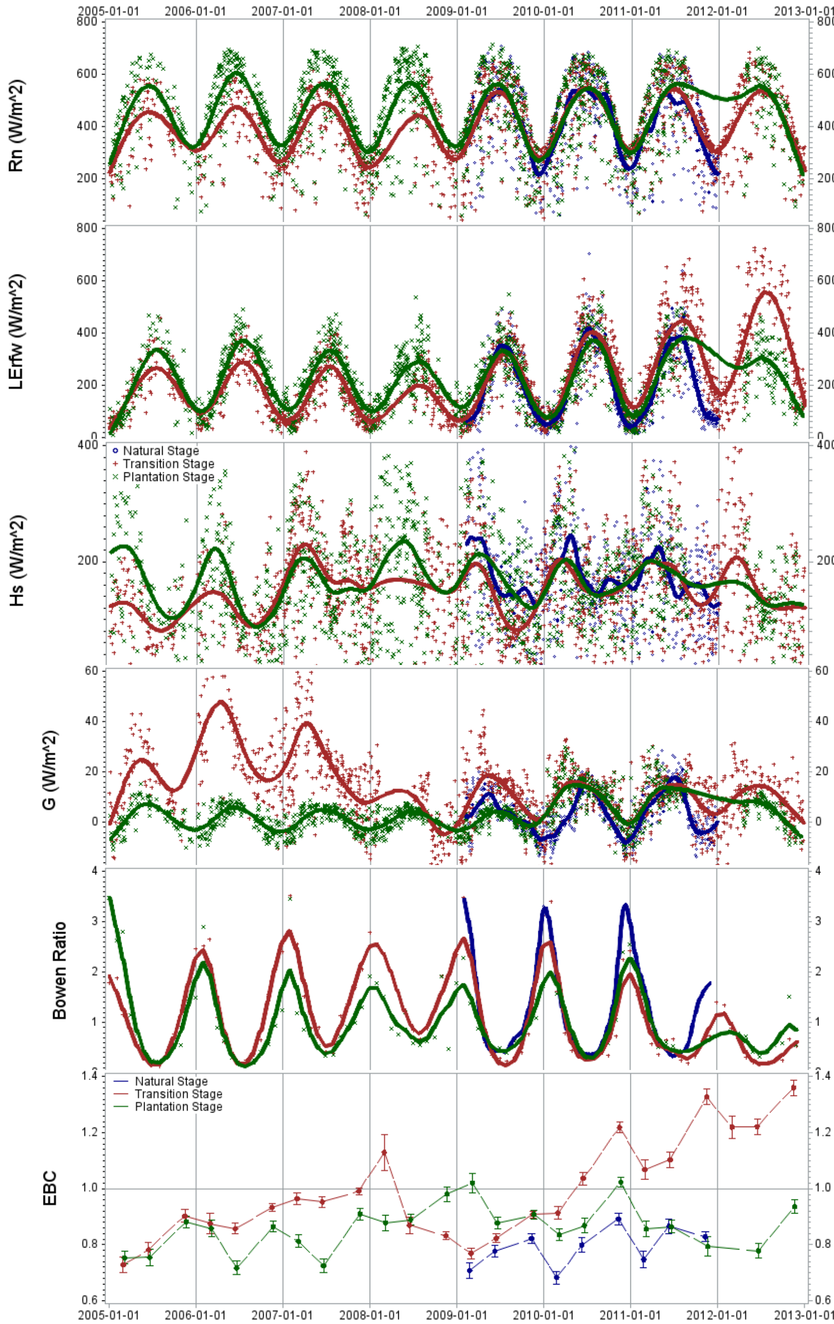


Figure 11. Daily MFI of net radiation (Rn), latent energy(LE), sensible heat (Hs), and ground heat (G) fluxes (all W/m^2) and monthly bowen ratios (unitless). The trend lines, created from SAS symbol interpolation set to I=sm20, are only valid when daily data are present (e.g. Trend line invalid for Winter 2012 at PS). Seasonal EBC with standard error bars (unitless).

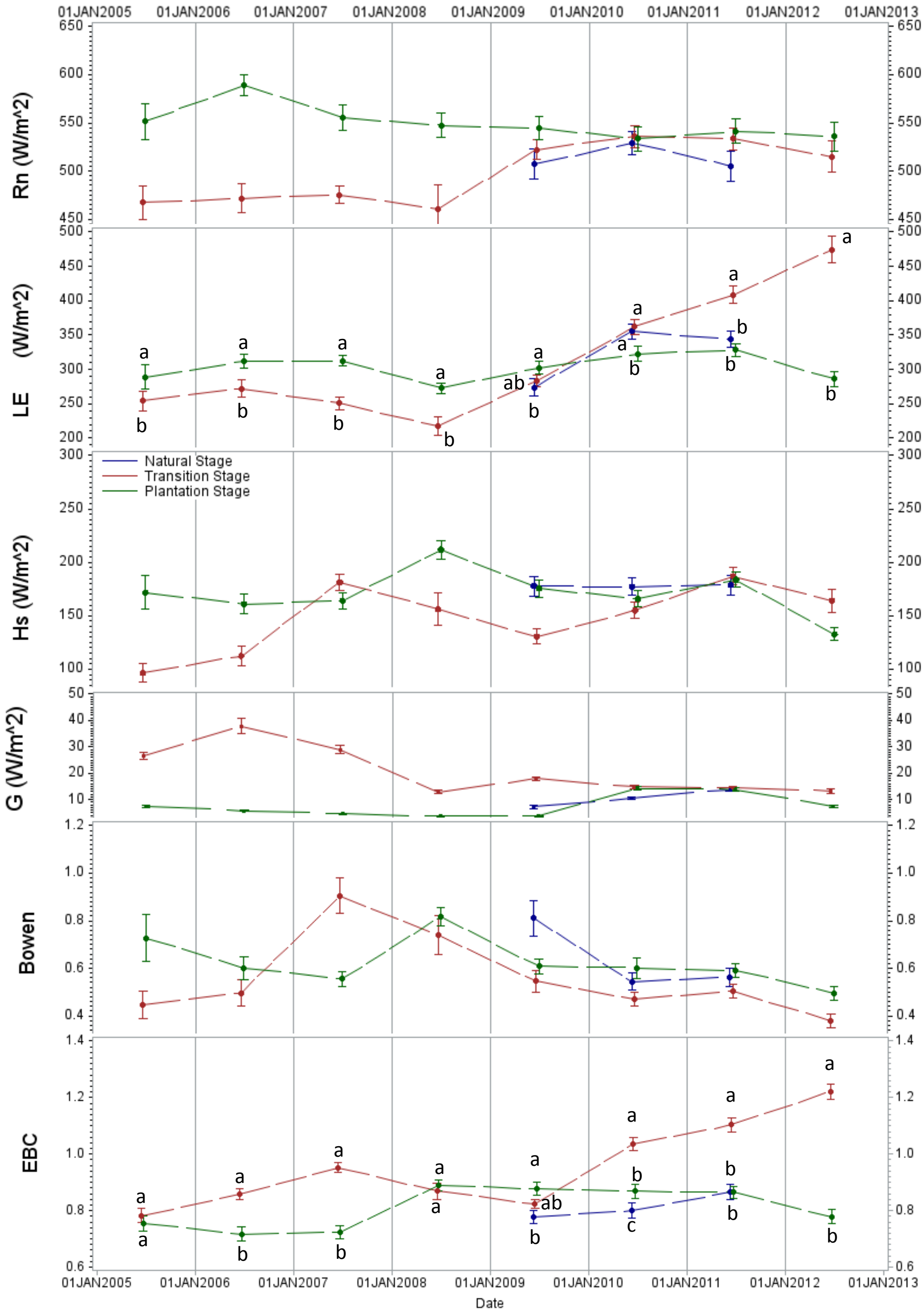


Figure 12. Growing season (Apr-Sep) means of MFI with standard error for (top down) net radiation, latent Energy, sensible heat, ground heat flux (all W/m^2), bowen ratio and energy balance closure (unitless). Within each year, different lower case letters denote significant differences (LE and EBC only) among sites.

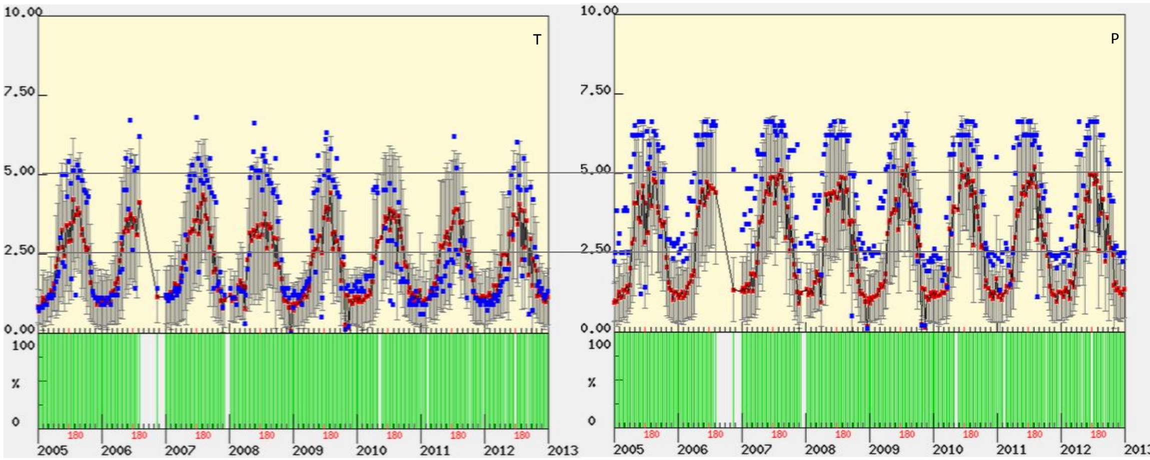


Figure 13. All-sided LAI at the TS (left) and PS (right) calculated by Modis 8 day composite values for, average of Pixels in 7x7 Grid having Valid Data (red), and Site/Tower Pixel (blue) having Acceptable Quality.

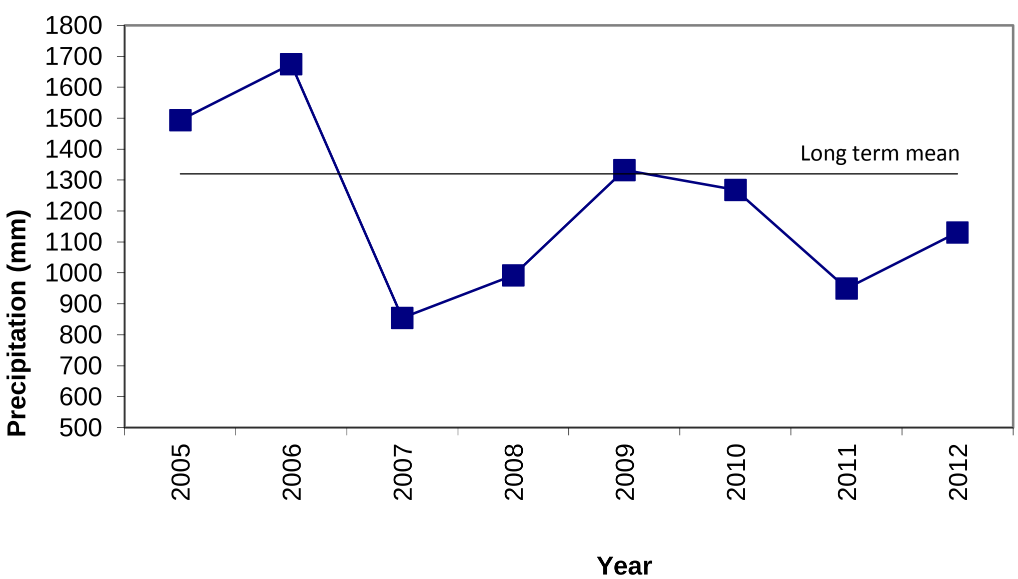


Figure 14. Annual precipitation totals from Plymouth, NC

5. Discussion

Limited data exist on the effects of LUC on the energy balance and especially on the effects related to ditching and draining a wetland for timber production. This study was unique in measuring these changes across a chronosequence of a natural forest to an intensively managed pine plantation. Results indicate that energy partitioning, LE and EBC vary throughout the stages of this LUC.

5.1. Filter and Data Quality

Relationships with EBC and the parameters involved in the filter were both consistent and varied across the sites. Both Wind direction and u* (Figure 9d) varied between the sites. The variation in EBC with wind direction and the implications of eddy covariance footprints is an obvious lead for further analysis. Stability was consistent across sites and seasons. Annual results from 2009 (Figure 4) indicated that the TOD relationship was consistent across the different sites, but TOD was not extensively investigated across different seasons, sites or years. The TOD filter selected only midday data because EBC was highest during the middle of the day during well-developed turbulence and unstable atmospheric conditions, consistent with earlier reports. However, it has also been pointed out that although the EBC is highest, the absolute amount of energy missing (R_{EB}) is also the greatest, (Barr et al. 2006, Barr et al. 2013, Hendricks Franssen et al. 2010) which should be considered in further investigations utilizing these midday data. The resultant filter may have removed most of the original data, but produced a dataset that showed differences between sites, seasons, wind directions and years that have been less distinguishable in previous studies (Oliphant et al., 2004, Stoy et al., 2013).

5.2. EBC

Growing season EBC during the later years of the study showed a similar trend to LE with the TS having the highest values and climbing (Figures 12 & 16). This was not the case in the early years, when EBC was also highest at the TS but LE was the lowest, and is a potential line of inquiry to understand what affects EBC. EBC was lower at the NS than the drained sites, consistent with earlier reports (Barr et al. 2013, Stoy et al. 2013). In fact, the low EBC at wetlands stands apart from other ecosystems to the extent that they have been excluded from analyses of relating EBC to landscape heterogeneity (Stoy et al. 2013). The standing water at these wetland sites and its high heat capacity compared with soil represents a large reservoir for energy storage which could contribute to the degradation of instantaneous and 30 minute EBR. Schneider and Eugster (2007) showed that albedo increased when converting wetlands with a potential cause being the capacity for standing water to absorb radiation. Moulders (1999) showed that air temperatures were lower over grassland vs. marsh due to the higher heat capacity of the wetland. Further investigations should explore the role of wetland standing water in the energy balance and its potential contribution to EBC degradation.

While differences among years at individual sites were not analyzed, Figure 12 and the significant intersite differences indicate that there are significant interannual differences at the individual sites which contrasts with the findings of Oliphant et al. (2004) who did not find statistically different EBC between years at a single site. The increased resolution present in this study could be because of natural site and climatic differences, or because of methods utilizing the growing season MFI, and not forcing closure, a common approach used in previous studies (Oliphant et al., 2004, Wohlfahrt et al., 2010, Barr et al., 2012).

5.3. Energy Partitioning

The LUC investigated in this study affects energy partitioning through a combination of factors driven by alterations to hydrology, soil properties and vegetation. The hydrologic changes from ditching and draining wetlands decrease water storage and standing water, increase the root zone above the water table, and release nutrients that were bound in hydric conditions. The change in vegetation affects species composition, canopy height, and canopy structure. These changes to ecosystem structure and composition are likely to be the primary causes in the differences reported in energy partitioning. Standing water, canopy height, and canopy structure all affect reflectance. LE is affected by species, age, root zone depth, water availability and climate. Energy storage is affected by differences in standing water and also in the amount of air and biomass between the ground and the top of the canopy. The interannual climatic variation at individual sites also affected energy partitioning; but, the more drastic effects caused by ditching, draining and forest management were apparent in the results and show that this LUC affects all energy fluxes.

Between the studied stages of this LUC, energy fluxes were most affected during the early years of the TS when all components of the energy balance showed substantial differences from the other site years (Figures 12 & 16). After the TS was 7–8 years old (2009–2010), Rn, Hs, and G became more similar to the other stages. LE however, continued to increase, reaching 40% higher values than the other sites during the last two years of the study. This point in this LUC where Rn, Hs, and G stabilize, and LE crosses the long term trend, marks a significant discovery in determining how this LUC affects the partitioning of energy at the ecosystem level.

Other studies that have compared ET and energy partitioning of different land covers resulting from LUC rarely include a transition period (Sakai et al. 2004) and usually only represent the before and after (Schneider and Eugster, 2007, Mao and Cherkauer, 2010). To compare the results of this study to other studies, it seems most appropriate to compare the NS to the PS. However, most LUC studies investigated have crops as the resultant landscape which could be more closely related to the TS than the other stages in this study.

5.3.1.Rn

Differences in Rn both between the sites and between years are part partially attributable to changes in canopy structure, including LAI. The differences in LAI between the TS and PS are evident (Figure 13), but the canopy closure and maturation of the TS stand is not apparent in these remotely sensed data, because the low pine LAI in the early years was complemented by the herbaceous ground cover. The canopy closure, however, is likely to be reason the Rn at the TS increased to a similar level as the PS. The decrease in Rn at the PS from the 2009 to 2010 growing season is likely due to a stand thinning during the winter of 2009.

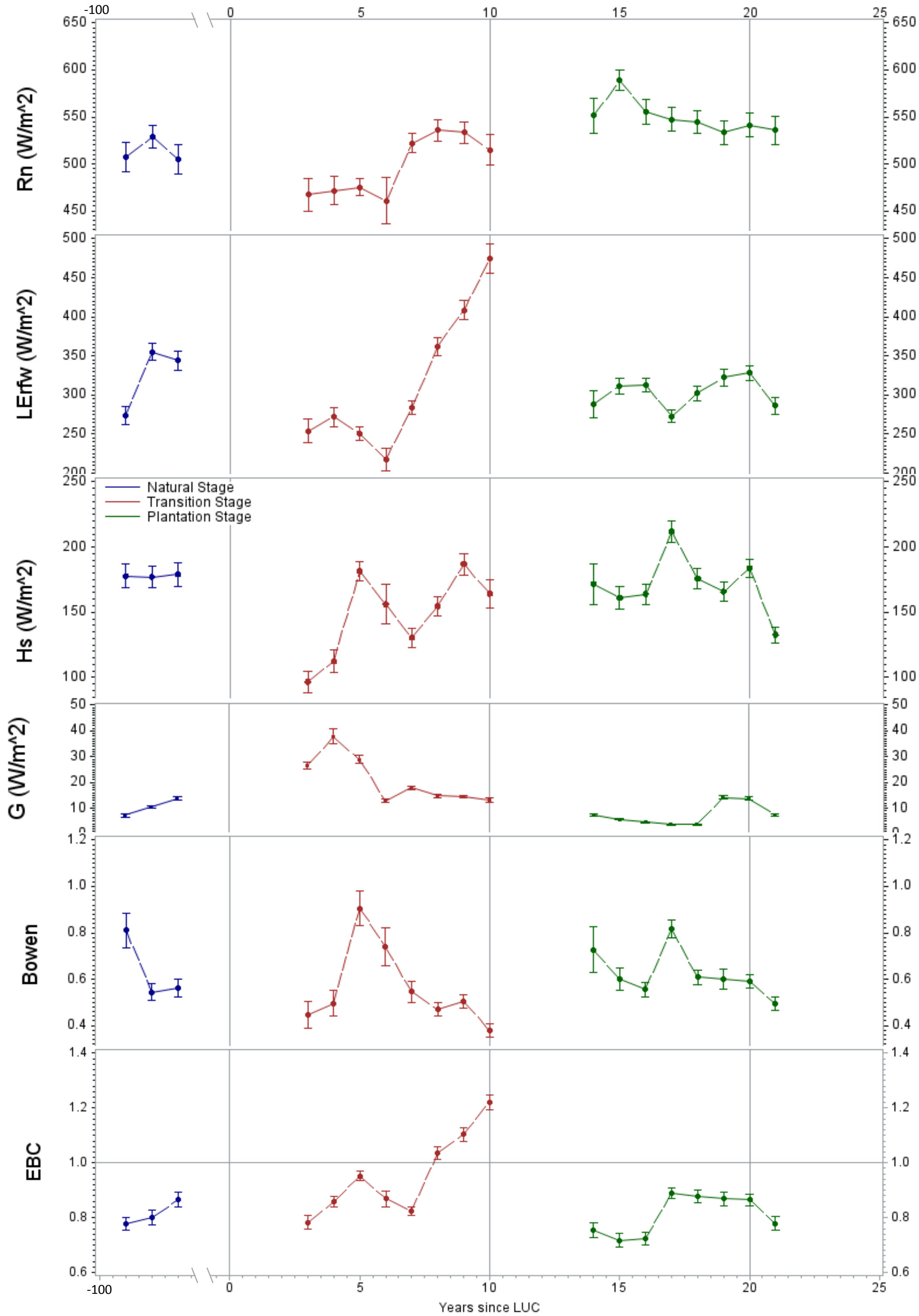


Figure 15. Growing season means with standard error of MFI for (top down) Net Radiation, Latent Energy, Sensible Heat, Ground heat flux (all W/m^2), Bowen Ratio and Energy Balance Closure (unitless) set in the time frame of LUC.

Schneider & Eugster (2007) modeled the effects on the energy balance from wetland drainage of LUC from mostly bog and wet meadows to croplands. Their results showed that midday Rn was reduced during all seasons, and up to 17 W/m^2 during the growing season, which contrasts to results from this study that show an increase in Rn caused by drainage (NS to PS). Stoy et al. (2006) found that Rn was similar between a deciduous forest and a pine plantation during the active growing season, consistent with results from this study. In the winter, however, the deciduous site had a higher Rn than the pine stand which contrasts to the current study where the dormant season Rn was higher in PS than in NS (Figure 11).

5.3.2.LE

While there were significant differences in LE between the NS and the PS, the largest differences in LE were between the TS and the other stages (Figure 12). Unlike the other energy fluxes, which became more similar between the sites over the study years, LE at the TS continued to increase beyond the other sites.

5.3.2.1. Early years and drought sensitivity

During the early years of the study LE was lowest at the TS and can be correlated to the low LAI of the young stand. Dry years in 2007 and 2008 (Figure 14) caused a decrease in LE at the transition and plantation stages, as well as an increase in the difference between the two sites, which indicates an increased drought sensitivity during the TS of this LUC. The shallower and less extensive root distribution of the younger stand is likely the primary cause of the increased drought sensitivity. The ditching and draining involved in this LUC reduces water storage (Vörösmarty and Sahagian, 2000) and thus decreases the drought tolerance of the ecosystem, reduces ET, and increases Hs and the feedback to climatic warming during drought periods. In 2009 and 2010 however, the NS (and the TS) show a greater variation in LE than the PS (Figure 12), which could be attributed to the memory effect conferred by the 2-year life cycle of needles in the pines. The needles formed in the drought years may not have allowed the pines to suddenly take advantage of the additional water available in 2010, whereas in the TS this effect may have been masked by the aggrading nature of the stand, with both higher LAI and root area in 2010 than 2009. Models are predicting greater fluctuations in future climates and understanding how this LUC affects sensitivity to varying climates is an important line of inquiry that should be further investigated.

5.3.2.2. Late years

During the later years of the study, growing season LE at the TS continued to increase to values at least 40% higher than the other sites. Max LE and stabilizing LE across the LUC are likely to occur between the 10 year old TS (2012) and the 15 year old PS (2005) (Figures 12 & 16). During these later years at the TS, LE was particularly higher in the fall season (Figure 11). The high canopy activity late in the growing season is likely exclusively attributable to pines, as the herbaceous ground cover typically dies by July. The growing season averages reported on Figure 12 do not include the fall months of October, November and December when the difference of LE between the TS and the other stages was greatest (Figure 11). Including the fall in annual averages or integrals could show an even greater discrepancy in LE between the TS and the other stages during the later years of the study. ET has been correlated with LAI (Mao and Cherkauer, 2009, Sun et al., 2011), but that is not the case in the later years of this study where the PS had the highest LAI and the lowest LE (Figures 17 & 16). This high productivity per leaf area at the TS could be partially attributed to the resources available to the expanding roots of the TS and the limitations at the PS where the roots have fully colonized the unsaturated zone.

5.3.2.3. ET in other studies

Compared to this study, previous studies have reported contrasting results on the effect of wetland drainage on ET and consistent results on the differences between ET in deciduous and coniferous forests. Results of LE at the NS and the PS are consistent with previous studies which have assessed the differences between evergreen and deciduous forests. Stoy et al. (2006) and Mao and Cherkauer (2009) reported that such forests are similar, with greatest differences in spring, fall and winter; and cumulative ET usually, but not always, higher (4–13%) in evergreen than the deciduous forests (Stoy et al., 2006, Figure 12). The conversion of wetlands has been estimated to lower ET (Schneider & Eugster, 2007) during all seasons except spring when ET was shown to increase because of the increase in fractional plant coverage at this time of year. In the current study, results indicate an opposing trend (Figure 11), with converted lands (PS) having higher ET than the NS except for the early growing season.

5.3.3.Hs and Bowen Ratio

The seasonal peaks in Hs apparent in other studies (Oliphant et al., 2004) and results from this study (Figure 11) occur in the spring before leaf out. Seasonal spring increase in Hs is expected due to elevated solar radiation before vegetation has developed enough to transpire in proportion to the available energy. The annual peaks in growing season Hs and Bowen ratios (Figure 12) are reflections of the drought years. Peaks at the TS occur a year earlier (2007) than at the PS (2008). These peaks correlate with decreasing water table coinciding with decreases in ET, and causing the partitioning of available energy to favor Hs. The delayed response at the PS can be attributed to a deeper rooting depth which was not significantly affected until the second year of the drought when the water table dropped even lower. The increased drought sensitivity during the TS is a significant component of the studied LUC. The trend for decreasing winter-time bowen ratios (Figure 11) through the LUC gradient may be a function of the fractional increase in evergreen coverage and the accompanying wintertime transpiration.

5.3.4.G

Although the magnitude of G is very small in comparison to other fluxes, the growing season means exhibit a longer-lasting effect from the LUC than the larger, and more variable, LE and Hs (Fig 16). Canopy closure can be reflected in G decreasing over time. For example, G at the TS across the study years decreased over time indicating closing canopy. The thinning of the PS in the winter of 2009 was apparent in the increase in G from the 2009 to the 2010 growing seasons. Even following the canopy closure at the TS, G remained higher than at the PS. Thus, the effect of LUC on soil microclimate may be longer-lasting than the stabilization of the fluxes.

The growing season means of G (Figure 12) were lowest at the PS in 2009 and lowest at the NS in 2010, a trend that is opposite from LE in these two years and indicates the influence of climatic variability on energy partitioning. The trend in MFI (Figure 11) however, shows G at the NS to be considerably less than the other sites during most of the year and is attributable to the NS being flooded during part of the growing season. First, the variable water table effectively changes the depth of the soil heat flux plates, with variable fraction of energy being stored above it, and second, surface water also affects the reflectance compared to exposed ground, altering the balance between absorbed and reflected energy. The interannual differences at NS are attributable to different WTD, and the variable submergence of the sensors. As the G sensors represent only about $10cm^2$ of ground area, and even the three replicate sensors across different microtopographic positions may not capture the true range of G at a given site, it is notable that the intersite and interannual dynamics in the means conform to the management and structural changes at the sites.

6. Conclusion

The land use change gradient sampled in the current study affected all energy partitioning, LE, and EBC. The greatest absolute effect and interannual variation was in LE. The recovery dynamics of the energy fluxes appeared to consist of two phases – the first phase of 7–8 years was associated with the clearing of land, and the establishment of the pine plantation when Rn, Hs, and LE were at minimum, and G was at maximum values during the LUC. Rn, Hs and G appeared to stabilize by the end of the first phase, but LE continued to increase. The LUC showed increased drought sensitivity during the first phase. The second phase of 8–15 years was associated with canopy closure when LE maximized and then decreased to the more stable values of the PS. The post-disturbance recovery was attributed to changes in canopy structure and canopy reflectance. Although the major differences in the energy fluxes associated with the structural disturbance lasted only a few years, the ‘recovery’ following the LUC should be viewed only as time required for the stabilization of the measured fluxes, and not a recovery to the pre-LUC conditions. Results from this study indicate that LUC in the Lower Coastal Plain affects both short and long term energy and water cycles, drought tolerance, and potential feedbacks to regional climates that should be considered in future land management decisions.

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8. APPENDICES

8.1. APPENDIX A. Issues with Data in Original (3-Step) Data files

Timestamp 11:30 pm. 24 hr. offset

There was an issue with the date on the timestamp for observations from 11:30pm. The date on these timestamps is for the next day. To correct this, apply the following code:

If time=23:30 then date=(date-1).

The distribution of this issue between 2009 and 2011 is summarized in Table A.1

Ground Heat flux

G(hft) sensor sign correction

Some of the G data (parameters hft1,2,&3, and hftmean in data sets) originally had the incorrect sign, likely because of opposite wiring of the sensors. It was first noticed in seasonal trends of monthly averages (Figure 16) of hftmean which showed peak values in winter (TS and LP). To find the exact date and time of when the sensor wiring was corrected, the same approach was used on daily cycles which should have peak values during midday. This had to be assessed for each individual G sensor, of which there were up to 3 at each site (hft1, hft2, and hft3 in 3Step data sets). The sign was changed for signals showing incorrect daily cycles, and hftmean was recalculated.

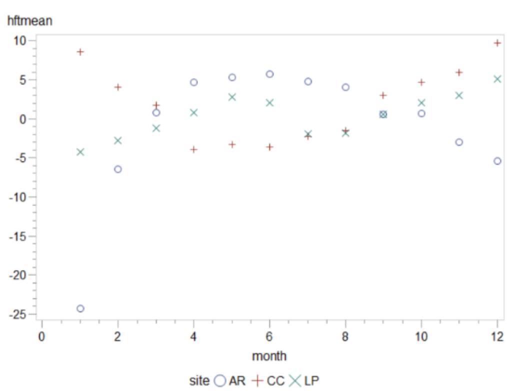

Figure 16. Monthly averages of Ground heat fluxes (hftmean) during 2009 at all sites.

1.1. Summary of G (hft) issues

hft (Ground heat flux) data issues with 3 step files 2009-2011				
		2009	2010	2011
AR	hft, no data			
	hft inverted			
	23:30 issue	x	at least->2/27	no
TS	hft, no data		12/14-12/30 hft1 and hft3 constant. These were cut out and hftmean represents hft2	1/1-1/12 no data
	hft inverted	all year	1/1-8/25	
	23:30 issue	x	x	jan only
LP	hft, no data	4/25-5/28 night data missing. Likely due to low battery	1/1-7/12 **NO DATA**	8/25-12/31 NO DATA
	hft inverted	7/1-12/?	7/12-8/24	
	23:30 issue	x	?	?

Table A.1 Summary of issues with Ground Heat Flux (hft) data.

1.2. Missing G Data & Gapfilling

The half a year (2010) of missing G data at the LP motivated gapfilling so that EBC could be calculated. Smaller gaps were also filled. The models were based on 2010 and 2011 data because of poor R^2 produced from 2009 data. The LP was filled from the TS, the TS was filled from the LP, and the AR was filled from the TS. The parker tract sites were modeled from each other because of the similarity in location and drained soils, and the AR was modeled from the TS because of the greater data availability (LP missing 2010 data) and the increased likelihood of capturing interannual variations. The results of the models (Simplified to slope only because the intercepts were so close to the origin) were used to fill gaps in the G (hftmean) parameter. The resulting new parameter, hftfill, was used throughout the analyses of this study.

Ground Heat Flux (hft) gapfill model parameters							
Based on 2010 and 2011 data (after "G(hft) sensor sign correction" was applied							
IndVar > DepVar	SEASON	TYPE	DEPVAR	INTERCEPT	SLOPE	_EDF_	_RSQ_
TS > LP							
	spring	PARMS	hftlp	-0.0286136	0.838237	2830	0.86786
	spring	SEB	hftlp	0.07382566	0.006148	.	.
	summer	PARMS	hftlp	-0.4700599	0.934858	9395	0.854797
	summer	SEB	hftlp	0.03835217	0.003975	.	.
	winter	PARMS	hftlp	0.88820122	0.686438	6493	0.884786
	winter	SEB	hftlp	0.04179937	0.003074	.	.
TS > AR							
	spring	PARMS	hftar	0.08834117	0.384552	5653	0.397274
	spring	SEB	hftar	0.08240266	0.0063	.	.
	summer	PARMS	hftar	3.55701078	0.671426	14684	0.44557
	summer	SEB	hftar	0.0641749	0.006181	.	.
	winter	PARMS	hftar	-0.6825742	0.265562	13017	0.33371
	winter	SEB	hftar	0.04881774	0.003289	.	.
LP > TS							
	spring	PARMS	hftcc	-0.1841002	1.035339	2830	0.86786
	spring	SEB	hftcc	0.08197662	0.007594	.	.
	summer	PARMS	hftcc	0.85330967	0.91436	9395	0.854797
	summer	SEB	hftcc	0.03720401	0.003888	.	.
	winter	PARMS	hftcc	-1.9738857	1.288954	6493	0.884786
	winter	SEB	hftcc	0.05393376	0.005772	.	.

Table A.2 Summary of model parameters developed to gapfill missing G (hft) data.

1.3. Parker tract wind direction discrepancy

The TS and LP are located only 3km apart and similar wind patterns were expected from the two sites. However, there was consistent (2009-2011) discrepancy (Figure 17) between the wind directions at the two Parker tract sites. In radial coordinates, this translates into a greater values for CC than LP when measuring clockwise from north.

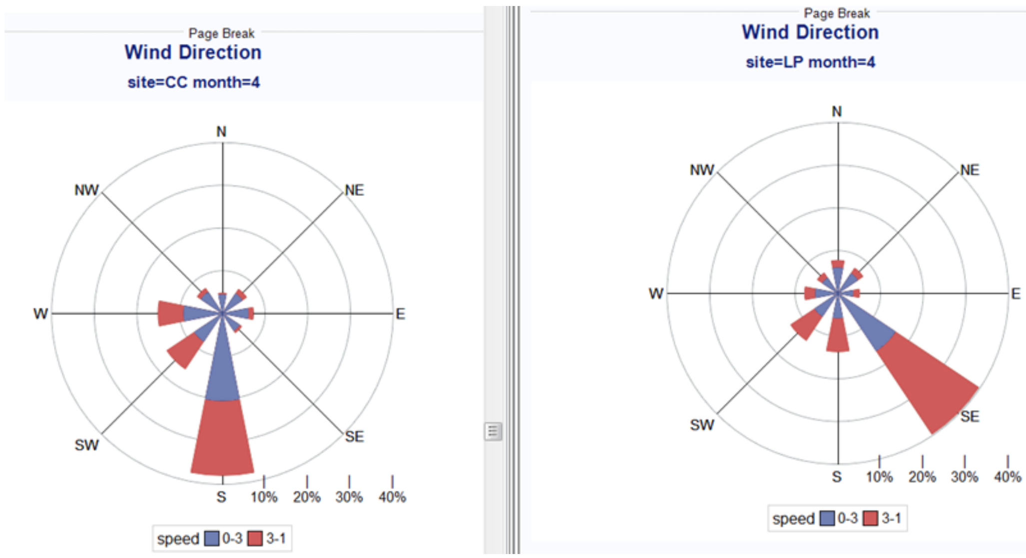

Figure 17. Windroses at the TS(CC) and the PS (LP) during a single month.

2012 NS data

The data from 2012 at the NS was available, but it was processed with different methods, was missing some of the quality flags, and produced questionable results that are not presented in this study. There was an obvious difference in the distribution of stabilities which were uniformly distributed throughout the six classes in the 2012 NS data and concentrated in classes 3 and 4 in the other site years shown in this report. Future investigations should confirm that the different processing methods are calculating stability in the same way.

8.2. APPENDIX B. Data availability and Filter conditions

Availability of energy flux data and effects of filter conditions on data from 2009-2011.

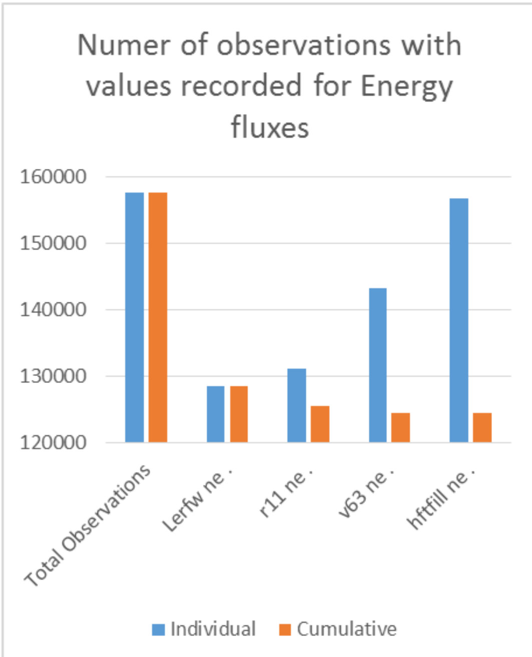

Figure 18. Availability of energy flux data from 2009-2011

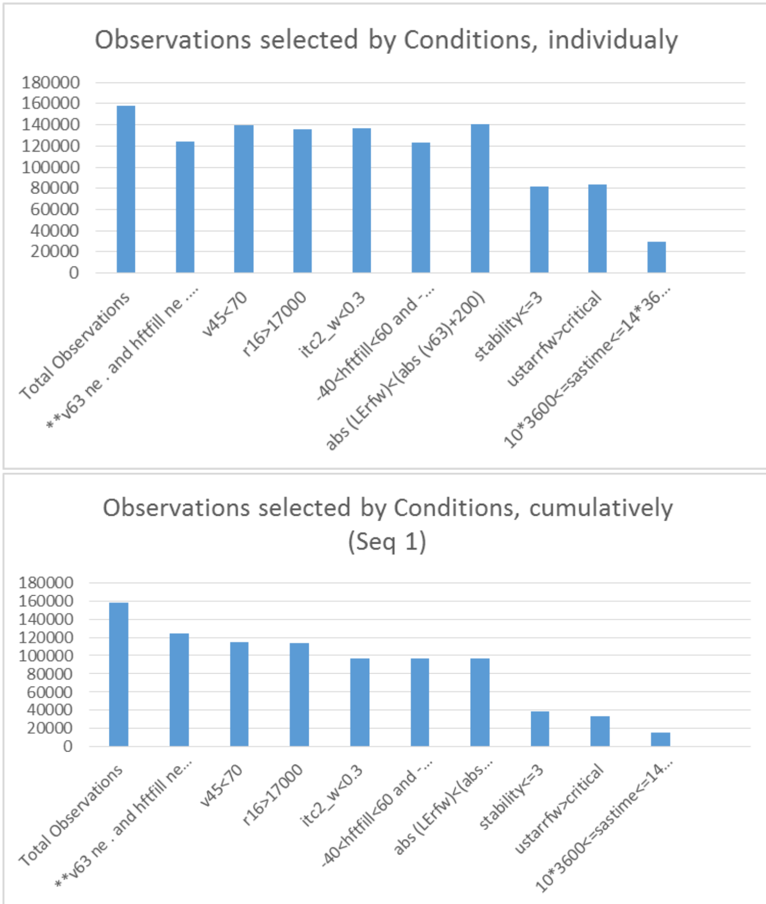

Figure 19. Effects of filter conditions on data availability