Relevant changes:

- Additional year of data added to analysis
- U* filter threshold redefined
- Use of Reichstein et al. 2005 LUT for gapfilling
- Revised wind direction filter at Pine Upland so that more fluxes are available
- Removed energy budget closure correction for LE and H
- Added CH4 molar model for gapfilling
- Estimated monthly uncertainty as root mean square sum of random uncertainty and gap-filling uncertainty.
- Added local despike filter for LE, H, +-NEE, CH4 fluxes
- Added some detail on management implications
- Editorial edits

Interactive comment on “Carbon exchange between the atmosphere and subtropical forested cypress and pine wetlands” by W. B. Shoemaker et al.

Anonymous Referee #1

Received and published: 15 December 2014

This article reports on the dynamics of Net Ecosystem Exchange of CO2 (NEE) and energy fluxes (sensible and latent heat, H and LE respectively) using one year of data from three distinct ecosystem types in or near the Florida Everglades (a cypress swamp, a dwarf cypress wetland, and a pine upland forest). In one site (the dwarf cypress), methane flux is also measured. The data from the cypress sites have the potential to improve our understanding of ecosystem carbon cycling in warm subtropical wetlands, which are certainly underrepresented in the current network of flux monitoring sites. The upland pine site is not a wetland site; nonetheless, it represents a historic ecosystem type (i.e. open pine savannah experiencing frequent fire) that is the focus of many restoration efforts in the region.

Thus, studies that help us to understand patterns and drivers of carbon and water cycling in such a forest should be viewed as valuable contributions to the literature. Finally, these studies are located in an important conservation area (i.e. the Florida Everglades) reknown for its biodiversity and subject to much regional and national attention from the environmental community. Thus, while the significance of these results is potentially large, the current study suffers from a number of shortcomings, many of them methodological, which reduce the strength of the conclusions and the relevance of these results for predicting long-term patterns of carbon and water cycling in these sites.

Thank you for reviewing this paper. Author responses are in bold.
First, the authors present only one year of flux data from each of the three sites. Interannual variability in NEE can be quite large, and a snapshot based on just one year of data can provide a biased view of the carbon uptake capacity. Undoubtedly, the manuscript would be strengthened with the inclusion of an additional year of data. The study period for these results is December 2012 – November 2013. If the towers are still running, then an additional year of data should exist at this point.

Agree, another year of data was added to the manuscript. The paper now covers water, energy and carbon fluxes from 12/2012 to 11/2014.

Next, the authors take an unorthodox approach to filtering, gapfilling, and partitioning the NEE fluxes, which leads me to view the reported annual values with some skepticism, especially since they are among the highest values ever reported in the literature (see Baldocchi et al. 2008, Australian Journal of Botany for reference). First, while they apply a u* threshold to remove data collected under insufficiently turbulent conditions, this threshold is extremely low (< 0.05 m/s). If nocturnal data are retained that are collected under stable conditions, then vertical and horizontal advection fluxes may be important missing components of the flux balance, which could suppress inferred respiration model and thus lead to very high |NEE|.

Agree, the u* threshold was redefined based on plots of u* versus nighttime (9PM to 4AM) NEE normalized by air temperature and vapor pressure deficit, as described by Aubinet et al. (2012, pg. 147). NEE appeared to be considerably different as u* approached a 0.1 threshold at each site. u* filters were therefore increased to 0.1.

Second, daytime NEE data were gapfilled using a relationship between NEE and LE, which in my view is not appropriate as LE can represent a significant contribution from evaporation, which is not mechanistically coupled to carbon assimilation or respiration. This is particularly true in sites that support standing water!

Agree, the NEE(LE) gap-filler was replaced with a conventional look-up table from Reichstein et al. 2005.

While I do not believe that all flux data must use a uniform set of gapfilling & partitioning approaches, some justification for novel approaches should be provided, and evidence should be given that these approaches are more site-appropriate than the well-established procedures that are widely used by the community (see, for example, Reichstein et al. 2005 or Lasslop et al. 2010). In the case of this particular study, I believe the results would be much stronger if the site-specific fluxes were presented alongside flux estimates derived from standardized approaches. Towards that end, the authors may find this Online Flux Partitioning and Gapfilling tool helpful: http://www.bgc-jena.mpg.de/_MDIwork/eddyproc/. The Reichstein et al. (2005) and Lasslop et al. (2010) approaches are discussed thoroughly on that website.

Agree to use well-established procedures as documented by Reichstein et al. 2005.

Third, as the authors acknowledge, export of carbon through surface water flow can be an important component of the carbon balance in wetland ecosystems. Unfortunately this was not measured in these sites; this is okay, but the authors should do a better job of discussing the relevance of this missing term, and also make its absence clear in the abstract.

Agree, “unmeasured” overland flow was added to abstract. This issue is mentioned in the text beneath equation 1 as “Technical difficulties inherent in measuring “sheet flow” and the dissolved/particulate organic/inorganic C concentrations within surface water did not allow quantification of this term.”

Finally, the discussion of the drivers of these ecosystem fluxes is largely focused on seasonal patterns in meteorological conditions and EVI (or leaf area). Their principle conclusions seem to
be: a) NEE and LE will be more decoupled in sites with open water, and b) replacing green leaf area with open water will decrease the magnitude of carbon uptake. Neither of these are particularly surprising and both could have been predicted a priori. Disagree, the relative magnitudes of transpiration and evaporation are uncertain and debated - albeit verbally in science discussions of ET in greater Everglades wetlands. This paper demonstrates the magnitude of transpiration (and C uptake) is resolvable with EC methods and sufficient to alter bulk ET over cypress and pine forested wetlands with standing water. Furthermore, periphyton production at open water sites has been suggested as a mechanism for C uptake. A priori, it was unclear whether growth and decay of periphyton would produce similar C uptake rates as cypress, pine or sawgrass productivity. This study provides some clarity on these issues.

I wish the authors had focused more closely on the unique physical and physiological features of the site (i.e. variation in water table depth, the effect of burning in the pine upland site, the exceptionally warm and mesic climate, etc), as in doing so their results may have represented a more novel and meaningful contribution to our understanding of carbon and water cycling in these ecosystems, and the sensitivity of these fluxes to ongoing changes in climate and management regime. Agree, another year of data was added to the analysis, creating an opportunity to discuss soil respiration responses to water levels dropping below land surface for an extended period of time at all three sites. Soil oxidation is of keen interest in south Florida. We are able to link enhanced respiration to dry conditions using the 2nd year of data. We are unable to address the effects of fire and controlled burns on C cycling, as there were no fires on record during our study time period. A controlled burn recently occurred (during Jan 2015) near the Dwarf Cypress site. Preliminary analysis indicates the burn areas were outside of our C flux footprint.

Some minor comments follow: Section 2.1: Can the authors report on leaf area index for the study sites, rather than using a qualitative approach to describing canopy cover (i.e. open vs dense?). Our attempts to collect LAI data during field runs have failed, either due to bad equipment or safety issues associated taking measurements while hanging from tall towers. We feel panoramic photos in Figure 2 provide readers with an understanding of LAI at each site.

Section 2.3, page 15760, lines 1 - 10: These threshold filters seem to be too limiting. How were they chosen, and what is the effect of using thresholds that have a higher absolute magnitude? Agree, the thresholds seem somewhat subjective and biased by expert judgment of unrealistic limits. After advanced processing with EdiPro, our 30-minute fluxes were somewhat “spikey”, especially at the Cypress Swamp site (see Figure 6B). Higher thresholds created “spiker” daily results. Some of the “spikes” could be real ebullition or large uptake events; however, it is difficult to know this for sure as processes such as ebullition are active areas of research. Furthermore, rapid events are difficult to model for gap-filling procedures. We acknowledge this issue as limitation of our work.

Section 2.3, page 15760, lines 12-17: A very large amount of data from the pine upland (60%) is removed in an effort to avoid contamination from fossil fuel burning occurring to the east of the tower. More details need to be provided about when the data originates from the east (for example, is it principally at night or during the day)? Also, it is possible a footprint model could be used to more carefully exclude questionable data, and thereby improve data availability?
Agree, more details were added regarding seasonality in wind-direction, mean day/night wind directions, and data availability after the wind direction filter. We also reduced the filter to exclude data originating from 15 to 130°, which increased data availability for trend identification and C flux modeling.

Section 2.3, page 15761, lines 1-10: The authors correct the energy balance fluxes in order to force energy balance closure. This is not an approach that I recommend, as there are many reasons why energy balance closure may be low at any given site, and the synthesis of Foken (2008) and Stoy (2013) suggest that macro-scale heterogeneities will likely affect the observation of sensible heat for than latent heat flux, which invalidates the assumption of accurate measurement of the Bowen Ratio. If the authors insist on this approach, at some point the pre-corrected energy balance closure should be reported. It would also be helpful to report the estimates of annual sensible and latent heat flux before and after the correction.

Agree, thank you for this clarification of the literature. We removed the energy budget closure correction for H and LE.

Section 2.3, page 15762, Lines 11-22: Was the methane data missing evenly over the course of the year, and over the course of a representative day?

Agree, we clarified that CH4 was missing mostly during the months of 12/2012 to 5/2013; 10/2013 to 1/2014; 4/2014 to 5/2014; and 11/2014. Missing data also was identified on Figure 5C.

Section 3.3., page 15766, lines 24 - 26: Can these correlations between NEE & LE be placed into context by including previously reported values at other sites.

We were unable to find published correlations of NEE and LE at other sites. These correlations may become more available in the literature, as deployment time increases for the relatively new LICOR 7500 gas analyzers.

Interactive comment on “Carbon exchange between the atmosphere and subtropical forested cypress and pine wetlands” by W. B. Shoemaker et al.

A. Desai (Referee)
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This manuscript reports on one year of eddy covariance observations of carbon, water, and heat flux at a trio of sites in Florida, USA that present fluxes at a topographic gradient across pine upland, cypress swamp, and dwarf cypress vegetation within and near a preserve. These are understudied ecosystems and its C sequestration has important implications for wetland restoration. It’s good to see more of these kinds of sites reported in the literature and I believe this paper should be published. However, there are some methodological shortcomings and areas for additional analysis that will require major revision before I believe it should be accepted in BG.

Thank you for taking time to review our paper, author responses are in bold.

Major:

The sites were certainly challenging to measure and a result a number of gaps occurred. The presence of oil drilling nearby complicated one site, while methane sensor window cleanliness
affected another. Further, the GEE/RE partitioning method is somewhat novel and motivated
mainly from the perspective of poor correlations with standard variables (T, maybe PAR?). I
think if the authors wish to present annual sums of various flux components, much more work
should be done on estimating uncertainty in the flux estimates due to sampling error, gaps, and
partitioning and these should be propagated through to estimate uncertainty of annual NEE,
GEE, RE, which will help later put into context any inter annual variability in future analyses and
also make the sites more comparable to the published literature. For sampling error, this could
be done with existing published methods. I believe EddyPro or other flux processing software
outputs at least an estimate of error. Generally, this is small.

Agree, random error for measured fluxes was estimated with EdiPro based on Finkelstein
and Sims (2001).

Gap filling error can be estimated either by a) propagating the uncertainty of the least-squares
regression parameters using a Monte Carlo approach or b) creating artificial gaps and
estimating the reliability of estimating fluxes using the gap filling model (i.e., within site cross
validation) - Partitioning error can be estimated in similar way to above.

Agree, artificial gaps (1, 5, 10 and 20% of available NEE) were created in observed NEE
for LUT gap filling based on Reichstein (2005). The standard error of residuals between
observed NEE and LUT NEE was used as an approximation of uncertainty. The
maximum standard error of the artificial gap scenarios was summed with random errors
into root mean square monthly uncertainty estimates.

In particular, the use of latent heat flux (and the inherent uncertainty of that value which is
greater than for temperature or other state variables) to fill NEE requires some more discussion
on mechanism and reliability. What about shortwave radiation?

Agree, the latent heat gap-filling function was replaced with a LUT approach from
Reichstein (2005). This LUT approach performed better than the latent heat correlation
for gap-filling NEE.

The authors might also consider comparing the NEE, GEE and Reco estimates from their
method to standard published methods, such as the MDS or temperature based non-linear
regression. Even though the fit is bad to temperature, it is worth showing what the standard gap
filling models produce. MDS relies on sampling across measured observations and there are
pre-compiled R packages and online gap filling tools at http://www.bgc-jena.mpg.de/bgc-
mdi/html/eddyproc/index.html

Moffat, A.M., Papale, D., Reichstein, M., Hollinger, D.Y., Richardson, A.D., Barr, A.G.,
Beckstein, C., Braswell, B.H., Churkina, G., Desai, A.R., Falge, E., Gove, J.H., Heimann, M.,
comparison of gap-filling techniques for eddy covariance net carbon fluxes, Agricultural and

Desai, A.R., Richardson, A.D., Moffat, A.M., Kattge, J., Hollinger, D.Y., Barr, A., Falge, E.,
covariance GPP and RE decomposition techniques, Agricultural and Forest Meteorology, 148(6-

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C.,
Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havranova, K., Ilvesniemi, H., Janous,
D., Knoll, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F.,
Ourcival, J.M., Pumpenan, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G.,

The LUT approach from Reichstein (2005) was applied in this paper. Comparisons between the latent heat gap-filler and LUT approaches were not presented, as the goal of this study is to present approximate magnitudes and trends in C fluxes for cypress and pine-forested wetlands. A separate paper could be written about the relative performance of various gap-filling procedures.

In particular, with 80% of CH4 missing, the authors just chose to average across existing data to create monthly means, if I understood the manuscript correctly. This seems problematic if the distribution of missing data is biased from month to month. Either this needs to be disproven or the authors should consider MDS or similar gap filling method, and certainly an uncertainty budget is required. Further, this provides another motivation for uncertainty analysis.

Agree, the distribution of missing data was biased from month to month. We clarified that CH4 was missing mostly during the months of 12/2012 to 5/2013; 10/2013 to 1/2014; 4/2014 to 5/2014; and 11/2014. Missing data was identified on Figure 5C. CH4 averaging was replaced with a CH4 molar flux model driven by air temperature and water levels at daily resolution. The standard error of the molar flux model was used for uncertainty analysis.

3. Lateral flows are neglected and that seems appropriate at this stage. However, there are published estimates from other sites of the % of C in lateral flow in marshes, wetlands, and so forth. Some discussion on what that value might be for these sites and what that implies for the NECB would be useful. See, for example (for northern sites):


Disagree, the lead author is not comfortable presenting lateral C flux results from other studies as a proxy for the greater Everglades. Lateral C fluxes are currently being measured near our stations as part of another study; however, the results are preliminary and evolving. Combining lateral C fluxes in the Everglades with our atmospheric fluxes is the focus of future work.

There is a lot of confusion in various parts on methane. There is a report value of 12 gC/m-2/yr. Yes, many of the global warming potential estimates use a value of 20 gC (in the abstract) and 15 gC (in the manuscript). Why not use 12? It is almost as if these were written before the final value was inserted into the text! Further, there is good literature showing that IPCC based GWP estimates for CH4 emission from wetland is not appropriate for two reasons: 1) GWP is based on an instantaneous mass pulse of CH4 and CO2 and relative contributions to radiative forcing that are time-scale dependent (hence the 100-yr vs 25-yr values) whereas wetlands have continuous emissions, which alters the net GWP - as most of the past wetland CH4 emissions are already CO2 in the atmosphere - why use 100? and 2) wetlands have been emitting methane and sequestering carbon likely for the past thousands of years whereas GWP is an
expected radiative forcing change for a perturbation to the atmosphere. This wetland is not perturbing the background state unless it is converted to something else. For more discussion, I recommend this paper by Frolking et al: Frolking, S., N. Roulet, and J. Fuglestvedt (2006), How northern peatlands influence the Earth’s radiative budget: Sustained methane emission versus sustained carbon sequestration, J. Geophys. Res., 111, G01008, doi:10.1029/2005JG00091. So I don’t object to including GWP estimates, but caution on their use for wetlands must be mentioned.

Agree, we clarified the CH4 and C-CH4 fluxes. We stated some of the limitations you mention regarding GWP multipliers - specifically, “We recognize GWP multipliers are controversial due to assumptions such as instantaneous CH4 and CO2 release, and time-scale dependence of the radiative forcing contributions. Careful use of GWP multipliers for wetlands is suggested”. We emphasized our conclusion regarding methane is its relative insignificance in the C budget for altering land surface topography.

5. Some more justification of various aspects of data processing are required. The u* cutoff are quite low and at least in water covered surfaces, diffusive fluxes scale directly with u*.

Agree, the u* threshold was redefined based on plots of u* versus nighttime (9PM to 4AM) NEE normalized by air temperature and vapor pressure deficit, as described by Aubinet et al. (2012, pg. 147). NEE appeared to be considerably different as u* decreased approximately below 0.1 threshold at each site.

Correcting latent heat flux by Bowen ratio energy balance closure has published in Twine, but future papers all recommend against this as a standard practice. It puts certain assumptions on where the underestimation occurs, which do not have justification.

Agree, we removed the energy-budget closure correction for H and LE.

Finally, strict screening criteria are applied to NEE observations which require at least some discussion of the fraction of large fluxes screened. I worry that "real" events of flushing or large uptake are being missed if too conservative in the screening. Why not apply a 3-sigma type local despike filter?

Agree, we removed half-hour fluxes that fall outside 3 standard deviations within a moving 7 day window. This local de-spike filter significantly improved trend identification.

Further, the authors do not measure storage flux, only the turbulent flux. For analysis of half-hourly fluxes in tall canopies (such as the upland and the forested wetland), this adds an additional source of uncertainty (in some cases, previously screened turbulent fluxes may be actually brought back into the threshold by consideration of storage) - at least 1-point storage flux could be computed for the canopy towers.

Disagree, our stations are over 16 m tall. We decided against including 1-point storage changes in light of guidance in EdiPro: “In eddy covariance applications where profile concentration data are not available, storage fluxes are approximated by using one-point time derivatives, assuming that all gradients nullify at ground level and that the profile is linear from the measurement point to the ground. Evidently, this is an extreme assumption that has little relation to the actual situation. This is why we encourage users to consider storage fluxes provided by EddyPro as purely indicative. For the same reason, storage fluxes are not summed to turbulent fluxes to provide Net Ecosystem Exchange (NEE) estimations, that would be affected by unacceptable inaccuracy.”

For the wind direction screening for the oil drilling, perhaps a supplemental figure of wind direction versus CO2 flux might be useful to see, or a footprint model.
Agree, more details were added regarding wind-direction seasonality, mean day/night directions and data availability. We reduced the filter to the edge of our comfort zone (15 to 30), prior to re-submitting this paper. Over ten-thousand NEE fluxes remained for trend identification and gap-filling after the contamination filter at the Pine Upland site. Seasonal trends were apparent and diurnal NEE variations were resolvable into surrogates for respiration and photosynthesis.

6. It appears water depth by pressure transducer was measured and the introduction cites literature on the importance of water level on fluxes at other nearby sites. Yes, there is very little discussion of this other than to mention that dry/wet season differences in fluxes cannot be estimated with only one year of data. However, regression at the half-hourly or daily scale of NEE to water depth within each season might be useful to do for evaluating mechanisms and comparing to other papers - certainly some variability occurs. I wonder to what extent water level may be a better variable for gap-filling and partitioning instead of LE too?

Agree, a year of data was added to the analysis. This data extension created an opportunity to discuss soil respiration responses to water levels dropping below land surface for an extended period of time at all three sites. Soil oxidation is of keen interest in south Florida. We are able to link suppressed respiration to flooding using the 2nd year of data.

7. Given the importance of the ecosystems locally, it would be nice for the paper to attempt to scale these fluxes across the region. How important are they for the BCNP? Can a simple upscaling be accomplish to discuss total area C sink capacity and current uncertainty?

Disagree, upscaling is planned for future study. The lead author would like to improve maps of the spatial distribution of plant communities, before upscaling and distributing results.

8. I recognize that USGS cannot make policy statements. However, the introduction hints at the importance of this study for wetland restoration locally. However, the discussion or conclusion does not fully discuss these implications. Without making a policy statement, I think the paper could make some stronger statements on what restoration might imply for C sink capacity of the area and the impact of changes to the landscape. Perhaps the scaling in the previous comment might help with that.

Thank you for acknowledging USGS sensitivity regarding policy statements. We added statements regarding the possibility of suppressing soil respiration with hydro-period management. We also state that a redistribution of plant communities toward more open-water ecosystems could create less C uptake and greater evaporative losses. The lead author feels the paper may need to be reapproved by the USGS for publication, if we add further managerial guidance.

9. Finally, I’d like to encourage the authors to share their flux data, perhaps by submitting to the Fluxnet archive upon publication of the paper. Open data goes hand in hand with open access publication.

Agree, we’ve made our flux and met data (with DOI’s) available on the following Federal public repository:


We hope to eventually share our data with Ameriflux and Fluxnet, as permitted by time, funding and Federal priorities.

Minor:
I recommend ending the introduction with a set of hypotheses or questions motivated by the Jimenez and other papers and the objectives. –

Agree.

Page 15764, line 8 - do you mean transpiration was limited by tree physiology?

Agree.

Page 15769 line 20 - the sentence links: were revealed, seems like it could be expanded to make a stronger statement. What links?

Agree, “such as photosynthetic water-use efficiencies” was added to the sentence

Carbon Exchange between the Atmosphere and Subtropical Forested Cypress and Pine Wetlands

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Abstract

Carbon dioxide exchange between the atmosphere and forested subtropical wetlands is largely unknown. Here we report a first step in characterizing this atmospheric-ecosystem carbon (C) exchange, for cypress strands and pine forests in the Greater Everglades of Florida as measured with eddy covariance methods at three locations (Cypress Swamp, Dwarf Cypress and Pine Upland) for one two years. Links between water and C cycles also are examined at these three sites, and methane emission measured only at the Dwarf Cypress site. Each forested wetland showed net C uptake (retained in the soil and biomass or transported laterally via overland flow) from the atmosphere both monthly and annually. Net, as indicated by net ecosystem exchange (NEE) of carbon dioxide (CO₂). For this study, NEE is the difference between photosynthesis and respiration, with negative values representing net ecosystem uptake. Net uptake from the atmosphere that is retained in the ecosystem or transported laterally via overland flow (unmeasured for this study). NEE was greatest at the Cypress Swamp (-900 to -1000 g C per m² year), moderate at the Pine Upland (-900650 to -700 g C per m² year), and least at the Dwarf Cypress (-500400 to -450 g C per m² year). Methane emission was a negligible part of the C (12 g C per m² year) budget when compared to NEE. However, methane (CH₄) production was considerable in terms of global warming potential, as about 20 g CH₄ emitted per m² year was equivalent to about 500 g CO₂ emitted per m² year. Changes in NEE were clearly a function of seasonality in solar insolation, air temperature and water availability from rainfallflooding which suppressed heterotrophic soil respiration. We also note that changes in the satellite-derived enhanced-vegetation index (EVI) served as a useful surrogate for changes in net and gross atmospheric-ecosystem C exchange NEE at these forested wetland sites.
1 Introduction

Wetlands At global scales, wetlands are generally considered large natural sources for methane emission (Whalen 2005, Sjögersten et al. 2014) and sinks for atmospheric carbon dioxide (Troxler et al. 2013, Bridgham et al., 2006). Wetlands in southern Florida’s greater Everglades (http://sofia.usgs.gov/) are expansive subtropical ecosystems that are generally believed to be carbon (C) accumulating over geologic time scales (Jones et al., 2014). Here we report a first step in characterizing modern rates of atmospheric-ecosystem carbon (C) exchange, for cypress strands and pine forests in the Greater Everglades of Florida.

The primary goal of this paper is to quantify the magnitude and controls of C exchange within cypress and pine forested wetlands: in this paper, these wetland communities are defined by McPherson (1973) and Duever et al. (1986, 2002). Quantities of interest include net atmospheric/ecosystem C exchange (NEE), ecosystem respiration (RE), gross ecosystem exchange (GEE), and methane emissions. Latent heat flux (LE) and evapotranspiration (ET) also are quantified so that links between water and C cycles can be quantitatively studied, such as photosynthesis and water use efficiencies. We address several specific objectives on daily, monthly and annual time scales, including (1) the magnitude of cypress (tall and dwarf) and pine forested wetlands as net atmospheric C sources or sinks, (2) site differences in water and C exchange metrics (i.e., NEE, GEE, RE, and surface energy fluxes), and (3) the magnitude of methane emission over a dwarf cypress wetland. Results from this study are expected to help define and predict subtropical forested wetland responses to regional (e.g., freshwater discharge) and global (e.g., air temperature) environmental change, and to provide some insights into the relationships between carbon, water, and methane fluxes.
In addition to the insight provided by this study on the role of subtropical forested wetlands in the global carbon cycle, this research also is expected to be useful for determining the consequences of land-use changes in the Everglades region. Canal building and drainage projects in south Florida have reduced the original extent of the Everglades (Parker et al., 1955) and diminished ecosystem services, decreased peat accretion rates and total carbon stocks, and reduced ecosystem services. Hohner and Dreschel (2015), for example, estimate the Greater Everglades has less than 24% its original peat volume and 19% of its original carbon. In response, State and Federal governments are planning and executing complex projects to restore Everglade’s wetlands (http://www.evergladesplan.org/) while concurrently avoiding flooding in urbanized areas and maintaining water supply.

Restoring ecosystems will affect water, energy and C cycles, as plants and soil processes adjust to changing water levels, albedos, salinities, nutrient loads and forest fires fire regimes. For example, Jimenez et al. (2012) and Schedlbauer et al. (2010) indicate that additional deliveries of water into peat and marl sawgrass wetlands may diminish C accumulation within these wetlands. Eddy-covariance derived estimates of net ecosystem productivity declined with increasing inundation during the wet season (Jimenez et al., 2012; Schedlbauer et al., 2010). These results were partially attributed to the amount of vegetation that, due to flooding, could not directly exchange carbon dioxide with the atmosphere. The opposite trend was observed in a tidally influenced mangrove forest in Everglades National Park. Lowered salinities, resulting from increased freshwater flow, resulted in increased daily PAR-use efficiency (i.e. ratio of gross ecosystem productivity to photosynthetically active irradiance (PAR), Barr et al., 2010; Barr et al., 2012). Also, ecosystem respiration losses were lower during periods of inundation (Barr et al., 2010; Barr et al., 2012), which increased net C uptake
over the mangrove forest. These studies provide insights on water and C cycling over coastal
sawgrass wetlands and mangrove forests. C cycling over other subtropical wetlands, such as
cypress strands and pine forests, is largely unstudied (Sjogersten et al. 2014).

The primary goal of this paper is to quantify the magnitude and controls of C exchange
within cypress and pine forested wetlands. These wetland communities are defined by
McPherson (1973) and Duever et al. (1986, 2002). Quantities of interest include net
atmospheric/ecosystem C exchange (NEE), ecosystem respiration (RE), gross ecosystem
exchange (GEE), and methane emissions. Latent heat flux (LE) and evapotranspiration (ET)
also are quantified so that links between water and C cycles can be quantitatively studied. We
address several specific objectives on daily, monthly and annual time scales, including (1) the
magnitude of cypress (tall and dwarf) and pine forested wetlands as net atmospheric C sources or
sinks, (2) site differences in water and C exchange metrics (i.e., NEE, GEE, RE, and surface
energy fluxes), and (3) the magnitude of methane emission over a dwarf cypress wetland.
Results from this study are expected to help define and predict responses of subtropical forested
wetlands to regional (e.g., freshwater discharge) and global (e.g., air temperature) environmental
change.

2 Methods

2.1 Site Description

The study area is the Big Cypress National Preserve (BCNP) in southern Florida (Figure
1). A variety of subtropical forested and non-forested wetland ecosystems are present in BCNP,
including Pine Upland, Wet Prairie, Marsh, Hardwood Hammocks, Cypress Swamps, Dwarf
Cypress and Mangrove Forests as formally characterized by McPherson (1973) and Duever et al.
(1986, 2002). The distribution of ecosystems and plant communities in the BCNP is controlled
by topography, hydrologic and hydrology, fire regimes, and soil conditions (Duever et al., 1986).

Marsh, Cypress Swamp, and Mangrove Forests typically occupy low elevations (< 2.5 m National Geodetic Vertical Datum, NGVD-29), Wet Prairie occupies middle elevations (3 to 4 m NGVD-29), and Pine Uplands and Hardwood Hammocks occupy high elevations (>4 m NGVD-29). These wetlands provide floodwater protection, hurricane buffering, substrate stabilization, sediment trapping, water filtration, and other ecosystem services for urban areas and coastal estuaries.

Water and C fluxes were determined over Pine Upland, Cypress Swamp and Dwarf Cypress ecosystems (Figure 1, Table 1) from December 2012 to December 2013-November 2014 (Shoemaker et al., 2015d, e, f). The Pine Upland site (Figure 1, Table 1), is classified as a mixed lowland pine site, and is located in an extensive open-canopy pine forest with numerous small- to medium-sized cypress domes. The canopy is dominated by slash pine (*Pinus elliottii*) with an understory of saw palmetto (*Serenoa repens*), small trees and shrubs including holly (*Ilex cassine*), swamp bay (*Persea palustris*), myrsine (*Myrsine cubana*), and wax myrtle (*Myrica cerifera*), and scattered sabal palms (*Sabal palmetto*) (Figure 2). The ground cover is a diverse mix of short (less than 1 m) grasses, sedges, and forbs that are scattered in open-to-dense patches around the site. The open character of the site indicates regular burning with fire recurrence every 5 years, on average. Large cypress domes have a dense canopy of cypress, but open subcanopy and shrub strata, probably due to frequent fires. Substrates are primarily limestone bedrock, with sandy marl in the shallow depressions. Cypress domes in the area have a shallow organic substrate in the deeper areas.

The Cypress Swamp site (Figure 1, Table 1) is classified as a swamp forest (Duever et al., 1986) and supports a tall dense cypress forest with a subcanopy of mixed hardwoods (Figure 2).
Plant varieties include bald cypress (*Taxodium distichum*), holly, swamp bay, maple (*Acer rubrum*), an open-to-dense shrub layer with coco plum (*Chrysobalanus icaco*), myrsine, wax myrtle, an open-to-dense ground cover of swamp fern (*Blechnum serrulatum*), and a variety of grasses, sedges, and forbs. The substrate is primarily topographically irregular limestone bedrock with organic accumulations in depressions in the rock.

The Dwarf Cypress site is classified as scrub cypress and is dominated by cypress, *Taxodium distichum*, and scattered (5 to 10 percent cover) sawgrass less than 1 m high (Figure 2). Small to medium-sized cypress domes are present, and periphyton is seasonally abundant (Figure 2) from about July to December. The substrate is shallow marl overlying topographically irregular limestone bedrock.

### 2.2 Carbon Balance

A mass balance equation can be used to conceptualize C fluxes. Net ecosystem C balance (NECB) is the amount of C accumulating in the ecosystem, in units of mass per area-time (Chapin et al. 2006, Troxler et al., 2013). NECB can be partly approximated using eddy-covariance methods by measuring (1) the net vertical (1-dimensional) exchange of carbon dioxide (-NEE) across the ecosystem-atmosphere interface, (2) the net lateral flux (F<sub>net</sub>) of dissolved/particulate organic/inorganic C leaving the system, and (3) the C released from methane emission (F<sub>CH4</sub>):

\[
NECB = -\text{NEE} - F_{\text{net}} - F_{\text{CH4}}
\]

A negative sign for NEE indicates a loss of carbon dioxide from the atmosphere. The net lateral flux of C (F<sub>net</sub>) occurs primarily within surface water that flows down topographic gradients toward mangrove wetlands on the coast (Figure 1). Technical difficulties inherent in measuring “sheet flow” and the dissolved/particulate organic/inorganic C concentrations within
surface water did not allow quantification of this term. Therefore, we only report exchanges of gases between the atmosphere and the ecosystem. Methane emission \( F_{\text{CH}_4} \) at the Dwarf Cypress site was determined using a LICOR-7700 open-path methane analyzer. (Shoemaker et al., 2015d). The cost of the methane analyzer and safety issues related to climbing tall towers limited measurements of \( F_{\text{CH}_4} \) to a single site (Dwarf Cypress, Figure 2). Thus, our daily and annual NEE estimates likely are an upper bound for C accumulation at the Pine Upland and Cypress Swamp sites (and lower bound for atmospheric transfer to the ecosystem) due to uncertainty associated with methane emission and lateral C fluxes.

2.3 Eddy Covariance Method and Gap-filling

The eddy covariance method (Dyer, 1961; Tanner and Greene, 1989) is a one-dimensional (vertical) approach for measuring the exchange of gases within the atmospheric surface layer (Campbell and Norman, 1998). Key instrumentation (Table 2) includes sonic anemometers that rapidly (10-Hz) measure wind velocity and gas analyzers that rapidly measure gas concentrations (Table 2) in the atmosphere. The covariance between vertical wind velocities and gas concentrations determines the net exchange of gases between the ecosystem and atmosphere. Additional instrumentation (Table 2) was installed at each site to measure net radiation, soil-heat flux, soil temperatures, air temperature and relative humidity, and distance of water above or below land surface (using pressure transducers). Pressure transducers were placed in the bottom of groundwater wells to measure the distance of water above and below land surface. Pressure transducers were corrected monthly for instrumentation drift using manual depth-to-water measurements from the top of the well casings. The manual depth-to-water measurements allowed precise calibration of continuous water distance above or below land-surface. Monthly site visits were made to download data, perform sensor inspections and...
complete other site maintenance. All instrumentation was visually inspected, leveled, cleaned, or replaced as necessary.

Raw, 10-Hz, vertical wind speed, temperature, and gas concentration data were processed to half-hourly fluxes using EddyPro software (version 4.0.0) following Express advanced protocols that included random uncertainty estimates (Finkelstein and Sims, 2001), spiking filters, double coordinate rotations, blocked-average detrending, statistical filters, air density and oxygen corrections (Tanner and Thurtell, 1969; Baldocchi et al., 1988; Webb et al., 1980; Tanner et al. 1993), and high-pass filtering. Processed data yielded half-hourly mean values of NEE, methane, sensible and latent heat fluxes that were filtered to remove periods with unrealistic fluxes: (1) Cypress Swamp - latent heat fluxes >800 and < -100 watts m\(^{-2}\), sensible heat fluxes >400 and < 50 watts m\(^{-2}\), NEE >1025 and < 14030 µmol m\(^{-2}\) s\(^{-1}\) at the Dwarf Cypress site, NEE >25 and < 25 µmol m\(^{-2}\) s\(^{-1}\) at the Cypress Swamp site, latent heat fluxes >600 and < -150 watts m\(^{-2}\), sensible heat flux >500 and < -100, NEE >20 and < 2025 µmol m\(^{-2}\) s\(^{-1}\). FCH4 >0.5 and < 0.2; Pine Upland - latent heat fluxes >1000 and < -300 watts m\(^{-2}\), sensible heat flux >500 and < 200 watts m\(^{-2}\), NEE >125 and < 250 µmol m\(^{-2}\) s\(^{-1}\) at the Pine Upland site. (2). These thresholds may inherently disregard some naturally large uptake or efflux events. For instance, ebullition events can be an important mechanism for episodic release of methane to the atmosphere (Comas and Wright, 2012). However, at present, the drivers of these events are not well understood and thus difficult to model with physiological-based gap-filling procedures. Following EdiPro processing, local despike and friction velocity (u*) <0.05 m s\(^{-1}\) filters were applied to the gas fluxes (Shoemaker et al., 2015d, e, f). The local despike filter removed half-hour fluxes that fell outside 3 standard deviations of the fluxes within a moving 7-day window. Friction velocity is an indicator of time periods when turbulent wind conditions are
well developed. Eddy covariance methods are theoretically appropriate for turbulent wind conditions. The u* threshold was selected based on a sensitivity analysis of daily u* versus nighttime (9PM to 4AM) NEE normalized by air temperature and monthly gap-filled NEE to u* thresholds of 0.05, 0.15, and 0.25 vapor pressure deficit, as described by Aubinet et al. (2012, pg. 147). NEE was essentially the same under each appeared to be considerably different as u* decreased approximately below 0.1 threshold, while the u* filter of <0.05 m s\(^{-1}\) preserved more of the observed data and thus required less gap-filling. Roughly 4, 225, 17, and 21 percent of the water and C fluxes NEE values were removed by the u* filter, local despike and unrealistic value filters at the Cypress Swamp, Dwarf Cypress and Pine Upland sites, respectively. Relatively small u* values were generally observed at night, as expected, due to low wind velocity at night. A final mathematical filter removed all C fluxes at the Pine Upland site (Figure 3) when NEE contamination was possible due to fossil fuel combustion by generators and trucks supporting oil-drilling activities adjacent to the eddy-covariance tower. All carbon fluxes were removed at Pine Upland when the wind blew direction was from the east of the tower (915 to 130°). This filter removed about 50% of the carbon flux-remaining NEE data, under the assumption the NEE fluxes were likely affected by drilling activities. East winds were evenly distributed over day (145° mean wind direction) and night (167° mean wind direction). Winds originated from the east mostly during the winter (October to December) as regional-scale cold fronts moved southward with winds blowing over peninsular Florida from the Atlantic Ocean towards the Gulf of Mexico. Over ten-thousand NEE fluxes remained for trend identification and gap-filling after the contamination filter at the Pine Upland site.
Seasonal trends were apparent and diurnal NEE variations were resolvable into surrogates for respiration and photosynthesis, as described below.

Missing 30-minute latent heat fluxes were gap-filled with a regression-calibrated Priestley-Taylor (Priestley and Taylor, 1972) equation (Figure 3), using the methods of Shoemaker and Sumner (2006). The Priestley-Taylor equation was formulated as:

\[ AE = \alpha \frac{\Delta}{\Delta + \gamma} (AE) \]  

(2)

where \( \Delta \) is the slope of the saturated vapor pressure with respect to air temperature, in kilopascals per degree Celsius; \( \gamma \) is the psychrometer constant equal to 0.07 kilopascal per degree Celsius, \( AE \) is available energy (difference between net radiation and the soil heat flux), in watts per square meter; and \( \alpha \) is a regression defined coefficient (Figure 3) that minimized residuals between measured and computed (equation 2) latent heat fluxes.
Previous investigators describe a recurring problem with the eddy covariance method. The sum of measured latent- and sensible-heat fluxes is generally less than the measured available energy. Foken (2008) explained this discrepancy with low-frequency (large-scale) eddies unmeasured by the chosen averaging period (usually 30 minutes). Measured 30-minute latent- and sensible-heat fluxes were corrected to account for low-frequency (large-scale) eddies by assuming the ratio of turbulent fluxes (Bowen ratio; Bowen, 1926) was adequately measured and partitioning the residual available energy by the Bowen ratio (Twine et al., 2000).

Missing 30-minute NEE values were gap-filled using a sequential approach (Figure 3). Gaps with duration less than 4 hours were filled using a 4-hour centered moving mean, computed every half hour. Subsequent gap filling was based upon the predominance of photosynthesis or respiration (RE) within the NEE time series. Photosynthesis generally dominated during the day-time, resulting in negative values for NEE. Respiration generally dominated during the night, resulting in positive values for NEE. Negative NEE was gap-filled using relations between 30-minute NEE and latent heat fluxes (Figure 4) as measured or modeled with the Priestly-Taylor equation (Equation 2). Latent heat flux explained more NEE variability ($R^2 = 0.22$ at Dwarf Cypress, for example) than non-linear light response curves with solar radiation ($R^2 = 0.09$) and air temperature ($R^2 = 0.05$). Photosynthesis simultaneously released water while storing C, according to each ecosystem’s water use efficiency, which may explain improved performance of latent heat for gap-filling NEE. Furthermore, NEE and latent heat fluxes are auto-correlated through vertical wind velocity.

Positive NEE during the night was assumed to represent RE—ecosystem respiration (RE). RE was weakly correlated with quantities such as air temperature ($R^2 = 0.01$ and 0.03 for linear and exponential regression at the Cypress Swamp site, for example); thus, a statistical model was
used for gap-filling. RE was gap-filled with a 4-hour moving mean, followed by the statistical model predicting RE during the day. Daytime RE predictions were needed for gross ecosystem exchange (GEE) estimates. The statistical model randomly estimated values for daytime RE within one standard deviation of the mean RE measured each day. For example, if 20 RE (+NEE) values were available within a 24-hour period, the mean and standard deviation of RE was computed using the 20 available values. Subsequently, 28 missing daytime RE values were randomly estimated from a range that was one standard deviation from the mean. The statistical RE model also was applied to approximate RE during the day—Assuming day-time and night-time respiration statistics are equal could be a source of error in our results. Identification of an alternative to the statistical model was precluded by weak relations between respiration and ancillary variables such as air temperature.

Daily NEE and RE were converted from molar to mass units. Gross daily transfer of C from the atmosphere to the ecosystem (GEE, g C m$^{-2}$ d$^{-1}$) was calculated as the sum of NEE and RE. Daily NEE, RE, and GEE values were summed to generate monthly and annual totals.

Methane emissions ($F_{CH_4}$) at the Dwarf Cypress site had the most missing 30-minute data. Missing $F_{CH_4}$ fluxes were distributed evenly over day and night. About 80% of the $F_{CH_4}$ time series was missing, mostly due to poor signal strength of the methane CH$_4$ analyzer (signal strength filter <10) and spikes. Spikes in methane fluxes also occurred when the analyzer signal strength indicator (RSSI) changed by +10 between half-hourly time periods.

Despite these data gaps, roughly 6,466 methane fluxes (30-minute resolution) were available for analysis following the RSSI filters. Sub-daily gap-filling with empirical regression models was not attempted due to weak correlation with explanatory data, the greatest was $R^2 = 0.11$ with net radiation, barometric pressure. Correlations were similarly weak when isolating methane
emissions measured in the day-time between 10AM and 2PM, specifically, the greatest $R^2 = 0.12$ was with vapor pressure deficit. Given the sub-daily correlations, daily and monthly-over six-thousand molar methane fluxes were averaged by day and up-scaled to 357 molar fluxes of $F_{CH4}$ at daily resolution.

Seasonally, missing daily $F_{CH4}$ molar fluxes were more prevalent from 12/2012 to 5/2013; 10/2013 to 1/2014; 4/2014 to 5/2014; and 11/2014. Due to the seasonality of missing data, a $F_{CH4}$ molar flux model was constructed (daily resolution) as a power function of continuous variables that explained seasonality in methane emission, specifically, air temperature and flooding at the Dwarf Cypress site. The methane model was expressed as:

$$F_{CH4} = R \cdot e^{(BT_a(1+e^{a+b(stage)}) \}}$$

where $T_a$ and $stage$ were mean daily air temperature (Celsius) and water distance above (+) or below (-) land surface (meters), respectively. Least-squares regression defined values of $R=0.008628$, $B=0.04$, $a=-3.8$, and $b=2.7$ that minimized sum-of-squared differences between observed and computed by averaging the available data over days and months.F$CH4$molar fluxes (Figure 3). The $F_{CH4}$ model explained about 40 percent of the variability in mean daily $F_{CH4}$ fluxes.

Daily –NEE, RE, and $F_{CH4}$ were converted from molar to mass units. Gross daily mass transfer of C from the atmosphere to the ecosystem (GEE, g C m$^{-2}$ d$^{-1}$) was calculated as the sum of NEE and RE during the day. Daily GEE, -NEE, RE and $F_{CH4}$ were summed to generate monthly and annual C exchange totals. An upper bound for uncertainty in these totals was approximated using a root mean square error propagating method (Topping, 1972). To summarize, possible sources of error included random uncertainty (Finkelstein and Sims, 2001) and gap-filling error. Gap-filling error was approximated using the standard error for ±NEE gap-
filling by Reichstein (2005). Standard errors were computed by creating artificial gaps (1, 5, 10
and 20% removal) in observed NEE and predicting fluxes during the artificial gaps with the
look-up table. The maximum standard error of the artificial gap scenarios was used to
approximate an upper bound for uncertainty, as follows:

\[ U_{-NEE,RE} = \sqrt{\sum_{t=0}^{\text{month}} (U_r^2 + SE_{max}^2)} \]  

(3)

where \( U_{-NEE,RE} \) were monthly uncertainties in –NEE or RE in g C m\(^{-2}\) per month, \( U_r \) was
random uncertainty (Finkelstein and Sims, 2001) in g C m\(^{-2}\) sec\(^{-1}\), and \( SE_{max} \) was the maximum
standard error of the artificial gap scenarios (equal to 2.2, 1.1, and 2.0 g C m\(^{-2}\) sec\(^{-1}\) for Cypress
Swamp, Dwarf Cypress and Pine Upland, respectively). Uncertainty in monthly GEE was the
sum of uncertainty for –NEE and RE. Uncertainty in \( F_{CH4} \) was estimated with Equation 3 using
random uncertainty estimates (Finkelstein and Sims, 2001) for the methane fluxes and the
standard error (equal to 0.017 g C m\(^{-2}\) d\(^{-1}\)) of the methane flux model (equation 2).

3 Results and Discussion

3.1 Seasonality in Rainfall, Temperature, Water Levels and Energy Fluxes

The subtr...
surface water, creating large variations in both stored-heat energy and turbulent fluxes of heat and water vapor (Shoemaker et al., 2011).

During this study, air temperatures at all three sites (Figure 5A-C) were seasonally lowest (ranging from 15 to 25 °C) during December through March, and as low as 12 C for several days during the passage of cold fronts in the winter. Cold fronts typically lasted 5 days or less. During April and May, air temperatures rose above 25 C and were less variable as hot and humid air masses dominated the subtropical region. By late May, air temperatures were consistently 25 to 30 C and remained within this range until the onset of the dry season in mid- to late October. Water and soil temperatures (measured 0.15 m below land surface) were nearly identical (absolute differences < 1 C) but were 1 to 5 C higher than air temperature during the passage of cold fronts (Figure 5A). Land surface served as a heat reservoir during cold fronts, and water and soil temperatures seldom fell below 15 C. Cold fronts also increase vapor pressure deficits due to cool, dry air moving rapidly over the relatively wet and warm landscape.

Seasonality was observed in water levels at each site (Figure 5A-C, B and C) in response to rainfall duration and intensity. Water levels were lower in the winter and early spring due to reduced rainfall in the dry season (i.e., November to May). Water levels rose in response to increased rainfall at the end of April 2013 and May 2014, reaching ~1 m above land surface during July through October at the Dwarf Cypress site. In contrast, water levels declined as much as 1.0-1.5 m below land surface at Pine Upland during the early spring dry season in February from March to April-May 2014 (Figure 4A, B and C) creating an opportunity for enhanced soil respiration. Water levels remained approximately at the land surface or slightly
above land surface at the Cypress Swamp until rainfall in June 2014 eventually flooded each site for the entire study time period.

Surface energy fluxes reflected the seasonality in air temperature and rainfall (Figure 5A, B, C). Mean daily net radiation ranged from about 50 to over 200 W m\(^{-2}\) and was greatest in the summer months of June, July and August 2013 and 2014. Net radiation was least from November to February when incoming solar radiation was seasonally smallest. Net radiation was the primary driver of available energy and latent heat flux (Figure 3 and 4; equation 24A, B, C), the energy equivalent of evapotranspiration (ET). Mean daily latent heat fluxes ranged from about 0 to more than over 150 W m\(^{-2}\) and were greatest in the summer months of June, July and August 2013 and 2014 at the Cypress Swamp site. Latent heat fluxes were lowest from November to February when incoming solar radiation was seasonally lowest, and less water was available for evaporation. During these cooler and drier periods, surface evaporation also was limited by lower physiological activity of trees, especially of the deciduous cypress trees (Figure 2B) during fall-winter leaf drop (Figure 5B, C4B). Surface inundation combined with more incoming solar radiation resulted in more energy partitioned as latent versus sensible heat during May to November. Also, cypress leaves were notably greener during this period suggesting increased physiological activity and seasonally higher transpiration rates.

3.2 Carbon Exchange between the Atmosphere and Forested Wetlands

All three sites were generally sinks of atmospheric carbon dioxide (CO\(_2\)) on daily (Figure 6), monthly (Figure 25A, B, C) and annual time scales (Table 34). The sink strength of CO\(_2\) at the Cypress Swamp and Dwarf Cypress sites each site, as evidenced in by --NEE, was reduced during the fall and winter of 2012 and 2013 and 2014 (Table 34, Figure 6 and 7). Reductions in daily --NEE were less dramatic during the same Seasonality in daily --NEE was least at the Pine Upland site were less dramatic during the same
Dwarf Cypress with daily NEE ranging from 1.5 to 2.5 g C m\(^{-2}\) per day compared to 0 to 1.2 g C m\(^{-2}\) and 1 to 2 g C m\(^{-2}\) at the Dwarf Cypress and Cypress Swamp site in the winter and summer, respectively. Pine seasonality in NEE was more extreme Cypress Swamp and Pine Upland with rates ranging from -1 to -5 g C m\(^{-2}\) d\(^{-1}\) in the winter and summer, respectively. Lack of forested vegetation at Dwarf Cypress likely explains the dampened seasonality in C fluxes. Furthermore, pine trees grow and maintain leaves all year (evergreen trees), which may explain dampened seasonality in NEE at the Pine Upland site relative to Cypress Swamp.

The Moderate-resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) served as a useful qualitative surrogate for seasonal terrestrial photosynthetic activity and canopy structural variations (Figure 75), as reported for some other studies (Huete et al. 2002). EVI over tall mangrove forest, for example, varied seasonally between 0.35 and 0.55, and decreased to ~0.2 following defoliation after hurricane Wilma (Barr et al., 2013). Likewise, EVI over evergreen forest (Xiao et al. 2004a) varied seasonally between 0.25 during the winter and 0.5 during the summer growing season. MODIS was launched by National Aeronautics and Space Administration (NASA) in 1999 on the Terra (EOS AM) Satellite, and in 2002 on the Aqua (EOS PM) satellite. EVI data were obtained from the MOD13A1 product of MODIS (EOS; http://modis.gsfc.nasa.gov/). Sixteen-day composite EVI values for the pixel corresponding to each station, and the 8 adjacent pixels were extracted for comparison with monthly C fluxes (Figure 25). This 9-pixel domain approximately corresponds with the measurement footprint of each flux station.

Seasonal patterns in NEE and GEE were consistent with changes in EVI (Figure 7A-B, C), most notably at the Cypress Swamp site. Increases in EVI from 0.25 to 0.35 (Figure 7B).
corresponded with the growth of cypress leaves on relatively tall (18 to 21 m) and densely-spaced cypress trees (Figure 2) beginning in about March to April. Cypress leaves discontinued growing in August to September and turned brown in October, eventually falling into the sawgrass and hardwood understory. This lack of photosynthetic activity corresponded with changes in EVI from 0.4 in the summer to 0.2 in the winter (Figure 7B, 5B) of 2013 and 2014 at the Cypress Swamp flux station.

Gross atmosphere-ecosystem C exchange (GEE) provides a first approximation of gross ecosystem productivity (GEP), or accumulation of C in the plant canopy. Growth and senescence of cypress leaves was most evident in monthly GEE (Figure 7A, Table 4) at the Cypress Swamp site, where rates increased from about 100 g C m$^{-2}$ in February 2013 to over 200 g C m$^{-2}$ in April 2013 (a 116% increase). Likewise, GEE increased from about 100 g C m$^{-2}$ in February 2014 to about 300 g C m$^{-2}$ in June 2014 (a 200% increase). At the Dwarf Cypress site, seasonal changes in GEE were more moderate; the February to April 2013 increase was from about 60 g C m$^{-2}$ to 90100 g C m$^{-2}$ (a 4166% increase). Foliage change at the Cypress Swamp site likely contributed to a larger fraction of the site’s change in photosynthetic CO$_2$ uptake compared to that of the Dwarf Cypress site, which consists of a sparse cypress canopy (Figure 2).

Of the three sites, the Pine Upland site exhibited the least amount of seasonal variability in GEE (Figure 7, Table 3). Pines grow and maintain leaves (needles) all year (evergreen), which may explain the lack of seasonality in GEE at this location.

Correlations between monthly RE and GEE at the Cypress Swamp, Dwarf Cypress, and Pine Upland sites were 0.82, 0.76, and 0.10, respectively, suggesting RE at Cypress Swamp and Pine Upland sites were linked to photosynthesis within green plants (autotrophic respiration) rather
than decomposition (heterotrophic respiration) of litter, periphyton and/or soil organic matter. Conversely, the lack of correlation between RE and GEE at the Pine Upland site indicates decomposition controls most of the variability in RE. Inundation at the A key water and ecosystem management issue in south Florida, and globally, is the preservation of organic soils within wetlands to (1) support ecosystem services, and (2) maintain or perhaps even grow topography. Growing topography via C accumulation in coastal areas could partly offset sea-level rise. At these cypress and pine forested wetlands, inundation suppressed respiration most remarkably at the Pine Upland and Cypress Swamp sites (Figure 5A, B). RE doubled from about 60 to 120 g C m⁻² from February to May 2014 when water levels were below land surface at Cypress Swamp (Figure 5B). Enhanced RE also was observed from March 2014 to July 2014 at Pine Upland (Figure 5A) when water levels were below land surface. Enhanced RE was likely due to heterotrophic soil respiration supplementing autotrophic respiration when water levels were below land surface for extended periods of time. These results suggest hydro-period could be managed for maintenance of organic soils and peat accretion in these subtropical cypress and pine forested wetlands. Dwarf Cypress and Cypress Swamp sites may have suppressed heterotrophic respiration, as observed water levels were generally above land surface (Figure 5A). Additional RE data during dry periods is needed to confirm suppressed heterotrophic respiration at the Dwarf Cypress and Cypress Swamp sites due to flooding. Likewise, additional data are required to rigorously assess the impact of flooding on RE at the Pine Upland sites (Figure 5).

3.3 Links between C and Water Cycles

Relationships between net ecosystem C exchange (-NEE) and latent heat flux (LE) illustrate an important link between water and C cycles (Figure 4-6): that is, plant stomatophotosynthesis releases water (transpiration) while storing C.
R² between \(-\text{NEE}\) and \(\text{LE}\) provides an indication of the relative magnitudes of transpiration and evaporation at each site. Stronger correlations between \(\text{NEE}\) and \(\text{LE}\) indicate increased transpiration relative to evaporation, as water is transpired during photosynthesis while the plant fixes a unit mass of \(\text{C}\). In contrast, weaker correlations indicate a site with more open water evaporation where the source for \(\text{ET}\) is less related to photosynthesis and more related to evaporation from a water or soil surface. Correlations between \(-\text{NEE}\) and \(\text{LE}\) were 0.3735, 0.36 and 0.2219 (Figure 46) at the Cypress Swamp, Pine Upland and Dwarf Cypress sites, respectively. These correlations indicate transpiration is a larger portion of evapotranspiration at the forested wetlands with their larger and more densely spaced cypress and pine trees (Figure 2). Closed or partially closed forested canopies reduced penetration of solar radiation to water surfaces, creating lowered lapse rates between the water surface and canopy crown (Barr et al., 2012), and added resistance to evaporation. Collectively, these results suggest a redistribution of plant communities toward more open-water ecosystems (such as sparse sawgrass) could result in less \(\text{C}\) uptake and greater evaporative losses. Prior studies of \(\text{C}\) accumulation further support this generalization; for example, NEE rates were greater over mangrove systems (Barr et al., 2010; Barr et al., 2012) than over sawgrass wetlands (Schedlbauer et al., 2010). Prior ET studies (German, 2000) indicate ET losses are greater over Everglades wetlands with sparse sawgrass and open-water conditions.

Coupling between water and \(\text{C}\) cycles was examined via water-use efficiencies (Table 5) computed as the ratio of (1) daily \(\text{GEE}\) to \(\text{ET}\) (WUE’s, Figure 8) and (2) ratio of annual NEE to \(\text{ET}\) (Table 4). As such, WUE are the net (Table 4) or gross (Figure 8) mass or moles of \(\text{C}\) transferred to the ecosystem per mm or mole of \(\text{ET water vapor}\). Computing WUE with NEE accounts for the loss of \(\text{C}\) through \(\text{Re}\). The Cypress Swamp and Pine Upland sites were most
efficient at using water to store C, with WUE equal to about \(1.7\) and \(1.6\) g C per mm ET, respectively, on a GEE basis (Figure 8). Accounting for the loss of C though respiration (Table 4), the Cypress Swamp and Pine Upland sites were still most efficient at using water to store C, with WUE equal to \(1.0\) g C per mm ET, \((1.0\) to \(1.4\) moles CO\(_2\) per mole of ET). About \(0.5\) g C uptake occurs per mm of ET \((0.87\) moles CO\(_2\) per mole of ET) at the Dwarf Cypress site (Table 4). Apparently, wetlands with more open-water surface (Figure 2) are less efficient than forested wetlands at converting water use into net and gross C uptake. This conclusion is likely to be true both regionally and perhaps globally, and thus, may have implications for the global C cycle.

### 3.3 Methane Emission

Methane is produced by anaerobic bacteria decomposing soil organic matter, in the soil or surface water. Methane can be oxidized during transport from the soil to the atmosphere. Transport to the atmosphere can occur through (1) roots and stems of vascular plants (Wang and Han, 2005; Morrissey et al., 1993; Kim and Verma, 1998), (2) ebullition as gas bubbles from anaerobic soils (Comas and Wright, 2012), and (3) diffusion through the soil and surface water (Van Huissteden et al., 2006, Christensen et al., 2003a,b).

Methane is oxidized during diffusion through soils and surface water (Alberto et al., 2014). Methane emission is enhanced by temperature because anaerobic bacteria become more active as the soil warms at higher temperatures (Simpson et al., 1995). Increasing soil temperature also increases molecular diffusion and ebullition of methane (Alberto et al., 2014).

At the Dwarf Cypress site, methane emission increased with increasing air temperature and water level in the summer months from June to September 2013 (Figure 6C, 7C) as air temperature, solar radiation and water levels increased (Figure 5A–5C). In contrast, methane emission was suppressed from April to June 2014 due to dry conditions and perhaps the memory
of dry conditions from July to September 2014. Anaerobic bacteria may take some time to reestablish following dry conditions. This reestablishment or “memory” of dry conditions would reduce methane emission despite warm conditions and flooding from July to September 2014.

Methane emission peaked at different times in the summer of 2013 compared to GEE at the Dwarf Cypress site (Figure 7C). GEE peaked with photosynthesis in July 2013 whereas methane emission peaked in August 2013. This time lag indicates that processes governing C exchange and methane emissions are quite different, with GEE controlled by photosynthesis of cypress leaves and sawgrass which grow vigorously from March to April and discontinue growth in August to September. In contrast, methane emission is likely-driven by anaerobic decomposition of organic matter with subsequent oxidation through the soil and surface water.

Decomposition Organic decomposition was enhanced in August 2013 by flooding and relatively warm air, soil and surface-water.

Methane Although methane emission is believed to be important in terms of global warming potential (GWP), it appears to be immaterial in C budgets that build and maintain subtropical wetland alter or “grow” land-surface topography. C released from methane emission was relatively small (averaging about 4210 g C per year) compared to NEE (about 500 g C per m² year, Table 3). Thus, C cycling studies that address changes in peat accumulation may not benefit from monitoring methane fluxes. However, approximately 15 about 14 g CH₄ was released to the atmosphere which emission per year is roughly equivalent to about 330350 g CO₂, assuming the GWP of CH₄ is 25 times greater than CO₂ (over a 100-year period, IPCC). These results suggest that methane monitoring is needed when assessing the GWP of wetlands. In contrast, C cycling studies that address changes in peat accumulation and land-surface topography may not benefit from monitoring methane fluxes. We recognize GWP multipliers are...
controversial due to assumptions such as instantaneous CH₄ and CO₂ release, and time-scale dependence of the radiative forcing contributions. Careful use of GWP multipliers for wetlands is suggested.

3.4 Comparison of C Uptake with Prior Studies

Comparison of our results from this study with –NEE from selected prior studies (Schedlbauer et al. 2010; Jimenez et al. 2012; Barr et al. 2010; Botkin et al. 1970; Jones et al. 2014) reveals substantial spatial and temporal heterogeneity in C uptake from the atmosphere over geologic time and among different ecosystems (Table 4.6). Subtropical forested wetlands exchange more C than temperate forests (Botkin et al., 1970; Sjogersten et al. 2014). A study assessing this C exchange on a geologic time scale (Jones et al. 2014) also concluded that long-term rates of C uptake in the Everglades are higher than in northern latitudes, and in some cases rival C uptake in tropical peat-lands, such as Indonesia. Mangrove ecosystems may serve as an upper limit for subtropical C uptake, with NEE of about –1170 g C per m² year (Barr et al. 2010). Sparse sawgrass wetlands in the Everglades, such as Taylor and Shark River Sloughs, are relatively minor atmospheric C sources or sinks, with –NEE ranging from -50 (Taylor Slough) to +45 (Shark River Slough) g C per m² year (Table 5). Jones et al. (2014) also concluded that sloughs sequester the least amount of C in their study of C accumulation over geologic time scales. Given the C released from methane emissions (4210 g C per m² year, Table 4.4), as measured at Dwarf Cypress (Figure 6 and 7), sparse sawgrass wetlands may generally be atmospheric C sources at monthly and annual time scales, with questionable value as local, regional and global C sinks.
4 Conclusions

Atmospheric/ecosystem carbon dioxide exchange, methane emission, latent and sensible heat fluxes were estimated with eddy covariance methods for subtropical forested cypress and pine wetlands for one year two years. Seasonality in solar insolation, air temperature, plant physiological activity and rainfall and water levels created seasonality in C exchange rates and surface energy fluxes. Links between water and C fluxes also were revealed such as photosynthetic water-use efficiencies.

Each forested wetland was an atmospheric C sink on monthly and annual time scales.

NEE was greatest at the Cypress Swamp site (-900 to -1000 g C per m² year), moderate at the Pine Upland site (-900 to -650 to -700 g C per m² year), and least at the Dwarf Cypress site (-500 to -400 to -450 g C per m² year). The size (about 20 m) and number of cypress trees enhanced C uptake at the Cypress Swamp site and seasonality in C uptake rates was enhanced by the growth of cypress leaves in early April and decay of cypress leaves in late October, as confirmed by changes in the satellite-derived EVI index. Changes in EVI (from 0.25 in the dry season to 0.4 in the wet season) served as a useful surrogate for monthly and seasonal changes in net (NEE) and gross (GEE) ecosystem C exchange.

Respiration was enhanced when water levels dropped below land surface within these cypress and pine forested wetlands. In fact, respiration doubled when water levels dropped below land surface for several months at the Cypress Swamp and Pine Upland flux stations.

Increases in respiration were likely due to heterotrophic soil respiration supplementing autotrophic respiration. These results highlight the importance of flooding and hydro-period management for maintaining organic soils and peat accretion within subtropical cypress and pine forested wetlands, a key water and ecosystem management issue in south Florida and globally.
Links between water and C cycles were examined via (1) WUE’s water-use efficiencies (WUE) expressed as the ratio of (a) daily GEE to ET and (b) annual NEE to ET, and (2) correlations between -NEE and LE. Computing WUE with NEE accounts for the loss of C through respiration. The Cypress Swamp and Pine Upland sites were most efficient at using water to store C, with WUE’s WUE equal to about 1.7 and 1.60 g C per mm ET, respectively, on a GEE basis. About 40.5 g C was stored in the ecosystem per mm of ET at the Dwarf Cypress site. Accounting for the loss of C through respiration, the Cypress Swamp and Pine Upland sites were still most efficient at using water to store C. These results indicate that wetlands with more open-water surface are less efficient at using water to store C than forested wetlands. This pattern is likely to be true both regionally and perhaps globally, and thus, may have implications for the global C cycle.

Correlations between -NEE and LE reflected an important link between water and C cycles, specifically, photosynthesis which released water as transpiration while storing C. The strength of the -NEE and LE correlation provided an indication of the relative magnitudes of transpiration and evaporation at each site. Transpiration was a large proportion of evapotranspiration at the Cypress Swamp and Pine Upland sites, as indicated by correlations of 0.3734, 0.36 and 0.2218 for the Cypress Swamp, Pine Upland and Dwarf Cypress sites, respectively. These results indicate that a redistribution of plant communities toward more open-water ecosystems could create less C uptake and greater evaporative losses.

Methane emission at the Dwarf Cypress site was considerable in terms of global warming potential, but immaterial in C budgets that build and maintain land-surface topography. Approximately 4514 g CH₄ was released into the atmosphere, roughly equivalent to 330350 g CO₂, assuming the global warming potential of CH₄ is about 25 times greater than CO₂.
Methane emission, however, did not reverse carbon accumulation for building and maintaining topography at the Dwarf Cypress site, because as the C released from methane emission (about 10 g C per m² year) was relatively small compared to NEE (-500 g C per m² year).

These results indicate that while methane monitoring is needed when assessing the global warming potential of wetlands; C cycling studies that address changes in topography and peat accumulation may not benefit from monitoring methane fluxes.

5 Acknowledgements

This study was funded, in part, by the U.S. Geological Survey (USGS) Greater Everglades Priority Ecosystems Science (GEEES). Nick Aumen is gratefully acknowledged for helpful conversations about the Everglades during project meetings and fieldwork in BCNP. Michael J. Duever provided detailed vegetation descriptions and guidance during site selection. Steve Krupa and Cynthia Gefvert from the South Florida Water Management District funded tower construction. PeerUSGS peer reviews by Lisamarie Windham-Myers, Frank Anderson, Dave Sumner and Kim Haag of the USGS improved the quality of the manuscript. Biogeoscience peer reviews by Ankur Desai and an anonymous referee also greatly improved the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.
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B.H., Nykanen, H., Martikainen, P.J., Oskarsson H.: Factors controllinglarge scale variations in


Table 1. Site locations, tower heights and summary of vegetation.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Height of tower (m)</th>
<th>Height of vegetation (m)</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwarf Cypress</td>
<td>25.7624</td>
<td>-80.8934</td>
<td>16.8</td>
<td>0.5 to 10</td>
<td>Small cypress and sawgrass</td>
</tr>
<tr>
<td>Cypress Swamp</td>
<td>25.8265</td>
<td>-81.1020</td>
<td>38.1</td>
<td>0.5 to 21</td>
<td>Tall cypress</td>
</tr>
<tr>
<td>Pine Upland</td>
<td>26.0004</td>
<td>-80.9260</td>
<td>38.1</td>
<td>0.5 to 21</td>
<td>Pine, sawgrass and cypress</td>
</tr>
</tbody>
</table>
Table 2. Instrumentation installed at the Dwarf Cypress, Cypress Swamp and Pine Upland flux stations.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Model</th>
<th>Measurement</th>
<th>Dwarf Cypress</th>
<th>Pine Upland</th>
<th>Cypress Swamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonic anemometer</td>
<td>CSAT(^1), Gill Windmaster Pro(^2)</td>
<td>Wind velocity and direction</td>
<td>15.5</td>
<td>35.8</td>
<td>35.7</td>
</tr>
<tr>
<td>Gas analyzer</td>
<td>LI-7500A</td>
<td>Gas concentrations</td>
<td>15.5</td>
<td>35.8</td>
<td>35.7</td>
</tr>
<tr>
<td>Methane analyzer</td>
<td>LI-7700</td>
<td>Methane concentration</td>
<td>15.5</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Pressure transducer</td>
<td>CS450</td>
<td>Water depth</td>
<td>-0.8</td>
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<td>-0.5</td>
</tr>
<tr>
<td>Air temperature</td>
<td>HMP-45C</td>
<td>Air temperature</td>
<td>15.5</td>
<td>35.8</td>
<td>35.8</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>HMP-45C</td>
<td>Relative humidity</td>
<td>15.5</td>
<td>35.8</td>
<td>35.8</td>
</tr>
<tr>
<td>Net radiometer</td>
<td>NR-Lite</td>
<td>Net radiation</td>
<td>13.2</td>
<td>33.7</td>
<td>33.9</td>
</tr>
<tr>
<td>Soil heat flux</td>
<td>REB’s</td>
<td>Soil heat flux</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>107L</td>
<td>Soil temperature</td>
<td>-0.2</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

\(^1\)CSAT deployed at the Dwarf Cypress and Pine Upland sites.

\(^2\)Gill Windmaster Pro deployed at the Cypress Swamp site.

<table>
<thead>
<tr>
<th>Month</th>
<th>Cypress Swamp</th>
<th>Dwarf</th>
<th>Pine</th>
<th>NEE</th>
<th>CH4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CypressH⁴</td>
<td>UplandL²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Month</td>
<td>Filling Quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>A</td>
<td>2239</td>
<td>1059</td>
<td>506</td>
<td>NE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>B</td>
<td>1054</td>
<td>5431</td>
<td>18N</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>C</td>
<td>389</td>
<td>634</td>
<td>24N</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>D</td>
<td>1292</td>
<td>34</td>
<td>5421</td>
<td>11N</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>E</td>
<td>120H</td>
<td>111F</td>
<td>120F</td>
<td>20F</td>
</tr>
<tr>
<td>Mai</td>
<td>F</td>
<td>120H</td>
<td>111F</td>
<td>120F</td>
<td>20F</td>
</tr>
</tbody>
</table>

**Dwarf Cypress**

<table>
<thead>
<tr>
<th>Month</th>
<th>Filling Quality</th>
<th>NEE²</th>
<th>CH4²</th>
<th>R²</th>
<th>E²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
<td>A</td>
<td>152680</td>
<td>884365</td>
<td>240597</td>
<td>155</td>
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 Inserted Cells
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<table>
<thead>
<tr>
<th></th>
<th>Jul-13</th>
<th>Aug-13</th>
<th>Sep-13</th>
<th>Oct-13</th>
<th>Total fluxes</th>
<th>Percent rejected</th>
<th>Pine Upland Annual total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling Quality A</td>
<td>9001</td>
<td>9997</td>
<td>23554</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Filling Quality B</td>
<td>133</td>
<td>132</td>
<td>124</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Filling Quality C</td>
<td>241</td>
<td>242</td>
<td>294</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Total gap-filled</td>
<td>9328</td>
<td>10378</td>
<td>20018</td>
<td>142521</td>
<td>35424</td>
<td>12578</td>
<td>23534</td>
</tr>
<tr>
<td>Total fluxes</td>
<td>35424</td>
<td>35424</td>
<td>35424</td>
<td>35424</td>
<td>35424</td>
<td>35424</td>
<td>35424</td>
</tr>
<tr>
<td>Percent rejected</td>
<td>26</td>
<td>28</td>
<td>33</td>
<td>46</td>
<td>20</td>
<td>58</td>
<td>58</td>
</tr>
</tbody>
</table>
1Sensible heat flux. 2Latent heat flux.

Table 4. Monthly and annual C and methane fluxes.

<table>
<thead>
<tr>
<th>Month</th>
<th>Cypress Swamp</th>
<th>Dwarf Cypress</th>
<th>Pine Upland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Nov 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Oct 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Sep 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Aug 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Jul 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Jun 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>May 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Apr 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Mar 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Feb 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Jan 13</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
<tr>
<td>Dec 12</td>
<td>1165±116</td>
<td>214±21</td>
<td>265±26</td>
</tr>
</tbody>
</table>

1Units are g C/m2 month or g C/m2 year for net ecosystem exchange (NEE), respiration (Re), gross exchange (GEE) and methane production (CH4).
Table 45. ET, NEE and WUE at the flux stations.

<table>
<thead>
<tr>
<th>Site</th>
<th>ET&lt;sup&gt;1&lt;/sup&gt;</th>
<th>-NEE&lt;sup&gt;2&lt;/sup&gt;</th>
<th>WUE&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine Upland</td>
<td>955 (yr1&lt;sup&gt;4&lt;/sup&gt;)</td>
<td>700 (yr2&lt;sup&gt;5&lt;/sup&gt;)</td>
<td>0.97 / 1.0 (yr1&lt;sup&gt;4&lt;/sup&gt;) / 0.7 / 1.0 (yr2&lt;sup&gt;5&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Dwarf Cypress</td>
<td>943 (yr1&lt;sup&gt;4&lt;/sup&gt;)</td>
<td>450 (yr2&lt;sup&gt;5&lt;/sup&gt;)</td>
<td>0.5 / 0.87 (yr1&lt;sup&gt;4&lt;/sup&gt;) / 0.4 / 0.7 (yr2&lt;sup&gt;5&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Cypress Swamp</td>
<td>1150 (yr1&lt;sup&gt;4&lt;/sup&gt;)</td>
<td>1000 (yr2&lt;sup&gt;5&lt;/sup&gt;)</td>
<td>0.9 / 1.4 (yr1&lt;sup&gt;4&lt;/sup&gt;) / 0.9 / 1.4 (yr2&lt;sup&gt;5&lt;/sup&gt;)</td>
</tr>
</tbody>
</table>

<sup>1</sup> Units are millimeters per year

<sup>2</sup> Units are g C per year

<sup>3</sup> Units are g C per millimeter ET or (/) moles CO<sub>2</sub> per mole ET

<sup>4</sup> yr1 from 12/1/2012 to 11/30/2013.

<sup>5</sup> yr2 from 12/1/2013 to 11/30/2014.
Table 56. Comparison of annual totals for NEE for different studies.

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>NEE</th>
<th>Climate</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taylor Slough (short sawgrass)</td>
<td>-50</td>
<td>Subtropics</td>
<td>Schedlbauer (2010)</td>
</tr>
<tr>
<td>Shark River Slough (short sawgrass)</td>
<td>45</td>
<td>Subtropics</td>
<td>Jimenez (2012)</td>
</tr>
<tr>
<td>Mangrove</td>
<td>-1170</td>
<td>Subtropics</td>
<td>Barr (2010)</td>
</tr>
<tr>
<td>Cypress Swamp</td>
<td>-920</td>
<td>Subtropics</td>
<td>This study</td>
</tr>
<tr>
<td>Dwarf Cypress</td>
<td>-464</td>
<td>Subtropics</td>
<td>This study</td>
</tr>
<tr>
<td>Pine Upland</td>
<td>-822</td>
<td>Subtropics</td>
<td>This study</td>
</tr>
<tr>
<td>White Oak</td>
<td>-296</td>
<td>Temperate</td>
<td>Botkin (1070)</td>
</tr>
<tr>
<td>Scarlet Oak</td>
<td>-274</td>
<td>Temperate</td>
<td>Botkin (1070)</td>
</tr>
<tr>
<td>Pitch Pine</td>
<td>-124</td>
<td>Temperate</td>
<td>Botkin (1070)</td>
</tr>
<tr>
<td>Everglades</td>
<td>-100</td>
<td>Subtropics</td>
<td>Jones et al. (2014)</td>
</tr>
</tbody>
</table>

Units are g C per m² year

1


Figure 1. Location of the study area and vegetation communities, modified from Duever (2002).
Figure 2. Panoramic photos of the (A) Pine Upland, (B) Cypress Swamp, and (C) Dwarf Cypress plant communities.
Latent heat flux (LE) gap-filling

Preisley-Taylor model
9, 14, 10% of LE

Final LE

+ NEE gap-filling

- NEE gap-filling

-NEE(LE)
1, 26, 72% of -NEE

Final -NEE

4-hour moving mean

Respiration model

Final +NEE

50, 45, 74% of +NEE

Includes da-y-time predictions of +NEE

1 Preisley-Taylor $\alpha = 0.45, 0.42,$ and $0.57$ with $R^2 = 0.57, 0.47,$ and $0.56$ for Dwarf Cypress, Cypress Swamp and Pine Upland sites, respectively.

2 Regression coefficients $m = -0.0115, -0.0284, -0.0341$ and $b = -1.2297, -1.403, 0.00$ with $R^2 = 0.22, 0.37,$ and $0.36$ for Dwarf Cypress, Cypress Swamp and Pine Upland sites, respectively.

Red, blue and green colors indicate the percentage of the time-series gap-filled with the model or function for the Dwarf Cypress, Cypress Swamp and Pine Upland sites, respectively.
Figure 3. Gap-filling equations for water \( \text{Observed} \) and \( \text{C-fluxes-computed mean daily molar} \) methane (CH4) flux at the Dwarf Cypress site.
A. Cypress Swamp

Net Ecosystem Exchange, in umoles per m$^2$ second

\[ y = -0.0284x - 1.4033 \]

\[ R^2 = 0.3703 \]

B. Pine Upland

Net Ecosystem Exchange, in umoles per m$^2$ second

\[ y = -0.0341x \]

\[ R^2 = 0.3623 \]

C. Dwarf Cypress

Latent heat flux, in watts per m$^2$

\[ y = -0.0115x - 1.2297 \]

\[ R^2 = 0.2261 \]
A. Dwarf Cypress

Explanation
- Air temp
- Soil temp
- Water temp
- Stage
- Latent heat
- Net radiation
- Sensible heat

Temperature, in degrees Celsius
Stage, in meters above (+) or below (-) land surface

Energy flux, in watts per m²

Figure 4. Relations between latent heat flux and net ecosystem exchange.
A. Dwarf Cypress

Explanation
- **Air temp**
- **Soil temp**
- **Water temp**
- **Stage**
- **Latent heat**
- **Net radiation**
- **Sensible heat**
- **Bowen ratio**

Temperature, in celsius
Stage, in meters above (+) or below (-) land surface

Energy flux, in watts per m²
Bowen ratio, unit-less

- **dry season**
- **wet season**

Legend:
- **Land surface**

Data points:
- 12/1/2012
- 1/20/2013
- 3/11/2013
- 4/30/2013
- 6/19/2013
- 8/8/2013
- 9/27/2013
- 11/16/2013

Graphs showing temperature, stage, energy flux, and Bowen ratio over time.
B. Cypress Swamp

Explanation

- **Air temp**
- **Soil temp**
- **Water temp**
- **Stage**
- **Latent heat**
- **Net radiation**
- **Sensible heat**
- **Bowen ratio**

Stage, in meters above (+) or below (-) land surface

Temperatures, in celsius

Energy flux, in watts per m²
Figure 5A-4A, B, C. Mean daily temperature and surface energy fluxes.
Figure 6. Daily carbon fluxes at the (A) Pine Upland, (B) Cypress Swamp and (C) Dwarf Cypress sites.
A. Pine Upland

Explanation
- GEE
- Re
- -NEE

- - EVI
- Stage

Flux, in g C per m² per day

Flux, in g C per m² per month

Stage, in meters above (+) or below (-) land surface

Dry season
Wet season

Dry season
Wet season

Dry season
Wet season
B. Cypress Swamp

Explanation
- GEE
- Re
- -NEE
- EVI
- Stage

Flux, in g C per m² day

Flux, in g C per m² month

Stage, in meters above (+) or below (-) land surface

EVI, unitless

Stage, in meters above (+) or below (-) land surface

Dry season

Wet season
Figure 6A, B, C. Daily C fluxes at the (A) Pine Upland, (B) Cypress Swamp and (C) Dwarf Cypress sites.
Figure 7A, B, C. Monthly C fluxes and monthly C fluxes, stage and EVI at the (A) Pine Upland, (B) Cypress Swamp and (C) Dwarf Cypress sites.
Figure 8. ET, GEE and WUE at the (A) Pine Upland, (B) Cypress Swamp and (C) Dwarf Cypress sites.
Figure 6. Relations between latent heat flux and net ecosystem exchange.

Cypress Swamp

\[ y = -0.0206x - 2.259 \]
\[ R^2 = 0.3641 \]

Pine Upland

\[ y = -0.0277x - 1.6177 \]
\[ R^2 = 0.3474 \]

Dwarf Cypress

\[ y = -0.0099x - 1.2613 \]
\[ R^2 = 0.1887 \]