ABSTRACT

RADECKI, ANDREW MARTIN. Why Eco-Hydrologically Based Management Plans are an Important Tool to Address both the Ecological and Economic Concerns of Terrestrial Ecosystem Management in the Coming Decades. (Under the direction of Jean-Christophe Domec and John King).

Freshwater management in terms of industry, agriculture, drinking water, and river transport are all under an increased threat due to global climate change. Extreme weather events such as large storms, droughts and floods are predicted to become more frequent and more intense. Understanding how these hazards will affect ecosystems services, land management, economics and policies is extremely important as worldwide consumption increases. Forest wetlands perform important ecosystem services such as carbon sequestration and water purification, and they provide habitat for important terrestrial, aquatic and migratory species. Coastal wetlands are predicted to be one of the most vulnerable ecosystems to climate change in the next 50 years, while they provide some of the important of the ecosystem services. However in the last 200 years large areas of wetlands in the southeastern US have been drained and ditched for agriculture and forestry purposes. Wetland ecosystems, such as those at the Alligator River National Wildlife Refuge, are highly influenced by interactions between the soil-water and the vegetation contained within the boarders of the watershed. While the low relief and high variability of water table's depth means runoff can vary from non-existent to 70% of water loss from the ecosystem during rain events. Which highlights the important role storage plays when investigating the water balance of the ecosystem. Although during the growing season the largest and perhaps the most important portion of water balance is evapotranspiration (ET). Which is why developing models that can be used to scale differences in leaf level water use between

separate plant species to the watershed and then to larger ecosystems is an area of interest to global, regional and local land managers, policy makers and researches. Additionally by investigating the statistical relationships between plant and ecosystem biological processes such as photosynthesis and respiration and the environmental drivers the regulate them we can develop strategies that promote and enhance desirable ecosystem services and management goals. In an era were terrestrial fresh water resources are being more heavily utilized it is necessary to investigate how the vegetation is responding and coping with climate change, development and industrialization. In this study, at the Alligator River National Wildlife Refuge, we partitioned both the water budget and evapotranspiration into their subcomponents. Which will provide further insight into the role water has on wetland succession and ecosystem services within our site. Additionally, in this study we investigate how the environmental drivers; photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and shift in the water table depth (WTD) interact with one another, the vegetation and the ecosystem to regulated plant water use and canopy conductance. Lastly, this study will investigate how separate species of trees respond differently to the same environmental factors, photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and shift in the water table depth (WTD) through estimates of stomatal conductance and stomatal sensitivity.

Why Eco-Hydrologically Based Management Plans are an Important Tool to Address both the Ecological and Economic Concerns of Terrestrial Ecosystem Management in the Coming Decades

by
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DEDICATION

This thesis is dedicated to all the people who have helped and inspired me throughout my life as I have charted an unconventional path, from a child building forts in small patch of woods behind my house to studying the biology, ecology, and physics of how plant function across the landscape. This path has always revolved around understanding the beauty, mystery, and importance of forestry, agriculture and the natural world, as well as how human interactions threaten this places and in turn threaten human food, water, and energy security. I could not have come this far without the help of my advisors JC Domec , John King, Asko Noormets and Ryan Emanuel, their knowledge, passion and quality of the work they do. A level I am still striving to replicate. I also would like to thank my parents an my sister Emily. A special thanks to David and Ginny Kelleher for all that they have helped me with, statistics would have been a lot scarier without David's advice. Martha of course I could not have done this without your continual support and the example you set for me every day. And to all that may stumble across this document and find it relevance to what they hold sacred.

BIOGRAPHY

Andrew Radecki grew up in Indianapolis IN, and then moved to Asheville NC, where he finished with a BS in Biology and Environmental Studies from Warren Wilson Collage, while working on the Forestry Crew and captaining the men's soccer team. After graduation he interned at Highlands Botanical Gardens, Highlands, NC and after that at Hickory Nut Gap Farms in Fairview, NC. Once he completed his internships Andrew work as a carpenter, mason, and landscaper until he was hired as the head grounds keeper at Historic Chanteloupe Estates in Hendersonville, NC. Where he had the opportunity renovated the spring-fed cistern and quarry irrigation system designed by Fredric Law Olmsted. It was during his travels through Europe and Australia, spending time on river in the mountains and lakes in the Midwest as well as working with gravity fed system irrigation on the farm and at the estate that Andrew became fascinated with the way water moves and how in interacts with the topography and soil. It was this curiosity that led Andrew to North Carolina State University to study Tree Physiology and Ecohydrology while working on his master thesis in the Department of Forestry and Environmental Resources.

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I would like to thank everyone in John King's Tree Physiology Lab those mentioned in the dedication but especially, Guofang Miao, David Zietlow, Eric Ward, Wen Lin, and Aletta Davis, and in Ryan Emanuel's Ecohydrology Lab, Nitin, Josh, and Susan bouncing my crazy ideas off you all has helped clear my head of all the clutter and I wrapped my head around the GIS, regression analysis, eddy covariance and sap flux. I would like to thank all my friends in Raleigh, Justin, Will, Ross, DD and Luke for the moral support. My Ma and Pa, love you both and my sister Emily for taking the time to edit the incoherent jargon the flows out of brain when I attempt to write, love you too. Finally, I would like to thank Martha, couldn't have done it with out you.

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CHAPTER 1

The Importance of Accounting for the Negative Effects of Industrialization and Intensive Agriculture on Terrestrial Ecosystem Land Management

To meet the resource needs of a quickly growing global human population understanding how landscapes respond to ecosystem stresses, such as extreme weather events shifts in climate, land use change, over fertilization, and loss of topsoil is essential. Ecosystem management in the next century needs to be planned and implemented over multiple generations to alleviate stress and to promote ecosystem services. Management plans need to be designed to accentuate desired functions of particular ecosystems. Management with the understanding of how a patchwork of landscape types and land uses come together to comprise a larger system, one in which the whole is more important then the sum of its parts. Additionally, ecosystem functions should be selected for so that their enhancement can have the largest impact on global ecosystem resilience and long-term productivity. However this may be a challenge because the current modus operandi in the energy, food, and industrial sectors of the global economy is to focus almost exclusively on short-term gain while ignoring long term trends. Or as Al Gore put it in his 2013 book *The Six Drivers of Global Change,* the current market-based strategy guiding natural resource investment and consumption is shot on long and long on short. Meaning there is more focus on the short-term quarterly profits of the business then in the sustainably of the ecosystems

systems from which those profits are derived. The broad scope of this paper may seem like a monumental task, but in the immortal words of Winston Churchill "*from great complexities come great simplicities*". It is with this in mind that this paper focuses on how to find ways to answer the questions: How can scientists develop ecosystem models that are tailored toward ecohydrological experimentation focused on addressing the pressing issues of energy, water and food security, both locally and globally? What solutions are needed to mitigate the predicted threats of climate change at multiple spatial and temporal resolutions, while staying true to the agreed upon mindset of the scientific community about climate change and sustainability? What data is needed to incorporate economics into these models, in a manner that shines a light on the need to develop economically feasible solutions that advance social habits and promote the efficiency of ecosystem services and ecosystem health? How can we accomplish these goals while providing funding for research that benefits both the public and private sectors of society? Can humanity move forward with the understanding that the most realistic way to reverse the perceived threats of climate change is by developing goals that produce market based solutions that address all the environmental issues facing humanity? Can we do this as the human population grows; global per capita consumption increases, vital natural resources become scarcer, and the methods we use to extract resources negatively affect both human and environmental health? The solution to saving our environment, or more accurately put humanities progress through time and space, cannot be realized by sequestering carbon alone. Rather, resolutions have to initiate economic, social, and political shifts that are based on sound science that addresses the causes of climate change. These shifts can then be used to develop landscape scale theories and practices that provide solutions. Solutions that sequester carbon, improve food water and energy security globally, reduce the frequency of extreme weather events, reduce the risk of forest fire, reduce the amount of toxins in the environment, improve human and ecosystem health, all within a realistic framework, both scientifically and economically.

Ecology, economy, and equity are concepts that are almost always viewed through separate lenses by societies, mainly because of the complexity of each of these topics. However, it is impossible to fully, honestly and directly address one of these global issues without affecting the other two. To accurately address how humanity has and is affecting the physical, social and biological environments of our world, it is necessary to strike a balance between human desire and sustainability. A good example of this is the Environmental Defense Fund, whose mission it is to try to find scientifically sound, market based solutions to environmentally sensitive problems, such as climate change, land use change, terrestrial and aquatic ecosystem health as well as human health. Who agree with the ecological view and the academic stance that coal fired power plants, loss of topsoil, large-scale deforestation for wood, pulp and farmland, as well as increased chemical fertilizer and pesticide use are among the leading causes of climate change. From an economic social view it is the poor regulation of large-scale agriculture, electric, oil and gas companies that is responsible for a number of health problems as well as widespread environmental degradation. Electricity generated primarily from fossil fuels accounts for more than 40% of U.S. water uses and approximately 37% is used for irrigation. From an equality view it is that these global industries are composed of some of the most influential governments, corporations, and individuals that allows degradation of ecological and human health to continue. These large corporate entities are some of the wealthiest in the world and their prosperity has largely been at the expense of those who cannot speak up for themselves. A recent and prescient example are the children of the founder of Wal-Mart whose combined wealth is more then the combined wealth of the bottom 30% of Americans. Additionally a large portion of Wal-Mart's employees receive low pay and depend on food stamps, yet a one-cent increase on product pricing could be allow Wal-Mart to pay a living wage to all its employees. At this time in the great human experiment in the same way maybe the few myopic big business interests should not be the deciding factor as to how our natural resources should be managed. Especially, in light of the fact that there are areas where science can improve long term investment and environmental goals at the same time, albeit at the expense of short-term profits, which is many of these corporation's bottom line. However, just as a wise investor will bet on solid long-term trends, over the capricious daily fluctuations in stocks, it is time to start betting on long-term management goals. These goals must be implemented at local regional and global scales so that human activities can be organized to be increasingly effective at managing terrestrial ecosystems. Ecosystems should be managed to increase or restore the resilience of ecosystems to environmental stresses, while at the same time helping an ever going human population meet their necessary food, energy and water needs. Humanity no longer has the luxury of mindless consumption with no regard to the limits of our resources, especially once they can't have what they currently take for granted, water, fresh food, and cheap energy.

Thus we come back to enveloping ecology, economy and equity with scientifically-sound-market-based approaches to make this earth a healthier world that will also positively affect the greatest number of people. Certainly, if this is not the goal of the human population, then maybe we should rethink what our goal should be. So with this goal in mind, it is essential to realize that the availability of healthy topsoil, access to fresh water, as well as expanding clean renewable energy are a few of the main factors that are going to influence the carrying capacity of the earth. These factors directly effect and are affected by human food, energy, and water, needs, as well as the wants, policies and patterns of human consumption. David R. Montgomery's book *Dirt: The Erosion of Civilizations* constructs a great narrative on the role soil, agriculture, and nutrient recycling play on the prosperity and eventual fall of numerous civilizations and empires. Furthermore, as a geologist he clearly explains the physical, chemical and biological factors involve in soil formation and erosion. He introduces archeological evidence that explains how land-use-change caused by humans, such as non-sustainable agricultural, and deforestation lead to the fall of advanced civilizations throughout history. In much the same way that Montgomery addresses soil, Brian Fagan's *Elixir*, Charles Fishman's *The Big Thirst,* and Fred Pearce's *When the Rivers Run Dry,* each address how water has, is, and will shape civilization. The fundamental idea in all of these books is that if one part of a cycle is broken then you disrupt the whole cycle. Think of the blood cycling through your circulatory system. When a key component of that cycle breaks, whether it be the blood cells ability to bind with oxygen, or physical stopping of heart contractions, or the transport of a pathogen that later infects other sensitive areas of the body, a person becomes less resilient, gets sick or dies. It is the same thing with terrestrial ecosystems except water is the blood, leaves are the lungs and carbon dioxide is the oxygen. Although this is not a perfect analogy it serves its purpose, which is that as with any system the ecosystem too has multiple parts that have to work in unison to accomplish a plethora of more intricate processes. It is true also; that many of these systems are tough, and have created multiple pathways to accomplish the same goals, in the chance a key component should break. Unfortunately, humans have been stressing many of these pathways for along time and using the fact that the systems are resilient as an excuse to why they shouldn't be monitored and managed for long-term success. Furthermore, from a physical perspective, humanity must address entropy and the complex systems that evolve to utilize the continually shifting nature of energy.

The southeastern United States and North Carolina more specifically offers several unique research opportunities in the field of terrestrial ecosystem science. The southeast is bordered by the Appalachian Mountains on the west, coast on the east and a gradient of eco-tones in-between. Furthermore, ample rainfall and other forms of precipitation blanked the landscape annually with 2300 mm near Highlands NC, and 1200 mm near the Outer Banks. There are large areas in forest, agriculture, including livestock, grain crops, vegetables and Christmas trees. Recently, several prime example of the imbalance between natural resources and economic development have been the headline issues in North Carolina. On top of this list is the Duke Energies failure to line coal ash ponds and protect headwater streams. A matter that Governor Pat McCrory must think is a shell game as he places the profits of Duke Energy the third largest energy company in the US over other the health of the people who depend clean water for drinking and irrigation. Another example of corporate interests caring about short-term profits over what is best for the larger community is North Carolina State University's pending sale of the Hoffman Forest. Whose sale of the largest forest holds of any university in the US, neglects to understand the importance research opportunities from coastal forested ecosystems, wetlands, and estuaries as, sea levels rise, saltwater intrusion into coastal wetlands, extreme weather events, and land use changes impact the function of these systems. In particular, the estuaries off the coast are prime habitat for shellfish and feeding grounds for migratory birds. While the wetlands provide innumerable benefits to coastal communities both ecologically speaking an economically. This next chapter explores coastal wetlands in more detail.

CHAPTER 2

Partitioning Evapotranspiration: An Investigation into the Key Environmental Drivers of the Four Dominant Overstory Species in a Coastal Forested Wetland and Their Effects on Transpiration and Stomatal Conductance at the Alligator River National Wildlife Refuge

Andrew Radecki, Jean-Christophe Domec, Asko Noormets, Ryan Emanuel, Guofang Miao, Eric Ward, David Zietlow, and John S. King

Abstract: According to the most recent Intergovernmental Panal on Climate Change (IPCC) report, coastal areas are under the most direct threat to climate change due to factors such as sea level rise, saltwater intrusion and development. Coastal wetlands provide food and habitat to a plethora of commercially and biologically significant flora and fauna as well and numerous irreplaceable ecosystem services. In an era were terrestrial fresh water resources are being more heavily utilized it is necessary to investigate how the vegetation is responding and coping with climate change, development and industrialization. In this study we partitioned both the water budget and evapotranspiration into their subcomponents will provide further insight into the role water has on ecosystem succession and ecosystem services. Additionally, in this study we investigate how the environmental drivers; photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and shift in the

water table depth (WTD) interact with one another, the vegetation and the ecosystem to regulated plant water use. Lastly, this study will investigate how separate species of trees respond differently to the same environmental factors, photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and shift in the water table depth (WTD) through estimates of stomatal conductance and stomatal sensitivity.

Introduction

Coastal wetlands play an important role in protecting water quality, providing habitat for plants and animals, especially for migratory birds and juvenile aquaic organisms, as well as in sequestering carbon. However, large portions of coastal wetlands have been drained over the past 100 years for agricultural and forestry purposes. The Alligator River National Wildlife Refuge, in particular, provides habitat for endangered red wolves and red cockaded woodpecker as well as federally threatened bald eagles and American alligators. Most studies investigating the effects of land use change and weather extremes on wetlands and terrestrial ecosystems-are conducted in highly managed ecosystems. The Alligator River National Wildlife Refuge provides a unique, understudied, and minimally managed environment consisting primarily of forested wetlands that are highly sensitive to environmental changes caused by climatic pulses, such as large storm events, flooding, and saltwater intrusion. The refuge is located in Dare and Hyde counties in eastern North Carolina, where the majority of the refuge is found in Dare County and land primarily consists of wetland or is being restored to wetland. In contrast, Hyde County is becoming increasingly developed and agrarian and offers a valuable resource for studying how different land-use practices affect historically similar landscapes. Additionally, changes in hydrologic inputs caused by anthropogenic forces, such as man-made ditches, levees and impervious surfaces are also having major impacts on these wetlands. Research directed at deciphering how these alterations are affecting wetlands as well as what physically drives water as it moves through the terrestrial ecosystems has been a major area of focus over the past several decades. Quantifying the water balance and partitioning water into distinct abiotic and biotic components has been used to facilitate analysis of ecosystem services and productivity (D'Odorico et al., 2010). Water plays a key role in almost every ecosystem function and crosses multiple spatio-temporal scales, where it is simultaneously driven by dynamics of water transport vertically through the soil–plant-atmospheric continuum and horizontally across the landscape. Water transport is affected by topography, soil characteristics, and feedback loops that are influenced by the distribution, structure, function, and dynamics of plant communities (Warren, 2011).

Evapotranspiration (ET) is a major flux of water and energy from terrestrial ecosystems, which is regulated by interactions between environmental conditions and plant biological responses to these changing conditions. Partitioning ET into separate evaporative (E) and transpirative (T) components enables researchers to investigate the role water takes in ecosystem function and development. Evaporation is a passive process that is regulated wholly by the physical conditions of the environment, while transpiration (T) is controlled by biophysical and physiological interactions between the vegetation and the environment. The primary environmental drivers of ET at the ecosystem or watershed levels are: soil moisture, solar irradiance and vapor pressure deficit.

ET has been one of the most elusive components of the water budget to accurately quantify until recent advances in sensor and data storage technologies have made it easier to detect and model. These advancements in monitoring techniques have facilitated ecosystem ET measurements by creating a platform for monitoring gas exchanges, such as eddy covariance, between the canopy and the atmosphere. Combining eddy covariance measurements of ET with sap flux measurements of canopy transpiration (Tc) at high temporal resolutions allows ET to be partitioned into its individual evaporation (E) and transpiration (T) components (Tang et al., 2008). Partitioning ET makes it possible to perform further statistical analysis between the vegetation and the environment that helps scientists to understand plant responses to dynamic environmental conditions. Correlating estimates of sap flux density (Js), canopy transpiration (Tc), stomatal conductance (Gs) and stomatal sensitivity (SS) with measurements of environmental drivers, such as, water table depth (WTD), vapor pressure deficit (VPD) and photosynthetically active radiation (PAR) provides a framework to compare plant water use with highly influential environmental drivers. This approach by Jarvis (1976) attempts to correlate variations in stomatal conductance and leaf water potentials with fluxes of radiant energy and VPD. A mechanistic approach to studying stomatal conductance was later adapted from this model and improved upon over the subsequent years (Brodribb, 2009; J-C Domec, et al., 2005; Oren, et al., 1999;

Ward, et al., 2008). Applying these methodologies lays out a strategy that utilizes the analogy between an electrical circuit and water flow through the conducting xylem of plants.

Historically transpiration has been thought to represent approximately half of ET in vegetated terrestrial ecosystems (Ge Sun et al., 2011). Although a recent study by Jasechko et al, (2013) suggest that two-thirds of all global water fluxes out of terrestrial ecosystems can be accounted for by the transpiration portion of the water budget and suggests that the lack of catchment-scale measurements and uncertainties in stomatal conductance restrict global-scale estimates of transpiration from climate models. Additionally, understanding what drives T, or the diffusive conductance of water through stomata, is an area of research in plant physiology and ecohydrology that needs to be studied in more detail because of the stomata's close link to soil water, hydraulic regulation of the plant, carbon assimilation, ecosystem productivity, and tree metabolic and biological processes. (Brodribb, 2009; Emanuel, et al. 2007; Tang et al., 2006; Warren, 2011) Stomatal conductance is a constructive measure of plant biophysical processes because it is a sensitive gauge for studying the effects of environmental stimuli, mainly VPD, PAR, and soil water content on plant water-use (Loranty, et al., 2010; McCulloh, 2012; Nachabe, et al., 2005; Oren, et al., 1999; Tuzet, et al., 2003). However, these inputs "must be scaled to canopy and landscape levels to ultimately address higher-order questions about forest water use and potential water conservation on ecosystem-scale processes" (Warren, 2011**)**. Most studies of this nature investigate ET in highly managed systems where annual reductions in transpiration are primarily due to drought stress. While coastal-forested wetland ecosystems, such as the

Alligator River National Wildlife Refuge, are unique in that they are sensitivity to environmental changes caused by large storm events, flooding, and saltwater intrusion.

The aim of this research at the Alligator River National Wildlife Refuge is to 1) Partition ET into its main components, canopy transpiration, understory transpiration and soil evaporation, and 2.) Investigate how the main overstory tree species respond temporally to fluctuations in the water table depth (WTD). It is believed that shifts in environmental conditions mainly WTD, PAR, and VPD as well as the timing of the shifts in the WTD will have a significant influence on the trees responses flooding. It is also assumed that the spatial distribution of vegetation will be influenced by shifts in topographic features across the site, such as higher clay soils and low lying peats. Additionally, the distribution of different species will affect the amount of transpiration within our site.

Methods and Materials

Site Description

The Alligator River National Wildlife Refuge (ARNWR) is primarily located in Dare County within a small section reaching into Hyde County on the Albemarle-Pamlico peninsula of North Carolina, USA approximately 32 km. from Nags Head in the Outer Banks region. The mean annual temperature and precipitation, taken from the climate records of an adjacent meteorological station in Manteo, NC for the period 1981-2010, are 16.9°C and 1270 mm, respectively (Miao et al., 2013).

This peninsula differs from coastlines to the north and the south because of a distinct combination of geomorphic features and lagoon environments, which results in the absence of astronomical tides making rainfall the main source of fresh water into the refuge (Moorhead and Brinson, 1995). Soils of the peninsula have a deeper organic layer than the adjacent mainland areas because they were formed at the outlet of the Alligator River, where organic sediments build up because of low intensity drainage caused by the very low relief (Miao, 2013).

The hydrology at the ARNWR differs from non-coastal wetlands further inland with similar plant compositions due to the influence of micro-topography, near-absent runoff and dynamic interactions between an upper unconfined aquifer and a deeper confined aquifer (Bryant, 2008). The height of the water table averages approximately 1 m. above sea-level while the total depth of the aquifer ranges from 3 to 50 m deep. The upper unconfined water table spans between 1.5 and 4.6 m. While the lower confined aquifer can reach an additional 9 m. in depth forming a lens-shape bulge that sits on top of more dense salt water. This lens expands and contracts depending on the amount of fresh water inputs through precipitation as well as from losses due to ET and through interaction with the zone of brackish water, which is sandwiched between the freshwater and saltwater layers.

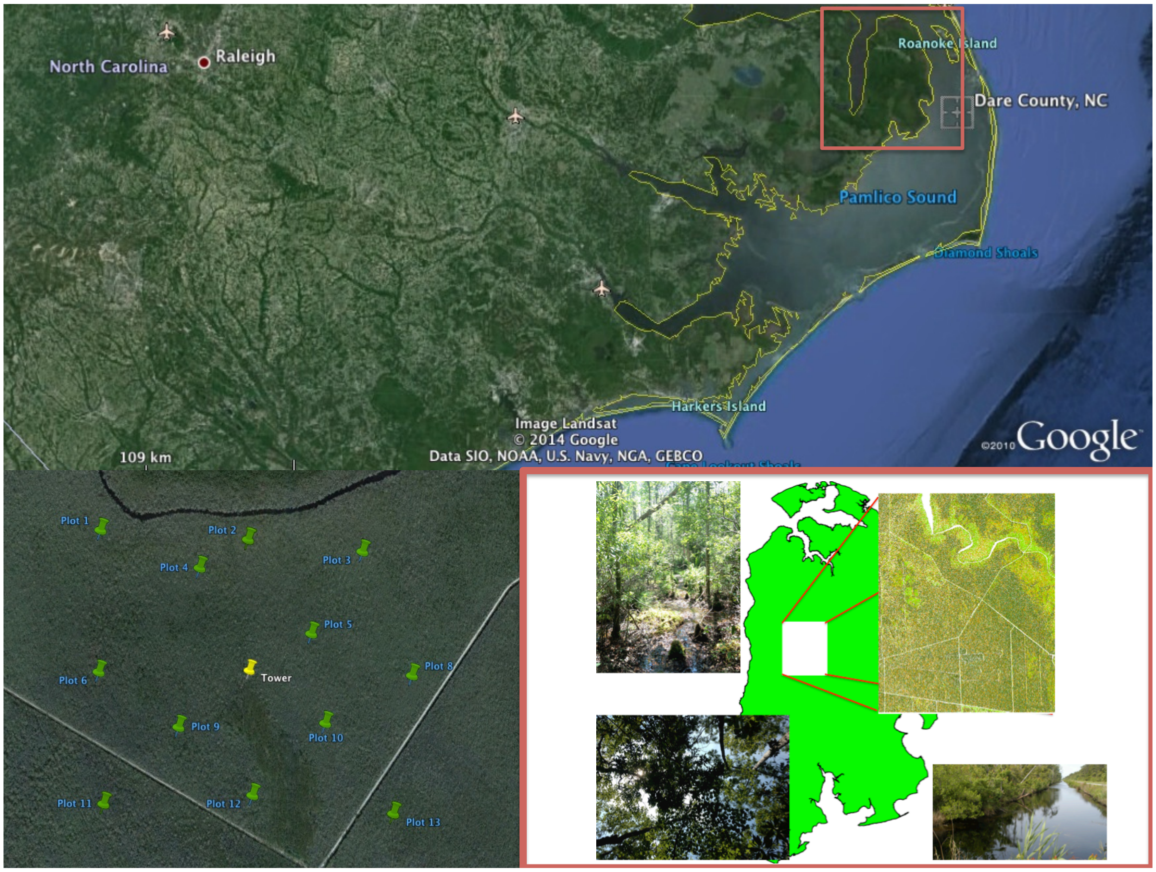

Figure 1: The Alligator River National Wildlife Refuge in Dare County, NC, along with the Site and Plots within the Site

The Alligator River National Wildlife Refuge was established in 1984 to conserve and protect pocosin wetland habitat and its associated plant and wildlife species (Bryant, 2008). The ecosystems within ARNWR cross a spectrum of forest and landscape types, transitioning between estuary, pine-hardwood forest swamps, pocosin wetlands, lowland mixed pine, as well as a large stand dominated by Atlantic white cedar. Approximately 70% of the ARNWR is characterized as a wetland or transitioning back to wetland from agriculture or forestry managed lands. Pocosin vegetation is variously described as boggy shrublands or flatwoods usually dominated by broad leaved evergreen shrubs, typically including titi (Cyrilla racemiflora), red bay (Persea borbonia), sweet bay (Magnolia Virginians), loblolly bay (Gordonia lasianthus), bitter gallberry (Ilex glabra), zenobia (Zenobia pulverulenta), wax myrtle (Myrica cerifera) and low trees. The overstory in wetter boggy environments is dominated by black gum (*Nyssa sylvatica var. biflora (Walter) Sargent*, bald cypress (*Taxodium distichum*), and red maple (*Acer rubrum L.).* While stands that occupy the higher more well-drained areas are composed of slash pine (*Pinus. elliottii Engelm*), pond pine (*Pinus serotina*), and planted loblolly pine (*Pinus taeda L.)* (Sharitz, 1982).

Approach

The research site is contained within a 4 km^2 area of forested wetland dominated by bald cypress, black gum, and red maple. The canopy height ranges between 15 and 40 m with a well-developed understory in the wetter areas approximately 2 m in height. There are 13 vegetation survey plots within the site. Each plot is centered on a dominant tree with a perimeter extended from that tree at a 7 m radius. In each plot, tree species, and DBH measurements are recorded for all trees over 3 cm in diameter to be used for scaling-up sap-flux-based transpiration estimates. At the center of the site (35°47′N, 75°54′W, plot 7), there is an eddy covariance tower, a micrometeorological station and a long-term soil respiration system.

Eddy Covariance-Based Evapotranspiration

The eddy covariance tower was erected in January of 2009 along with an understory micrometeorological station. On the eddy flux tower, instruments were mounted at 30 m and were about 16.7 m above the displacement height. Evapotranspiration (ET) can be calculated directly from the energy balance (Equation 1), where is the latent heat flux (LE) or the partition of net radiant energy (Rn) that is used to change liquid water into water vapor, Pw is the density of water and λv is the latent heat of vaporization. ET can occur either as evaporation (E) from the surfaces of the earth, objects, and vegetation, or as transpiration (T), which begins inside the leaf mesophyll and move into the atmosphere through the plants stomata.

Equation 1. $$ET = LE/(\mathrm{Pw} * \lambda \mathrm{v})$$

Eddy flux based evapotranspiration at the Alligator River National Wildlife Refuge was estimated using LE measurements ~~of~~ from an open-path infrared gas analyzer (LI-7200, Licor Inc. NE, U.S) and a three-dimensional sonic anemometer (CSAT3, Cambell Scientific, Logan, Utah). Data quality was evaluated during periods of well-developed turbulent mixing for atmospheric stability and flux stationarity, described in more detail by Noormets et al, (2010,) Sun et al. (2010), and Domec (2012). This method corrects 30-minute ET data for possible errors arising from warming of the infrared gas analyzer, fluctuations in air density, and poor data quality due to system failures and environmental interference.

The eddy covariance flux systems provide a large footprint from which ecosystem water vapor fluxes (ET) can be measured. However, the footprint of these fluxes is influenced by the direction and speed of the wind, and measurements are unreliable if turbulent mixing of air between the canopy and free atmosphere is low or absent. For this reason, the footprint measured by the tower can range from several hectares to several square kilometers. ET is a broad ecosystem measurement, so "finer-scale information is crucial for understanding how physical and biological factors interact and give rise to tower-measured fluxes in complex landscapes" (Emanuel, et al. 2011).

Micrometeorological Conditions

Micrometeorological conditions were measured both above the canopy alongside the eddy flux system as well as in the understory using a separate micrometeorological station. The above canopy measurements (at 30 m) included T_a and RH (HMP45, Vaisala), PAR (PARLITE), net radiation (R_n, NRLITE, KZ), and precipitation (P, TE525, Texas Instruments).

The understory micrometeorological station was deployed in November 2008 and measured understory air temperature (T_{au}), relative humidity (RH_u, HMP45AC, Vaisala, Finland), photosynthetically active radiation (PAR_u, PARLITE, Kipp & Zonen, Delft, Netherlands (KZ)), soil temperature (T_s) at 5 and 20 cm (CS 107, Campbell Scientific Inc., UT, USA (CSI)), volumetric soil water content (CS 616, CSI), and soil surface heat flux (HFP01, KZ).

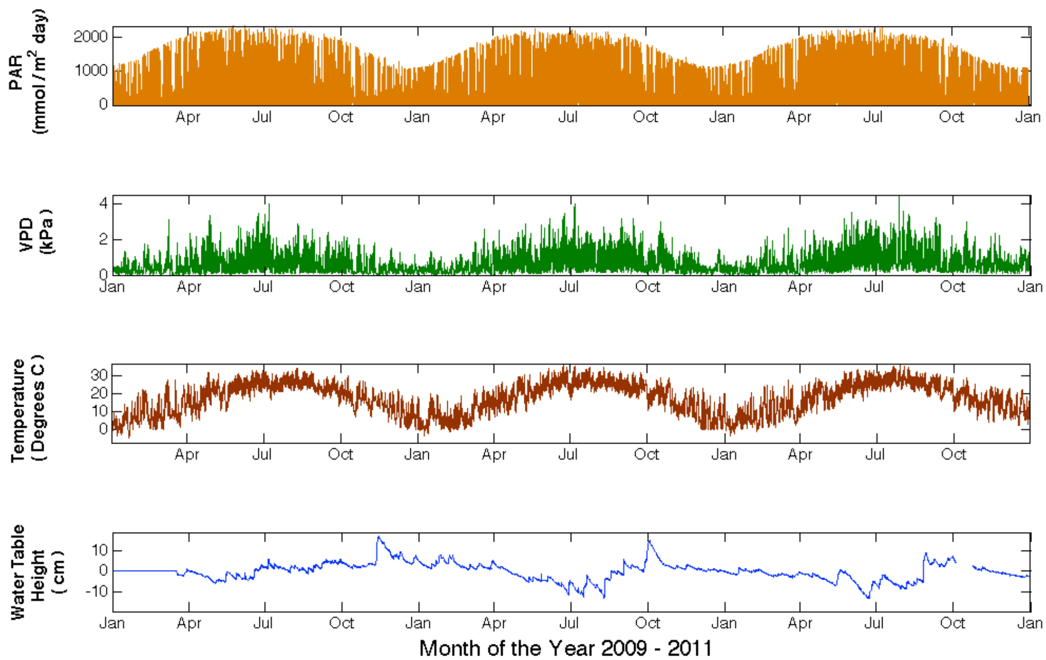

Figure 2. Micrometeorological Observations

Three years of high frequency measurements of the four main environmental drivers being investigated in this analysis. Water table depth (WTD) dropped significantly July – August 2010 mainly because of high transpiration rates of the vegetation and relatively little rainfall.

Soil Evaporation, WTD, and LAI Measurements

Plot measurements of soil evaporation (Es), water table depth (WTD) and leaf area index (LAI) were performed in the five central plots near the eddy flux tower. (plots 4, 5, 7, 9, 10) on Figure 1) Plot measurements of soil evaporation (Es), water table depth (WTD) and leaf area index (LAI) were performed in the five central plots near the eddy flux tower. (plots 4, 5, 7, 9, 10 on Figure 1. Soil evaporation (Es) was measured with a multichamber portable automated soil respiration system (LI-8100, Licor Inc.) with a multiplexer (LI-8150, Licor Inc.) and 4 chambers (LI-8100-104). The chambers were originally deployed to measure CO2 efflux as described in (Miao et al., 2013). However, the soil respiration system is equipped with a high-precision H_2O detector that has been used to reliably measure Es (Raz Yaseef et al., 2010, Domec et al., 2012). Chamber-based soil vapor flux was measured in five soil collars located around the eddy-flux tower. Measurements were carried out evenly throughout the entire research period (January 2009–December 2011). Maximum daily E_s was calculated at half-hour time intervals between 1000 h and 1300 h corresponding with the time of peak in diurnal ET. Multi-linear correlations between E_s and temperature, relative humidity and water table depth were used to estimate E_s for other periods.

Water table depth was also collected in the 5 most central plots. At 4, 5, 9, 10 with pressure water level data loggers (Infinities, Port Orange, FL, U.S.) and in plot 7 with another pressure water level data logger (WL 16, Global Water Instrumentation, TX). Water table data was normalized as described in Miao (2013) and conditions were considered flooded when the water table was 8.7 cm above the water table probe in the central plot.

Peak and dynamic leaf areas data were assessed using MODIS data from 2009 – 2011, these data were calibrated with auxiliary data collected using a Nikon camera with a fisheye lens and leaf litter baskets. In plots 4, 5, 7, 9, and 10, there were three leaf litter baskets per plot. Photos and leaf litter collection were intermittent until 2013. In 2013, LAI photos and leaf litter were collected every 2 to 3 weeks in order to gain a more complete understanding of how leaf area changes temporally throughout the year.

Sap-Flow Based Transpiration Estimates

From 2009 - 2011, twenty Granier-type sap flux probes were installed in 20 trees in order to estimate individual tree transpiration and species average in the predominant overstory species (black gum, bald cypress, loblolly pine, and red maple). Sap-flow based transpiration should always be underneath eddy flux based measurements of ET since sap flow based transpiration only measures canopy transpiration (Tc, mm day^{-1}) and does not account for understory transpiration (Tu, mm day^{-1}) or soil evaporation (Es, mm day^{-1}). Instrumented trees were located near the eddy flux tower, where 20mm probes were installed 1.4 m above the ground in the north-north-west side of each monitored tree.

The probes were covered with reflective insulation to protect them from heat sources external from the sapwood of the tree. A CR10 data logger (Campbell Scientific) was used to store thirty-minute averages of the temperature difference data. This signal was then converted to a sap flux density (Js, g m^{-2} s^{-1}), following the Granier (1987) heat dissipation probe method along with modifications to this method that take into account possible measurement and scaling errors such as non-zero nighttime fluxes on the signal baseline and radial asymmetry in the conducting xylem (Bush, et al., 2010; Jean-Christophe Domec, et al., 2010; Ewers & Oren, 2000; Ford,et al., 2007; Oishi,et al., 2008; Ward et al., 2013). The Js of each probe was then multiplied by the sapwood area (As) of each associated tree along with a radial correction term to estimate the transpiration rate (kg m^{-2} $halfhour^{-1}$) of each monitored tree. Radial correction values are applied to the sapwood area measurements because xylem often becomes less conductive closer to the heartwood of the tree. Radial correction terms are species dependent and literature values were used for each species in this study. Next, transpiration was averaged between trees of the same species. The species transpiration averages were then used to estimate species-level transpiration across the entire site by scaling the data with species distribution and DBH data gathered annually from the 13 subplots. Finally, species transpiration averages for the entire site were added together to acquire the Tc value for the whole site. These measurements were then compared to ET measurements derived from the eddy flux tower.

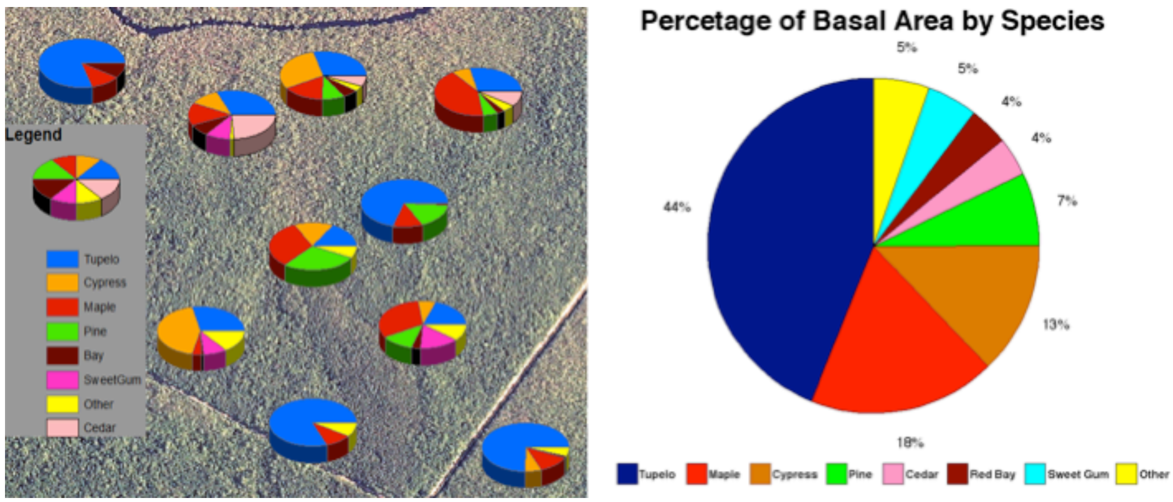

Figure 3. Species Specific Basal Area Distribution for Each Plot

(Left panel) Basal distribution for any 154m^2 of ground is highly variable within the refuge due to slight changes in micro-topography**. (Right Panel)** Tupelo, maple, cypress, and pine represent 82% of all the basal area measured across the site indicates that species distribution across the site is dominated by the four sap flux monitored trees.

Converting Transpiration per Unit Sapwood Area to Transpiration per Unit Leaf Area

Calculating transpiration on a leaf area basis (Tl, mmol day) is another approach to analyzing tree water use, since transpiration is the exchange of water vapor between the leaves and the atmosphere. This approach can be utilized to examine how environmental drivers such as root water stress affect how trees manage water use. However, in order to transform data to the leaf area footprint, a sapwood-area-to-leaf-area ratio (AS/AL) must be applied to the Tc term. Additionally, after converting Tc to Tl, the canopy stomatal conductance (Gs) of each species can be derived.

Stomatal Conductance

In a forest ecosystem, transpiration (T) can be attributed to gas exchanges between the canopy and the atmosphere. Canopy stomatal conductance (Gs) represents the rate at which transpired water exits the leaf through the stomata. A big leaf approach, which considers all tree species to transpire uniformly, has been utilized over the years to scale Tl and Gs to a canopy conductance. However, individual species react differently to similar environmental stresses. To accurately scale Gs to the canopy level, a LAI > 3 or sap-flow-derived estimates of Gs from individual plants are needed. Stomatal conductance estimates were derived from leaf-area-based transpiration (Montieth,

Equation 2. $Gs = \gamma(T) * \lambda(T) * El/(Cp * \rho(T) * VPD$

Where γ is the psychometric constant, λ is the latent heat of vaporization of water, Cp is the specific heat of the air, ρ is the density of liquid water, T is the temperature, VPD is the vapor pressure deficit of the air above the canopy, and El (mmol m^{-2} s^{-1}) is the canopy transpiration per unit of leaf area, scaled up from sap flux measurements.

A simplified closed water balance equation was developed the incorporate the measured and modeled water fluxes in the ARNWR.

Equation 3. $P = ET + D + \Delta Soil$

Where *P* denotes gross precipitation; ET is defined as the sum of soil evaporation (E_s), dominant tree and understory transpiration (*T*), and canopy interception (*I*); *D* is drainage flowing out of the watershed; and DeltaSoil represents the change in soil water storage (all in mm yr^{-1}) and. Although storage is a an important factor at weekly or monthy intervals at an annual time step it is near zero and E and T reprent the most influenctial flux of water from the site.

Statistics

All statistical analyses in the report were accomplished using MATLAB (MathWorks Inc. Natick, Massachusetts, United States). An one-way ANOVA statistical test was use to analyze the significance of the correlation between environmental factors, VPD, PAR, WTD with water fluxes, Gsref and SS. Binning the Gs data is a statistical approach used to gain more insight into how different environmental factors effect Gs. This method select for data that occurs during both saturated light conditions, PAR as well as when the VPD is held constant at 1 kPa. Results from previous analyses show that the errors for these aggregations are inconsequential and limit any autocorrelation (Jean-Christophe Domec et al., 2010; Oren, et al., 1999; Phillips & Oren, 1997; Tang et al., 2008). The binned data, termed reference stomatal conductance (Gsref), can be useful in regression analyses, which explore how tree hydraulics and the soil environment affects Gsref and Stomatal Sensitivity (SS).

Results

Components of Stand Water Balance

Precipitation in 2009 was 95% of the mean annual precipitation between 1981 and 2010, while 2010 and 2011 were only 77% and 66%, respectively (Table 1). In terms of precipitation, 2009 is characterized as a wet year compared to 2010 and 2011, which are characterized as dry years. It is noteworthy to mention that during the last 2 years of the study a large portion of precipitation came with tropical storms and hurricanes toward the end of the growing season. Additionally, in wetland ecosystems dominated by tupelo and cypress the tree canopy intercepts around 15% of precipitation measured above the canopy (Bryant, Bhat, & Jacobs, 2005). Which means only 85% of measured precipitation actually reaches the ground and contributes to WTD fluctuations.

Table 1. Partitioned Water Fluxes at the Alligator River National Wildlife Refuge

(mm)

	2009 Growing Season	2009 Annual	2010 Growing Season	2010 Annual	2011 Growing Season	2011 Annual
Precipitation	556.26	1,203.96	589.28	982.98	500.38	833.12
Canopy Interception	83.44	180.59	88.39	147.45	75.06	124.97
Through fall	472.82	1023.37	500.89	835.53	425.32	708.15
Water Table Fluctuations	39.16	108.3	**-41.92**	**-222.67**	**-63.58**	**-262.45**
ET	433.66	915.07	542.80	1058.2	488.89	970.60
Tc	183.2	302.0	268.4	417.31	266.2	438.75
Tu	200.3	360.8	205.4	352.11	179.6	249.62
Es	67.7	252.31	80.6	280.58	90.9	282.03

At the beginning of the analysis (January – March of 2009) the water table depth was 9.7 cm below the normalized flooded conditions, which is 8.7 cm above ground surface relative to the well in plot 7 near the eddy flux tower, that were established by Miao (2013). The WTD steadily dropped until mid-May and early June, when on May 27th Tropical Depression One resulted in a 3.5 - 4 cm rise in the water table. In November, remnants of Hurricane Ida sent the WTD to its highest levels of the entire research period, at 17.3 cm. In 2010 the WTD dropped to its lowest points of the year in late June, mid July, and mid August, where the WTD was approximately 22 cm below normalized flooded conditions. The WTD quickly rebounded in late August due to the effects of Hurricane Earl and reached its annual high in early October. In mid June 2011, the water table depth fell to its lowest level of the entire study, approximately 22 cm below the normalized flooded conditions. In late August, Hurricane Irene caused the water table to peak at 0.2 cm above the normalized flooded conditions.

During the 3-year observational period, annual precipitation only exceeded annual evapotranspiration in 2009, although during the growing season precipitation always exceeded ET. A large portion of the precipitation came towards the end of the growing season with larger tropical storms and hurricanes, which is clearly reflected in the WTD data, (Figure 2). Despite quantitative differences between eddy covariance and sap flux measurement techniques there is a high degree of qualitative similarity in the data over the time of the research, both diurnally, seasonally an annually. During the growing seasons, ET is closely split between Tc 43% and Tu 39%, with a considerably smaller portion of the flux leaving as Es 18%.

The hysteresis in the sap flux responses to PAR and VPD where similar to those listed for Mediterranean tree species (Link, 2014). Once these reaction times were accounted for the canopy conductance determined through sap flux measurements had a high degree of correlation with PAR and VPD measurements and are comparable to those of a hardwood forest in Michigan (Tang, 2006).

Components of Transpiration

Canopy

Tupelo transpiration measuring 649.67 mm represents 62% of the total canopy transpiration flux across all three years, tupelo was the dominant contributor to canopy transpiration at our site. Additionally, the other sap flux monitored trees including maple, cypress, and pine, contributed 157.03 mm, 159.22 mm, and 82.39 mm, or 15%, 15% and 8%, of canopy transpiration respectively. These trees, along with tupelo, represent approximately 70% of the total stems over 3cm across the site. The high transpiration value attributed to tupelos is due to both their high sap flux rate as well as the high percentage of tupelo basal area within the site.

Understory

Transpiration from the understory is comparable to Tc. This outcome is supported by leaf area estimates gather from MODIS whose total LAI values max out around 5, while data from fisheye photos suggest canopy leaf areas maxing out around 2.8. Transpiration from the understory was estimated by closing the ET portion of water balance once Tc and Es estimated were analyzed. This value is highly dependent upon the estimates of Tc, because slight changes in species distribution and sap flux density can alter estimates by large amounts.

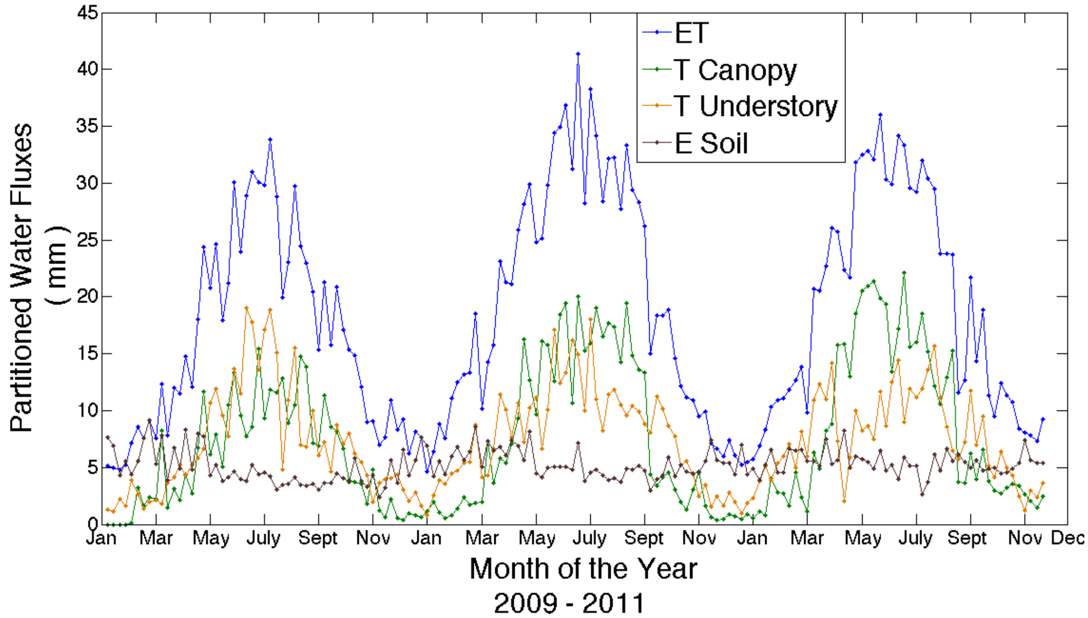

Figure 4. Measured and Modeled Components of Evapotranspiration (mm)

Distribution of Sap Flux Monitored Trees

On a stems per hectare basis, tupelo represents 44% of trees over 3cm DBH present throughout the site, while, maple, cypress, and pine represent 17%, 4% and 2% of stems present respectively. However, cypress and pine trees tended to be larger but less numerous, so in terms of basal area, cypress and pine represent a slightly higher percentage of tree biomass, at 13%, and 7%, which increase the total basal area for sap flux monitored trees to 75% of the biomass within all the plots (Table 2). Maple and cypress basal areas' represent similar ratios when derived on a hectare basis. This is due to the high number of small to medium sized maple trees, 970 stems, and infrequent but large cypress trees, 370 stems. Pine basal area is also representative of a small number of large trees within the site, 85 stems.

Sap Flux per Unit of Sapwood Area

Sap flux density (Js) for tupelo is the highest, with an average rate of 18.87 (g m^{-2} s^{-1}). This rate was followed by pine at 12.29 (g m^{-2} s^{-1}), maple at 11.07 (g m^{-2} s^{-1}), and cypress at 10.40(g m^{-2} s^{-1}). Sap flux density (Js) for tupelo, pine, maple, and cypress peaked in July each summer at approximately 60, 40, 30, and 30 (g m^{-2} s^{-1}), respectively.

Table 2. Summary of Tree Allometrics used in Analysis

	Tree Density Stems Per Hectare	DBH (cm)	Sapwood Area (m^2)	Basal Area (m^2)	AS/AL Ratio (m^2/m^2)
Pine	85.5	37.52	0.0015	0.0879	0.00027
Cypress	369.6	22.93	0.0043	0.0568	0.00019
Maple	970.2	15.29	0.0074	0.0215	0.00037
Tupelo	2525.6	16.53	0.0189	0.0161	0.00037

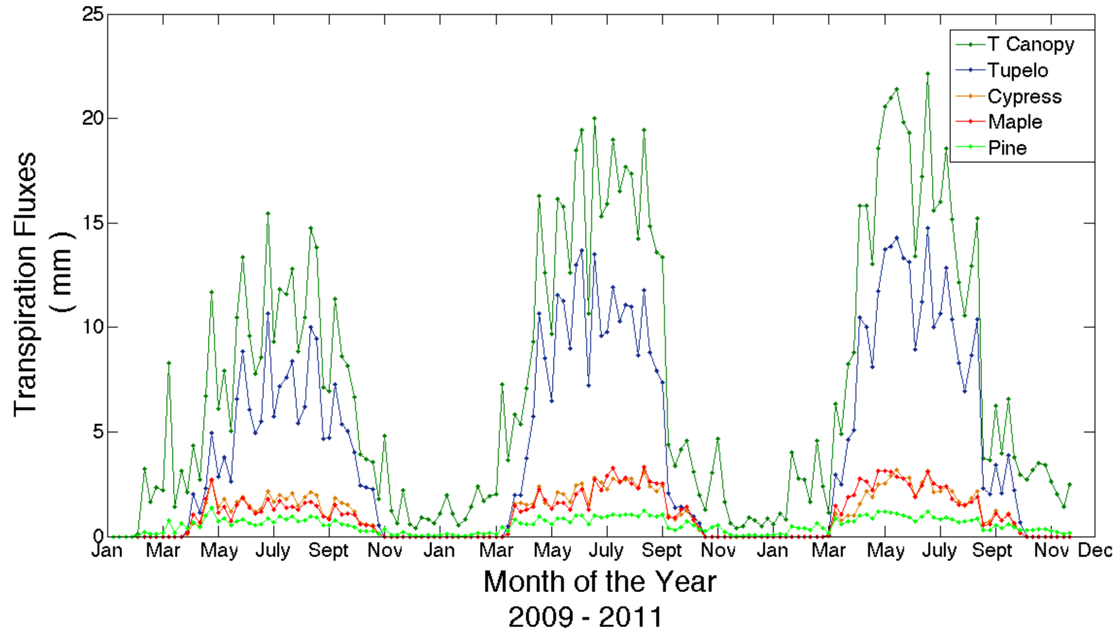

Figure 5. Sap Flux Based Transpiration and Tower Based Evapotranspiration (mm)

Table 3. The Average Water Flux from a Sapwood Area, Individual Tree, Site Basis, including Leaf Level Transpiration and Stomatal Conductance

	Sap Flux Density (Js) $g\ m^{-2}\ s^{-1}$	Transpiration Individual T_i $mm\ day^{-1}$	Transpiration Canopy (Tc) $mm\ day^{-1}$	Transpiration Leaf (Tl) $mmol\ m^{-2}\ s^{-1}$	Stomatal Conductance Gs $mmol\ m^{-2}\ s^{-1}$
Tupelo	25.33	5.41	0.58	4.38	53.40
Maple	15.42	3.14	0.13	2.17	26.51
Cypress	10.52	12.63	0.2	2.17	20.27
Pine	12.54	24.67	0.1	2.35	20.68

Statistics

The upper graph in figure 5 displays the reference stomatal conductance of each species for each week of the year. This data captures the seasonal changes in leaf area and the influence of major storm. This phenomenon is best represented in the tupelo data by the depression in the mid to late July of 2010 coinciding with Hurricane Earl. The lower graph displays weekly calculations of stomatal sensitivity. Again tupelo data appears to capture the trend of the way stomata respond to changes in environmental factors. A one-way ANOVA was used to determine the significance of the regression analysis in table 6 the summarized trends in the data between the WTD and each species Gsref and SS.

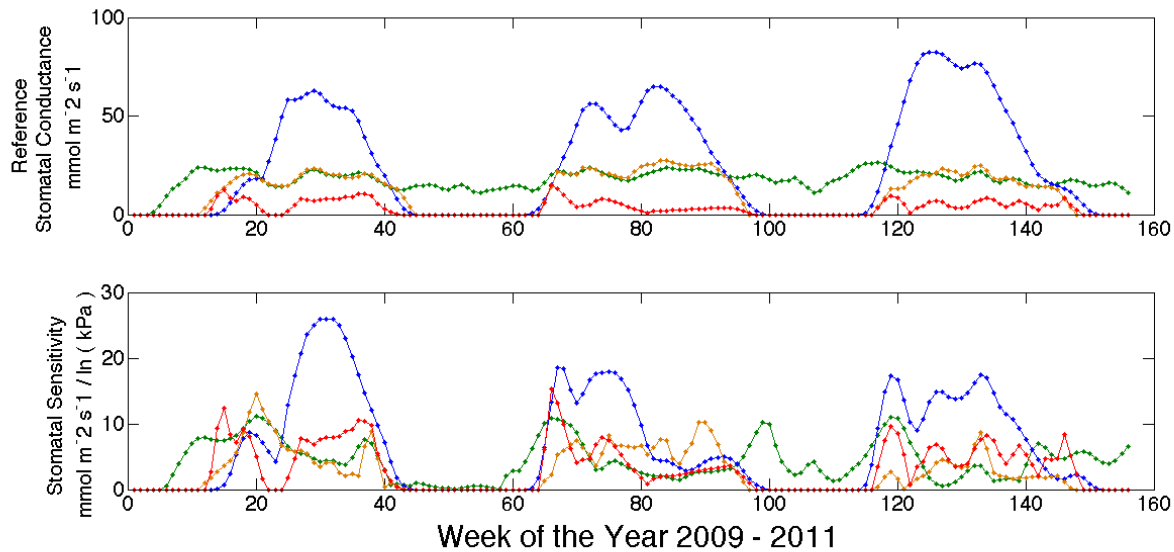

Figure 6. Gsref and Stomatal Sensitivity Plotted at a Weekly Time-step

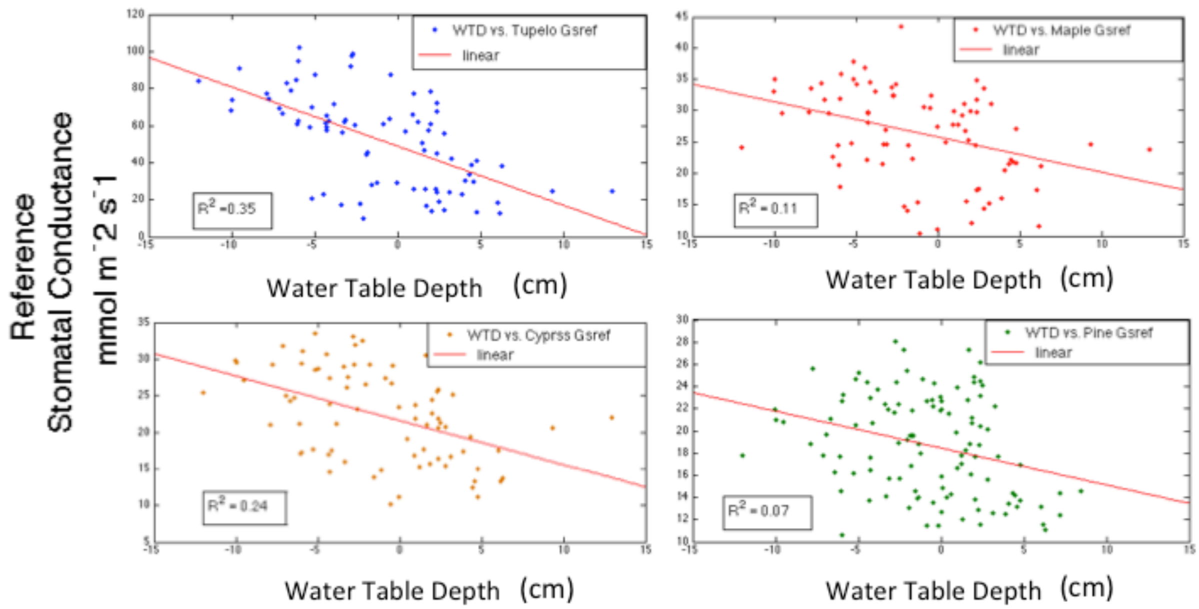

Figure 7. Reference Stomatal Conductance

WTD is plotted on the x-axis and the Gsref on the y-axis, for tupelo (upper left), maple (upper right), cypress (lower left), and pine (lower right) along with the coffecients of correlation for each species.

Influence of Water Table Height on Gsref and Stomatal Sensitivity

The reference stomatal conductance and stomata sensitivity were highest for tupelo, while cypress, maple and pine behaved within similar ranges. At week 46 pine's Gsref shot up during Hurricane Ida and quickly then returned to normal values. Tupelo had the most prominent response to the wet conditions; this is most clearly seen in the comparison between the wet 2009 growing season and the dryer 2010 and 2011 growing seasons (Figure 4). Regression analyses investigating the affect that the WTD has on Gsref and stomatal sensitivity of the four tree species indicated that tupelo is most sensitive to fluctuations in the water table (Table 4). This corresponds with the general trend in plants physiology that suggest that plants with high transpiration rates are more sensitive to environmental stressors. The data also suggests that maple, cypress and tupelo

Table 4. Gsref and SS Statistics

The upper table indicates the p-values of found using a one-way ANOVA analysis. While the lower table represents the R^2 values from the regression analysis of the Gsref and the stomatal sensitivity, for each species in this study, against the average WTD, for each week of the year, for all three years of this study. The coefficients of correlation represent the data for each year and for all three years combined.

P – values

4a	**2009**	**2010**	**2011**	**Total**
Tupelo	Not Significant	< = 0.05	< = 0.005	< = 0.05
Maple	Not Significant	< = 0.05	< = 0.005	< = 0.05
Cypress	Not Significant	< =0.05	< = 0.005	< =0.05
Pine	Not Significant	Not Significant	Not Significant	Not Significant

(R^2 values)

4b	**Gs**				**SS**			
	2009	**2010**	**2011**	**Total**	**2009**	**2010**	**2011**	**Total**
Tupelo	0.53	0.56	0.63	0.37	0.21	0.32	0.23	0.18
Maple	0.02	0.27	0.30	0.16	0.04	0.05	0.09	0.24
Cypress	0.22	0.11	0.38	.26	0.04	0.22	0.25	0.32
Pine	0.13	.14	0.05	0.04	0.04	0.07	0.07	0.05

Discussion

Reference stomatal conductance and stomatal sensitivity were estimated to investigate how variation in WTD affected water use in the dominant trees occurring in a forested wetland at the Alligator River National Wildlife Refuge in eastern NC, comprised mainly of tupelo, maple, cypress and pine. Canopy transpiration was partitioned based on averaged individual species transpiration rates and species basal area distributions across the refuge. Additionally, the primary components of ET: Tc, Tu, and Es, were estimate using sap flow sensors, eddy covariance techniques, and soil evaporation chambers. These data were then scaled up to the growing season and annual time steps for 2009, 2010, 2011, and used to calculate site water balance including precipitation, interception, through fall and storage components. Estimations of Gsref, were used to isolate the climatic effects of PAR and VPD to determine that high WTD significantly influenced leaf level regulation of water loss through stomatal closure in tupelo, maple, and cypress. These results may help explain why a large portion of ecosystem respiration during flooded conditions appears to be coming from above ground plant respiration (Miao et al., 2013).

Forest Structure

In the Alligator River National Wildlife Refuge Comprehensive Conservation Plan, our research site is primarily described as a mixed hardwood swamp, which makes up around 4,655.4 hectares of the refuge. While a much smaller portion of our site, the clay lens, is listed as loblolly forest, which makes up approximately 1,214.7 hectares of the refuge. Additionally, the forest types immediately adjacent to the site are mixed pine-hardwood forests, Atlantic white cedar forests, and cypress gum forests representing around 8,634.9 hectares, 2,711.5 hectares, and 3,030.3 hectares, respectively.

The canopy of our site is fairly uniform with the average tree height in the mixed hardwood swamp and loblolly forest around 15-20 m, in contrast to the cypress-gum forest with a canopy height of 30-37 m. Our forest is representative of a typical coastal wetland forest in the southeaster US and is sometimes described as a pocosin wetland. Tupelo represents 42% of basal area in our site, even though the average basal area for tupelo (16.53 cm) and maple (15.29 cm) are lower compared to those of cypress (22.93 cm) and pine (37.52 cm). This is because there are 2525.6 tupelo trees per hectare that are over 3cm in DBH, base on plot measurements. Compared to maple with 970.2 trees per hectare, and cypress with 369.6 trees per hectare, representing 18% and 13% of the basal area in the site respectively. It is important to note that larger cypress trees and an occasional large pine tree are randomly scattered throughout our site. Which means that although cypress transpiration is higher on an individual tree basis compared to maple, due to differences in species composition, and their physiology that their average transpiration rate per unit leaf area is the same at 2.17 $mmolm^{-2} s^{-1}$. In the same way pine contribution to leaf level transpiration is small, even though pines have a high individual tree transpiration rate, mainly because they represent so little basal area (7%) within the site. However pine is highly concentrated on the clay lens (aka. loblolly forest), and future research would be well severed to treat this site as a separate landscape type. Species distribution estimates are important to get right and the small plot sizes called for in the Ameri-flux protocol, which was used in this study, may not accurately represent the spatial distribution of species and if an alternative method was used to sample species distribution it could improve transpiration and stomatal conductance estimates.

Species Differences

Tupelo

Tupelo had the highest sap flux rate and was the largest component of canopy transpiration, although on an individual tree basis pine and cypress transpired more. This is due to two main factors. The first reason is that tupelo has the highest sap flux rate of the trees monitored with sap flow probe and secondly, that tupelo represents 44% of the total basal area across the site. Stomatal conductance in tupelo was also the most sensitive to flooding of the four over-story species monitored. This is consistent with recent research suggesting that swamp tupelo is well adapted to wetland environments (Duberstein, 2013) especially wetter, more flood prone areas (Hook, 1984), and that seedling leaf size and the spacing of their patchy stomatal openings are not affected by long-term flooding (Angelov et al., 1996). Tupelo has often been overlooked for its commercial value, however it is by far the most productive species in the physiographic setting represented by the study site at ARNWR. From a carbon sequestration perspective, tupelo represents the largest carbon sink in this ecosystem. However, research in a similar coastal-forested wetland in South Carolina found that *Taxodium distichum* was the most prominent and productive species (Jayakaran et al., 2014).

Bald Cypress

Taxodium distichum is well adapted to wetland ecosystems because it is flood tolerant (Oren et al., 2001; Oren, 1999) and salt tolerant (Krauss, 2010) , giving it a selective advantage during salt-water intrusion and long-term flooding events (Angelov et al., 1996). In the current study, significant correlation was found between flooding events, stomatal closure and stomatal response time, which is contrary to Duberstein, who suggested that bald cypress does not reduce transpiration when flooded. One reason for the differences between our results may be that our study was conducted with threes years of data, while their research was conducted only from May 19 to July 1, 2009. Additionally at our site large flooding events primarily came at the end of the growing season, outside the time period of their research. Plus the basal area distribution of bald cypress within our site was much lower than that of the South Carolina wetland (Krauss, 2014), representing about 13% of the total basal area in our site and 72% at the South Carolina site. This suggests that the sites may be more different than immediately apparent or their site may more closely resemble the cypress-gum swamp in other areas of ARNWR, mentioned above. Additionally the differences between the two sites could stem from a systemic distinctions such as age class, land used history, or current management strategies. Although sampling techniques between the two studies were different enough that if some of the inconsitecies in sampling were addressed, some of the uncertainty could be resolved. One issue with the current sampling method used at ARNWR is that it follows the Ameri-flux protocol for sampling, which creates plots that are circular in area, and are designated by a 7m radius centered around a dominate tree, a fairly small area when considering we are trying to scale the hectare level or beyond. Additionally, the dominant tree in many of these sites was selected because it is large and easy to spot in the dense underbrush. Even though this means the basal area of the central tree often represents a significantly large portion of the total basal area in their plot. Furthermore, the dispersed nature of mature cypress tree in the site means that if a plot is centered on at large cypress tree that, due to the small size of the plots, it is unlikely to include a second cypress, even though there may be several just outside the plots. However even with the differences between tupelo and cypress basal area between the sites, it is clear that along with the understory vegetation, tupelo and cypress are at a competitive advantage in colonizing wetter areas of coastal wetlands (Duberstein et al., 2013; Krauss et al., 2014). Pine and maple struggle in the low-lying areas in the current study, which may also be why the WTD vs. Gsref regressions for these species is so low. A hypothesis that is supported by the work done by Poulter (2008), that suggests that *Pinus taeda* although tolerant to both flooding and salt in terms of survival, have slowed growth and physiological processing when continually flood stressed, indicating a potential completive advantage tupelo and cypress may have at colonizing the wetter areas of ARNWR.

Pine

Leaf level transpiration estimates suggest that the pine at our site were slightly more productive than the pine inland at Plymouth NC, (Domec, 2010) and within the range of transpiration listed for the Hofmann Forest in Onslow County, NC (Aspinwall, 2011). The contribution of pine basal area to the stand limits pines importance to ET and carbon storage in this ecosystem, because the stem density was much smaller than that of tupelo, suggesting it does not grow well in the wetter areas. Pine was primarily relegated to higher microsites and the lack of correlation between stomatal conductance and WTD suggests pine has a limited mechanism for responding to flooding. Whether pine has a selective advantage on sites that experience less flooding because of the higher elevation or they exist in this location only because they were planted there is unclear. However, in either case, the limited BA distribution in pine suggests it has limited capacity to adapt to the wetter low-lying areas in the refuge. Although if they can be established in wetter areas through plantings, the lack of stomatal closure in flooded conditions may alternatively allow them to be a highly productive species in these water abundant ecosystems.

Maple

There are very few studies that investigate red maple transpiration in a flooded ecosystem as most studies including red maple are conducted in upland forests. However maple basal area and site level transpiration were similar to that of northern hardwood forest (Bovard). Although in their study maple stomata were highly sensitive to high VPD and low soil moisture. While in our study maple show a weak but significant sensitivity to flooding. The behavior of maple in this wetland environment was intermediate between that of tupelo and cypress. For example maple in the wetlands rarely grow into large mature trees, rather maple basal area consists of a larger number of small diameter stems per acre, similar to tupelo, although maple's contribution to canopy transpiration and stomatal sensitivity were more similar to cypress. Maple's sap flux rate per unity of conducting xylem was high, although transpiration on a per tree basis was the lowest. Furthermore, There is little data on red maple stomatal function in wetlands, most studies that investigate water regulation on red maple approach it from a drought stress and not as flood stress response, more research is needed in this respect.

Components of Evapotranspiration

Evapotranspiration

The average annual total ET at the site was 981.29 mm between 2009-2011 and was 76%, 108% and 116% of water exiting the site that entered through precipitation each year, respectively. These percentages of water loss through ET fall with published values of 70-113 % for a coastal plain in managed loblolly plantation (G. Sun et al., 2010), 76% for a low relief forested watershed (Dai, 2013), 70% for a mid rotation loblolly plantation near Plymouth NC (J. Domec et al., 2012) , and 56-60% from a white pine catchment in the mountains of western North Carolina (Ford, 2007) Evapotranspiration at ARNWR in 2010 (1058.2 mm) was the highest of the tree yeas the study, while ET in 2009 at 915.1 mm was the lowest, and ET in 2011 (970 mm) was closest to the three year average. Which fall between the ET at two loblolly pine sites in Plymouth, NC. These two studies overlapped in 2009 where annul ET at the ARNWR was 915.1 mm, ET at the Plymouth 4-year rotation site was 886 mm and at the 17-year rotation site it was 1001 mm. Additionally as a percentage ET is higher at ARNWR but in terms of water moved ET is also lower ARNWR then estimates of ET at Coweeta Hydrological Station of 1290-1505 mm from a white pine catchment in the mountains of western North Carolina (Ford, 2007).

Canopy Transpiration

In the current study, canopy transpiration was estimated by scaling sap flux measurements, however the trees monitored for sap flux only represented 82% basal area over 3 cm in DBH from out plot measurements that were scaled to the site. Additionally the species distribution estimates may under predict the true representation of species basal area because of small plot size, commented above, although it is acknowledged that this method was employed to follow Ameri-Flux protocol (Noormets, 2009). Some of these issues may be able to be better delineated by following methods used by making plots bigger, 25 m radius (Oishi, 2008), though more plots (Jayakaran et al., 2014), or improved GIS data (Riegel, 2013)

Soil Evaporation

The estimate of average annual soil evaporation at ARNWR for the three years of this study is 282.03 mm, with only 27 to 37% of Es occurring during the growing season. Soil evaporation at ARNWR is 2.7 times higher then the soil evaporation (105 mm) estimates for the 4-year rotation and 3.7 time larger then the 17-year rotation in Plymouth, NC (J. Domec et al., 2012). While the Es in high relief forested hill slopes is often neglected because it is such a small component of ET (Ford et al., 2007). The half hourly data and estimates suggest that Es rates are higher during the winter months when the water table is high and lower during the summer months when transpiration is high causing the water table to drop. In low relief coastal forested wetlands the micro-topography and the complex dynamics dictating how much of the water table is exposed to the free air is believed to play a large role in soil evaporation rates. A few centimeters difference in WTD could represent a large shift in the amount of water that is aboveground or below the ground surface. Which could shift a large portion of the ground surface from aerobic to anaerobic respiration or shift from photosynthetic to respiration dominated metabolic processes (Miao et al., 2013). Since runoff is low in this system when transpiration is high (Epps et al., 2013), during the growing season, the vegetation plays a significant role in regulating the water table and thus Es is low during the growing season. While the lack of transpiration in the winter months allows the water table to return to a higher stage. However this study also highlights the other side of this feed back loop that indicates that when the water table is high during the growing season it affects the physiological functions of tupelo, cypress and maple (Johnson, 2012; Krauss, 2010; Sun et al., 2002) .

Understory Transpiration

Average annual understory transpiration for 2009-2011 was 320 mm and 46%, 38% and 26% of ET, respectively, similar to that of the 4-year rotation loblolly. However when canopy interception is accounted for these estimates drop by 14-20% to 19% ,22 % and 12% of ET, respectively, which is more similar to 17 rotation loblolly stand (J. Domec et al., 2012). Additionally as mentioned above since Tc is only 82% of the species distribution and it is an underestimate, the Tu estimate may still lower then predicted, since our estimates assume Tu is the difference between ET and the combined value of Tc and Es. The best way to estimate Tu would be to take sap flux measurements and species distributions of the predominant understory species and to take through fall measurement to estimate canopy interception. Howerer this is both cost and time prohibitive which may be a reason there are so few studies of this nature. Although GIS may again be able to combined with field measurements to approach this issue from a different perspective (Riegel et al., 2013; Waring & Landsberg, 2011).

Components of Site Water Balance

Storage and Runoff

Annually storage with the site stays constant with large rains, often tropical storms or hurricanes, towards the end of the growing season refilling the water table just as the majority of the vegetation is senescing and going dormant. The unique hydrology of the refuge including the role the water table plays in the regulation environmental processes, through the swelling and contraction of the fresh water lens aquifer makes the ARNWR ideal for answering many questions about coastal-forested wetland ecology (Lockaby, 1997), timber management (Sun 2001) or desired ecosystem functions such as carbon sequestration, remediation of soils and waters or high quality habitat for terrestrial and aquatic biota. However the claim of near absent runoff by Bryant (2008) is more accurately expressed by (Epps et al., (2013) when he describes a system that switches from as much as 70% run-off when the water table is high and almost no run-off when the water table is low. Which implies that during the growing season when transpiration drops the WTD below ground level that ET and storage represent the main components of the site water balance. Which means almost all water exiting the watershed is through ET, and allows fluctuations in the water table to be used as a surrogate for storage in the system. The It is recognized, however, that this is not a perfect representation of water in or out of the system and any additional data that can be used to analyze the water table swelling and contracting or run-off would be beneficial (Sun 2002). What is known about the hydrology of coastal forest wetlands is that vegetation plays and important role in regulation water loss from the system, that position of the water table effects the vegetation's ability to transpire, and the position of the water table how influences whether the site is a carbon sink or a carbon source. Which is driven by two main factors, the first factor is whether the vegetation is transpiring and photosynthesizing or respiring. The second is what portion of the ground surface is above or below water. For example if the water table is high, and trees are stressed then their stomata are closed. This means that the above ground vegetation is respiring, producing CO_2 and may cause the refuge to be a carbon source (Miao 2013). However, when the water table is high anaerobic respiration is dominant in the soil environment and so are a carbon sink in this instance. Additionally, if the trees are not stressed and their stomata are open then transpiration and photosynthesis dominate and the refuge becomes a carbon sink. However this is complicated further because when het water table drops due to transpiration soil respiration switches from predominantly anaerobic to aerobic. Combining these two competing carbon dynamics is an issue to address in further research.

Precipitation

The timing the, amount and the intensity of rainfall all influence water balance dynamics in any watershed and at the Alligator River National Wildlife Refuge it is no different. For instance in 2009 when rainfall was around the 30 year average and a significant portion came during the growing season, transpiration rates were lower when compared to the drier of 2010 and 2011 growing seasons. Additionally during the time of this study the hurricanes came at the end of growing season, which did not have huge effects on the vegetation, although is this is not always the case and damage from high winds can impact large areas forest, and impact lager trees disproportionally more then shorter trees (Jayakaran et al., 2014). Additionally early and mid season hurricanes and tropical storms have the potential to reduce leaf area as well as slow transpiration by causing flooded stressed conditions for the vegetation. On the flip side of this discussion is the fact that dry periods allow the vegetation to be very productive although soil respiration increases too.

Conclusion

This study, through estimates of stomatal conductance that were derived from sap flux measurements, has provided evidence that supports the opinion that trees which are adapted to coasted forested wetlands of the southeastern US have developed a physiological response to water stress. However in this system water stress is from flooding, which illuminates the important role fluctuations in the water table has on water and carbon cycles within the refuge. Additionally this project combined three measurement techniques, eddy covariance, sap flux and soil evaporation chambers to partition ET and then incorporates micrometeorological measurements to partition the water budget for this site. Furthermore, this investigation scaled sap flux measurements from the four dominant tree species in the site to a ground area based estimate and to a leaf area based estimate of transpiration. Which allows this studies finding to be compared with a larger number of ecohydrological and tree physiological studies. An area of research that has a high potential to unravel the complex interaction of energy, carbon and water not just in a natural ecosystem, but in the context of what will be needed to meet food, fiber, clean fresh water and energy needs of world filled with more people who per capita are consuming more and more.

CHAPTER 3

Afterwords

The need to change the global mindset in regards to how we produce and consume our basic resources (food, energy, and water) is dire, but this change does not have to limit economic growth or slow the forward progress of humanity as we move into a more connected digital age. The UN Millennial goals on the environment and human rights reflect the need to balance the growth of nations with the carrying capacity of the earth. Over the past year the global human population has reach an all time high of 7 billion with another 2 billion predicted by 2050. Carbon dioxide levels have risen above 400ppm, a higher level than any time before in human history. For reference, 350ppm is where scientists think positive feedback loops will begin to show large changes in weather patterns and ecosystem succession. A large part of this increase is because atmospheric carbon has been accumulating continuously over the past 100-years due to the extractive nature of energy production. Energy produced which mainly occurs through the combustion of dense carbon sources harnessed from under the earth that provides fuel to heat homes, run appliances, move cars and freight, and even to grow our food. Basically, all our energy has in some way been tied to the combustion of carbon-based molecules. Even human life is dependent on breaking down carbon-based sugars and starches to provide the energy we need to grow and function. For all these reasons the world has evolved an economy that reflects our dependence on carbon combustion and fuel extraction. However, humanity has reached a point in history that is unprecedented. The gradual warming of the globe due to the increase in greenhouse gasses in the atmosphere is affecting climate, ocean currents and weather patterns such as the intensity and frequency of precipitation events. The continual increase in greenhouse gasses, mainly carbon dioxide, is strongly correlated to global industrial and agricultural revolutions, including the combustion engine and the fossil fuel intensive Haber-Bosh process that is used to produce nitrogen-based fertilizers. For decades humans have been ignoring the signs that our activities are permanently altering the world we live in, while ignoring the fact that our current actions will affect future generations. Moreover, we are forcing ecosystems away from their native cover and communities, to which the environmental and economic burdens are only just being realized. A simplified way of thinking about how we are changing ecosystem compositions is that these changes often caused by an increased limitation to essential resources, such as water, nitrogen, phosphorus, and topsoil. Furthermore, when ecosystems are altered to the point that human resources become limited people get nasty. Wars are currently being fought over access to natural resources, including petroleum, coal, precious metals, fresh water, food, and radioactive materials for nuclear reactors. Many of the world's social and political problems are underscored by limited access to fresh water, food, education, and the lack of global upward mobility. Problems that in today's global society can be more efficiently overcome as technologies such as the internet give billions access to information and insight into new ways of thinking and living. However the will to make these changes has to be put in more realistic terms for the masses to get behind them. Solutions have to be able to be understood by everyone, not just the experts and they have be well thought out so naysayers can be quickly disproven.

It has been argued that the largest ecologically based problems facing human societies today are balancing food and energy production with the availability of fresh water and the limited amount of arable land. Global warming exacerbates problems such as these and humanity has to choose whether to grow food, fiber, or energy across the earth's terrestrial ecosystems. However, it seems that there is little economic will to find an effective way to internalize the unaccounted for externalities of a fossil fuel based economy, mainly pollution. A major reason for the lack of innovation in this area is because of a conservative crusade on funding and research that could be used to develop extensive models to address all the issue specified above. However it is also because researchers neglect to include parameters in their models that explain how one could make money while accounting for environmental degradation, often categorized as externalities. However, one idea that has gained some traction over the last twenty years is the establishment of a carbon market or carbon tax. There has been much talk and more dismissal of a carbon market, largely due to a lack of understanding and unwillingness of corporations, governments and banks to invest in ideas that may limit their influence and their shareholder's profits. In modern terms it is the 1% dictating to the 99%, although this social structure has been the norm for much of human existence. However, at this time in world history, one must ask if profits to a few are more important than the survival of the global status quo in terms of quality of life, human well being, and world peace. Although if the carbon market is truly going to become a viable solution maybe profits are not the issue, maybe the issue really has more to do with the fear of losing influence, or a misunderstanding or misinterpretation about what the facts are telling us.

Global warming and cooling cycles on earth have been characterized by stable periods, where negative feedback loops regulate climate and the natural cycles of an ecosystem such as the water, carbon and energy balances as well as processes that regulate these cycles, including the weathering of rocks, the decomposition of organic matter, and the production of biomass. Historically, stable periods in the earth's climate, regulated by negative feedback loops, are interrupted by gradual alterations in geological, atmospheric, oceanic or terrestrial environments that eventually trigger positive feedback loops, which cause excessive warming or cooling cycles, tropical ages and ice ages respectively. Traditionally these warming and cooling cycles have been slow to start. Often occurring over geological time scales, until they reach a tipping point at which change happens at an exponential rate. Scientists, from a wide range of backgrounds and disciplines such as modelers, geologists, ecologists, hydrologists, terrestrial scientists as well as oceanic and atmospheric scientists, have all been studying these phenomenon's through their respective areas of expertise for the past several decades. A recent report put out by the American Association for the Advancement of Science (AAAS) states that 97% of all climate scientist have arrived at the same conclusions. While only 42% of Americans think scientist have come to an agreement. An agreement has more recently been solidified in the scientific community as technology has improved our understanding and ability to study earth and space from the quantum to the universal spatial scales and from the millisecond to geological time scales. These breakthroughs have allowed us to construct models that reconstruct many of the major earth changing events, from data gathered from air, rocks, soils, ice, and plants and develop theories that more precisely describe how the earth is changing using our improved understanding of biologic, chemical and physical processes.

The hard thing for many to wrap their heads around is the incredibly large amount of time that it took for each of these events to unfold. It is even harder still to understand how humans could accelerate this continually changing environment in just a few centuries, especially in a way that could compromise human survival on this planet in the near future. However this is the case, unless we start to examine what it is that made this planet habitable in the first place, and then use these principles to construct a more hospitable, sustainable and balanced approach to meet the energy, water, fuel, and economic needs of the 7 billion soon to be 9 billion humans on this earth. Honestly it is not that important whether humans have caused the changes in climate or not, the fact of the matter is that there are a lot of us on this earth and under the current trends in climate it appears that the resources needed for human survival are becoming more scarce. Furthermore, the technologies to overcome resource scarcity are either too expensive or simply not invented yet. Although, maybe just maybe this is not the case and the dots just have not been connected in the right order yet. However to the perceptive observer the answers may lay within plain sight and it is just our understanding of how these processes interact with one another that need to be unraveled further. Although once these processes are better understood humanity also has to be willing to develop technologies and implement changes that can help us mitigate the most time sensitive environmental issues. To accomplish something of this nature we must first ask ourselves, what makes earth so unique, physically? Is it the fact that water exists in solid, liquid and vapor phases, is it the temperature range that allows metabolic processes to persist, or the balance of carbon dioxide, oxygen, water, and other elements in the atmosphere? The simple answer is, YES! It is all of these things.

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APPENDICES

Appendix A:

Understanding the Interconnections between the Energy, Water and Carbon Cycles is Essential: If Future Land and Resource Management is going to be Sustainable.

The study of ecohydrology takes a multidisciplinary approach designed to resolve and quantify the effect waters movement has on ecological, hydrological, and geological processes as it moves through and across a landscape. Ecohydrologists have a large interest in deciphering how to partition water's movement within an ecosystem into is smallest components in order to gain a better understanding of the intricacies of the entire system. The ground, trunks, leaves and atmosphere are discrete parts of the larger ecosystem whose physical, biological and chemical constituents can be observed, measured or inferred by examining the tightly coupled energy balance, water balance and carbon budget of a terrestrial ecosystem. Ultimately the idea is to develop a set of key ecological variables that are inexpensive to measure but can supply a wealth of information about growth and health of an ecosystem as well as the ecosystem services provided by particular landscapes. This data can then be used to model ecosystem processes such as evapotranspiration, hydraulic redistribution, transpiration, carbon cycling, runoff generation, decomposition, and drought development. However, current equipment and technical software used to measure these cycles in a meaning full way are expensive and prohibit most land owners from being able to use them affectively.

A1 - Energy:

Radiant energy from the sun illuminates and warms an ecosystem and the globe; this can be measured with a radiometer as Net Radiation (Rn) in units of W/m^2. Radiant (shortwave) energy from the sun has only a handful of partitions it can ultimately end up in as it passes through the atmosphere and reaches the surface of the earth. Albedo consists of the shortwave radiation that is reflected back out into space, off of dust, clouds or the surfaces of the earth. This accounts for around 31% of all the shortwave radiation that reaches the planet. The other 69% of shortwave radiation can be accounted for in the energy balance, which states, that the net radiation shortwave (Rn) is either used to heat the air in the form of sensible heat (H), to warm the ground and oceans as stored heat (S), or is used to change liquid water into water vapor in the form of latent heat (LE).

The Bowen Ratio = H/LE is a helpful comparison between the sensible heat flux and the latent energy flux. This ratio is affected by the average amount of moisture in an ecosystem, which in turn influences the carbon balance of terrestrial ecosystems since water is often a limiting resource for terrestrial organisms. The latent heat portion of the energy balance is of particular interest to ecohydrologist, terrestrial ecologist/scientist and climate modelers because a significant portion of the evaporative water can be traced through the stomata of plants. This portion of evaporative water is termed transpiration. During transpiration water vapor from inside the leaf is exchanged for carbon dioxide (CO2) from the atmosphere to supply carbon for photosynthesis. Moreover, the latent heat flux may be of interest because when warm air rises and condenses (cools) the latent energy that was used to change water from a liquid to a gas is lost to the troposphere and never becomes part of the sensible heat flux, unlike stored heat, which will eventually be radiated back into the ecosystem as sensible heat.

In most studies the H and LE do not quite equal Rn, however, they approximate it closely enough with well over 80% closure to be useful in scientific research. Both the H and LE portions of the energy balance play important, but different, roles in how an ecosystem progresses as it matures and in how an ecosystem physically behaves due to complicated, dynamic and intertwined biotic and abiotic interactions. The combined behavior and fluxes into and out of ecosystems aggregate to influence global climate, energy, carbon and water cycles. Sensible heat describes the energy that we sense as changes in temperature. When discussing global warming it is H that is the cause of much of the commotion. To put this into perspective lets look at a few of the main effects or consequences of an increased global temperature as small as 0.8 degrees C or 1.4 degrees F. When temperatures rise, metabolic processes speed up, so there will be increased respiration from soil microbes, fungi, plants, and animals adding CO_2 to the atmosphere. Additionally, gasses and liquids expand at higher temperatures. What this means in a global perspective is that sea levels are rising because of the expansions of warmer water more then because of melting glaciers and receding icebergs.

At the Alligator River National Wildlife Refuge David Zeitlow is currently examining the energy balance in much more detail then in my own research. His goal is to improve the closure of the energy balance when measured through eddy flux and micrometeorological instruments. This is done mainly through creating a set of filter that screen for high quality data and exclude low quality data based on measurements of wind speed and the friction coefficient.

A2 – Water:

Fresh water is quickly becoming the new limited natural resource. Human demands on water for agriculture and industrial processes are quickly draining aquifers and reservoirs worldwide. Currently the Oglala Aquifer has dropped 9%, with 3% of that drop happening between 2001 and 2008. Recharges to below ground aquifers have been negatively impacted by land use change, increases in impermeable surfaces and altered weather patterns due to climate change. As ground water is an important source of recharge for surface water during times of little precipitation, these water levels are also being impacted. As global temperatures increase so too does the water holding capacity of the atmosphere because warmer air can hold more water. This higher water holding capacity of the atmosphere is what is causing precipitation events to become less frequent and more intense in many areas of the globe. Which means more drought and more floods and less fresh water for human consumption. Furthermore, plants primarily get the water they use from soil water once it has infiltrated into the micro-pores formed by the soil particles. This means that plants cannot utilize rainwater if it does not infiltrate into the soil. Another helpful way of looking at this issue is through the water balance of a watershed.

The water balance of a terrestrial ecosystem can be calculated at the watershed (drainage basin) scale with a mass balance equation. The equation simply states that all the water that enters a watershed through precipitation (P) must either leave through runoff (R), be stored (S) in soil and biomass of the watershed or leave through evapotranspiration (ET). Storage (S) in this mass balance equation is primarily influenced by water that percolates through the vegetation in an ecosystem and is able to slowly infiltrate into the soil. Several factors that hinder this process are the hydrophobic nature of dry soils, the velocity that raindrops have, and the increase of impermeable surfaces in heavily populated areas. Vegetation acts both as a barrier to keep direct solar radiation from drying out soils and as a cushion that slows down, or in science speak intercepts, rainfall, which along with root and mycelium, protects soils from erosions and increases infiltration. If water does not infiltrate soils plants cannot use the water and it leaves the watershed primarily through runoff but also through the evaporative portion of evapotranspiration. For this reason it is important to gain a more robust understanding of evaporation and transpiration individually.

The water balance at ARNWR is different than many terrestrial ecosystems because of the fresh water lens and virtually no runoff. For this reason ET represents the main flux of water out to the ecosystem, with transpiration split about equally between the canopy and understory accounting for most of the water lost through ET. Additionally, fluctuations in the water table effect the stomatal regulation of certain tree species and therefore the amount of water lost and carbon gained.

The hydrology of the Alligator River National Wildlife Refuge from a GIS perspective is basically modeling surface waters. There are several approaches that can be employed in these types of analysis. The first step is to develop a drainage raster dataset that carves out the primary stream channels. The second is a simulation of water pouring from a single point and slowly flooding the model from that spot based on the bare earth DEM elevation data. This can be used to simulate a saltwater intrusion event and to predict what areas of the refuge will be most affected by torrential rains and sea level rise.

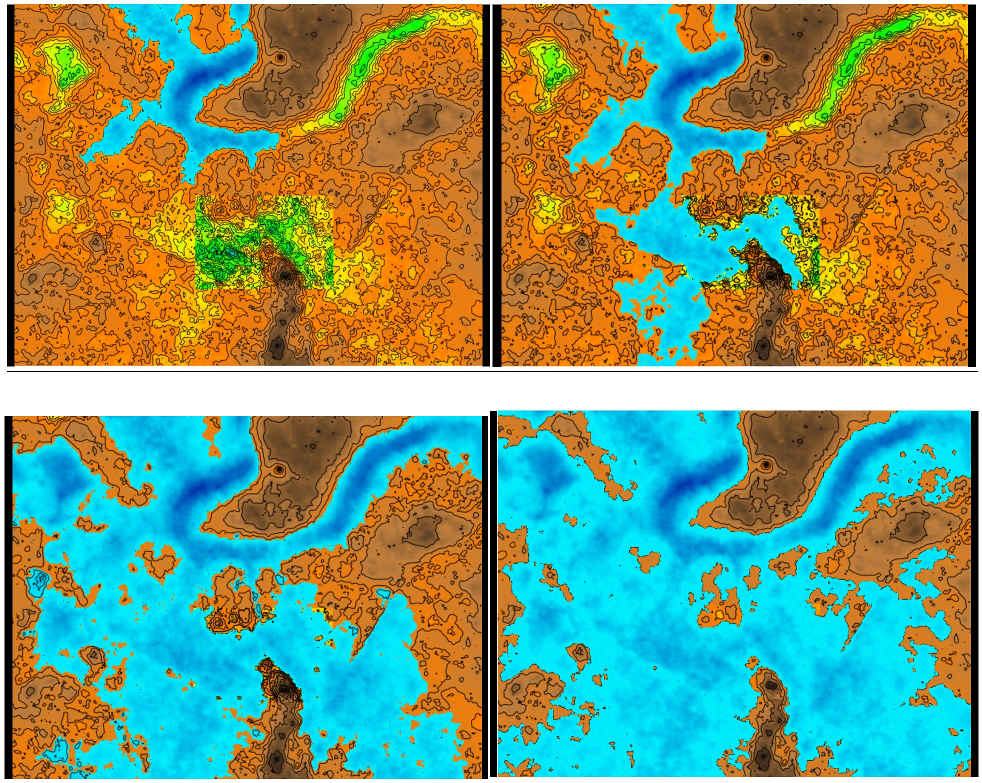


Figure 8. GRASS GIS Flood Simulation

Water table increases of one inch progressively flood a larger and larger area of ground within this site. This analysis could be used to simulate a saltwater intrusion event or a large rain event. The balance between flooded and non-flooded areas effects both transpiration and soil respiration rates.

A2a – Evapotranspiration:

Evapotranspiration can be calculated directly from the energy balance. Water that is changed from a liquid into vapor is either from the surfaces of the earth and vegetation (evaporation), or from the inside of leaves and eventually out into the atmosphere through the stomata as transpiration. The energy used for this phase change is the LE from the energy balance. In essence LE and ET are two ways of talking about the same idea, one from an energy perspective and one from a water perspective (Equation 1).

At the Alligator River evapotranspiration was measured from the eddy covariance tower. The eddy covariance (EC) tower was erected in January of 2009 along with an understory micrometeorological station, where instruments, were mounted at 30 m, and were about 16.7 m above the displacement height. The EC flux system consisted of LI-7500 open-path infrared gas analyzer (Licor Inc.), CSAT3 3-dimensional sonic anemometer (CSI), and CR1000 data logger (CSI). The 30-minute mean fluxes of CO2 were computed as the covariance of vertical wind speed and the concentration of CO2, using the EC_PROCESSOR software package (http://www4.ncsu.edu/~anoorme/ECP) (Noormets et al. 2010). The CO2 profile system consisted of a LI-820 infrared gas analyzer and a multiport system. CO2 concentrations and H2O vapor density at each level were recorded as 30-second averages every 5 minutes (Yang et al. 2007). Eddy covariance flux systems provide a large footprint from which ecosystem carbon and water vapor fluxes, NEE and ET respectively can be measured. However, the footprint of these fluxes is influenced by the direction and speed of the wind and measurements are unreliable if turbulent mixing of air between the canopy and free atmosphere is low or absent. This footprint can range from several hectares to several square kilometers.

A2b – Transpiration:

There are four partitions of the ET portion of the water balance at the Alligator River National Wildlife Refuge, interception (canopy evaporation), canopy transpiration, understory transpiration, and soil evaporation, Ec, Tc, Tu, and Es respectively.   ET was measured by the eddy flux system and estimates of Tc were derived from the sap flux measurements. Transpiration is the primary environmental measurement that can use to relate how changes in atmospheric conditions affect plants and therefor carbon assimilation. Transpiration also helps ecohydrologists understand how plants in turn may influence the water balance of a watershed, how plants support and compete with each other within an ecosystem, and how these local factors may influence weather patterns and climate globally. Transpiration is predominantly regulated by changes in turgor pressure in the guard cells that surround the stomata. The turgor pressure within a plant is essentially regulated by three environmental drivers, increases in the dryness of the air, the amount of photosynthetically active radiation that hits its leaves, and the amount of water available in the soil. When turgor is high, stomata are fully open and transpiration is at its maximum. When turgor drops the guard cells close around the stomata and transpiration is slowed.

From 2009 - 2011, At Alligator River National Wildlife Refuge twenty Granier type sap flux probes were used to estimate individual tree, species average transpiration and canopy transpiration across the site. Instrumented trees were located near the tower, with five probes installed into each species (bald cypress, black gum, maple and pond pine). Following the Granier heat dissipation probe method estimates of tree level transpiration were made by multiplying the Js of each probe by the sapwood area (As) of each associated tree. Additionally a radial correction value was applied to the sapwood area measurements because xylem often becomes less conductive closer to the heartwood (center of the tree). Radial correction terms are species dependent and literature values were used for each species in this study. Then transpiration was averaged between trees of similar species. The species transpiration averages were then used to estimate species level transpiration across the entire site by scaling the data with species distribution data gathered from the 13 subplots. However, since the Granier method calculates sap flux in time units of seconds, transpiration estimates were converted from seconds to 30 minutes values so that they can be compared to the eddy flux and micrometeorological values. Species transpiration averages for the entire site were added together to acquire a total transpiration value for the whole site. These measurements were then compared to ET measurements derived from eddy flux data.

A3 - Carbon:

Carbon assimilation is a kin to carbon sequestration, a buzzword in today's political, industrial and scientific communities. This is due to the fact that carbon dioxide is a major greenhouse gas and during the last century the carbon dioxide levels in the atmosphere have increased dramatically, causing global temperatures to rise. However, it is this very same molecule, carbon, which plants use to build tissues and make sugars. Portions of these sugars are exchanged with bacteria, animals and fungi often in exchange for selective advantages over their competitors or simply as a food source to support metabolic processes within organisms that cannot make their own food. Plants and other primary producers represent the first link in the food/energy web that supports almost all life on this planet. Additionally, it is the biomass created from organic life that returns to soil increasing the nutrient and water holding capacities of the soil and allows the cycle of life, death and decomposition to continue.

Less photosynthesis means less carbon sequestrations since it is through this process that plants convert atmospheric carbon dioxide into sugar and carbohydrates where they then cycle through terrestrial ecosystems. These sugar and carbohydrates form the bottom tier of the terrestrial food web and accumulate as organic matter in soils. Additionally wood or the xylem of trees is primarily composed of long carbon chains and if wood is used as building materials for houses, furniture and other products that survive many generations that carbon stays sequestered for a long time and reduces the global atmospheric carbon dioxide. It is also important to discuss biofuels or plant based energy and fuel production, which is often claimed as a way to reduce atmospheric carbon. The truth of the matter is that managed correctly this may be carbon neutral approach but it will not decrease atmospheric carbon as long as the carbon is released into the atmosphere when energy is produced. At the most basic level, for carbon to be sequestered long term it needs to be contained in plants and other living things, in soils as organic matter, or in long lived wood and plant products. That does not mean biofuels or short lived sequestered carbon is not important it just means that if that carbon is respired or combusted as CO_2 it reduces the net ecosystem productivity from which that carbon was produced.

Guofang Miao has done a wonderful job modeling the carbon dynamics at the Alligator River National Wildlife Refuge. Where she investigated ecosystem respiration (R_e), soil respiration (R_s) and the decomposition of coarse woody debris (R_{CWD}) from 2009 to 2011. Her research concluded that this forested wetland released more than 1000 g CO_2-C m^{-2} y^{-1} annually, that aboveground plant respiration (R_{agp}) may have been the main contributor to R_e during flooded periods and that seasonal variation of the R_s:R_e ratio exhibited a linear relationship with the fluctuation in the water table. Overall, the wetland was comparable to many upland forests. However, the hydrologic regimes resulted in a unique set of characteristics that directly effect the carbon dynamics causing this forested wetland to transiting between R_s:R_e ratios similar to boreal or temperate upland forests under non-flooded conditions and one that is similar to some tropical rainforests when flooded.

The Alligator River National Wildlife Refuge is relatively flat, but is composed of a complex topography of small mounds and depressions. These depressions are often inundated with water due to the low slope, low elevation, and slow drainage of the site. The amount of water in the depressions is reliant on the water table height, as well as the macro-topography and micro-topography of the site. Resolving the micro-topography of ARWR is important because soil respiration represents a significant portion gross carbon budget of and ecosystem. Modeling changes in the water table height is one-way to determine how much of terrain is flooded, which is important to know since soil respiration decreases under saturated anaerobic conditions and tree stomata respond to changes in WTD sensed at the root zone. Combining micro-topographic raster maps with water measured table data may be helpful to refine our analysis of soil respiration across the ARNWR in real-time (Figure 7).

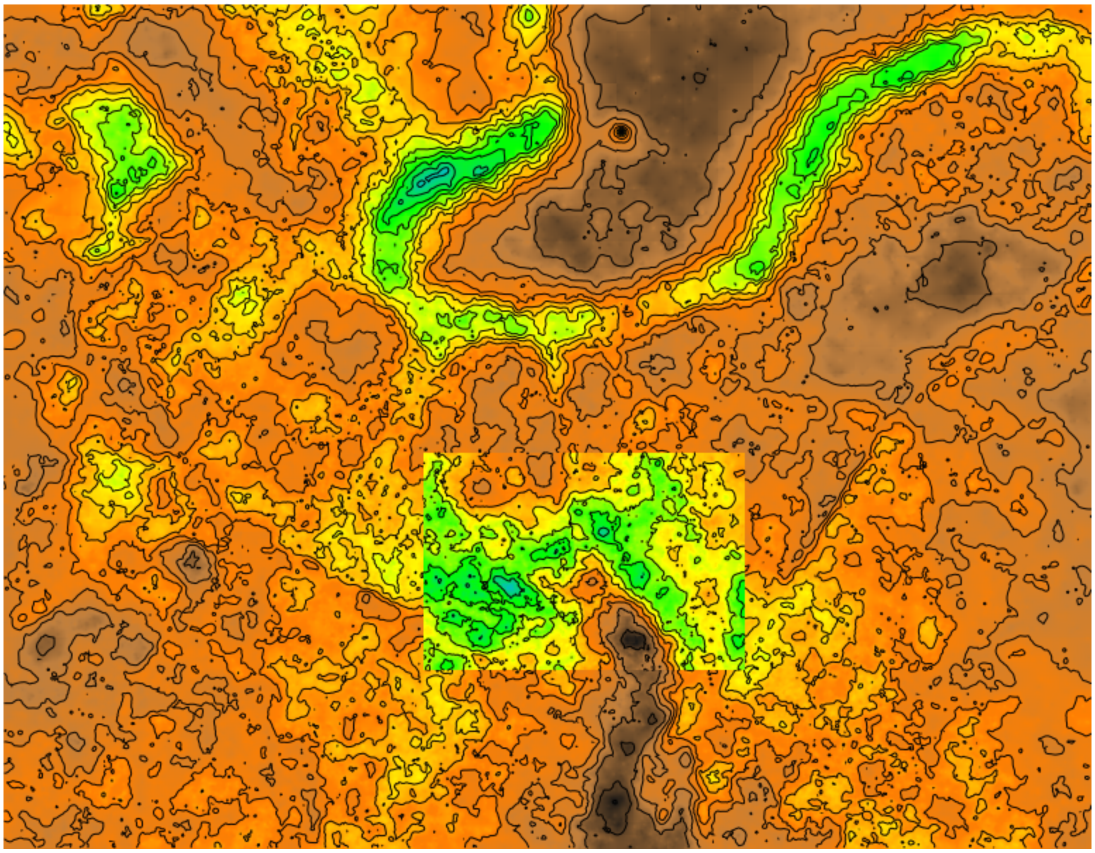


Figure 9. GRASS GIS Digital Elevation Model

Using a lidar elevation ranging form 0 to 1.8 ft. the following map was made using GRASS GIS. The inner rectangle is the same GIS dataset processed over a smaller window, which extracts more detail out of the lidar.

A4: - Vegetation:

Vegetation, through the process of photosynthesis represents a highly efficient mechanism for converting sunlight into terrestrial carbon. However in order to accomplish this task water has to be exchanged for carbon dioxide by the plants' leaves. It is commonly overlooked that the amount of water released to the atmosphere in exchange for carbon dioxide can be 1000 times higher then the amount of carbon sequestered (Eweres 2013). It is also true that in most terrestrial ecosystems access to water becomes limited for a least part of the growing season. Understanding how plants limit water loss while maximizing carbon accumulation is an important part of understanding plants relationships to carbon, water, and energy cycles. In the context of waters movement through a plant it is necessary to talk about the Soil-Plant-Atmospheric Continuum (SPAC) model. The SPAC or SVAT (Soil Vegetation Atmospheric Transfer) models are common analogies in plant physiology and ecohydrology used to describe the path water takes as it infiltrates into the soil and travels through vegetation back into the atmosphere. The SPAC model is often used to compare the movement of water by vegetation to an electrical circuit or to the flow of water through a pipe. Two important components of this model are the soil water content and the atmospheric demand for water. Currently at sea level the atmospheric pressure is approximately 101.325 kPa, which for simplicity sake can be rounded to100 kPa. At this pressure water vapor accounts for 0.4 kPa or 0.4 % of the gases in the free air that make up our atmosphere. Due to the low percentage of water in the atmosphere globally it acts as a continual sink for water vapor, even though locally air will saturate and cause precipitation events. A key component of the water cycle is that precipitation accounts for almost all the water that reaches terrestrial ecosystems. The portion of precipitation that becomes soil water, there by available for plant use, is almost completely dependent on the amount of precipitation that falls on and infiltrates into the soil. To understand the importance of the water cycle and how plants both influence and are influenced by the water cycle, water potentials must be discussed first in more detail.

Water potential is a term used to describe the passive movement of water due to forces such as gravity, osmosis, pressure and matrix potentials. The positive, negative, or neutral effects of these partial potentials in any given environment are summed to derive the water potential. Water tends to move from areas of high water potential to areas of low water potential. Plant water use can be quantified by measuring the water potential gradient that transports water from zones of high potential to zones of lower potential as water moves from soil to the roots, from the roots to the conducting xylem of the plant, then through branches, into the leaves, and from the leaves into the atmosphere respectively. Subsequently, the separate forces that make up water potential can enhance or detract from one another under differing environmental conditions. For example, as soils dry they are less apt to give up the diminishing water supply that hold tightly to the soil particles by matrix forces, which are more easily understood as the soils natural attraction to water because of their differences in polarity. Additionally, the amount of water that falls on and is stored in soils directly affect the weathering of mineral soils and bedrock, erosion, and the accumulation or degradation of topsoil. Furthermore as air becomes drier, increased temperature or shifting weather patterns exert a stronger demand for soil water. Plants attempt to balance these competing compartments of water through the opening and closing of stomata that are located on the surface of the leaves.

Measuring the conductance of water through the stomata is useful because inside the leaf the liquid water that originated in the soil is energized into a vapor state before moving to the atmosphere. The water exiting the leaf is replaced with air containing carbon dioxide, which is the source of carbon used in the photosynthetic process to produce sugars that are use in metabolic processes such as respiration and to build tissues such as xylem and phloem.

A4.1 Scale

Ecosystem processes can represent complex biogeochemical and biophysical interactions and for this reason cannot always be measured empirically. In these cases it may become necessary to derived or estimate other important variables using equations and models. However, finding the appropriate scale to communicate complex relationships between water, energy and carbon can be challenging. Scale is an issue that every scientist has to deal with when they design and conduct experiments. In the field of ecohydrology this statement could not be more true. Particularly, ecohydrologist are interested in examining ecosystem processes at a variety of scales, ranging from microscopic to global levels. However, most analyses take place at more moderate scales, ranging from ecosystem to individual samples of trees or soil (hectare to mm^2) levels. In ecohydrology point measurements of environmental variables are taken at high temporal resolutions (10 hertz) and are then scaled up to estimate ecosystem wide phenomenon. This is achieved by multiplying these point measurements by the area of the ecosystem being measured, for example, estimates of transpiration on a leaf level have to take into account the amount of vegetative surface area at the canopy level and how they scale per unit of sapwood area and per unit of ground area to accurately examine how changes in the soil environment affect leaf-atmospheric interactions.

A4.2 Leaf Area:

Leaf area estimates are easily under or over estimated based on the methods used to derive each estimate. This in large part because leaf area depends on species present, how they are distribution horizontally across the landscape and how they are stacked vertically in up to the canopy. Dynamic factors that change with the season as well as with stand maturity. Leaves represent a large turnover of carbon every year, some of which stays in the ground and some of which moves through the food chain and is respired. Gaining a more robust understanding of leaf litter effect on decomposing, build topsoil, water holding capacity, and cation exchange capacity will allow land owners information that will allow them to make more informed management decisions on their property

There are many ways to estimate the leaf area of an ecosystem, however most are labor intensive and tend to over or under estimate leaf area, depending on the method. At our sit MODIS imagery, fisheye photography, and leaf litter traps have all been employed in the past. However the top down MODIS approach and the bottom up fisheye approach give us very different estimates which leads one to think that MODIS is capturing total leaf area, canopy and understory, while the fisheye lens is primarily estimating canopy leaf area. There is another GIS approach, normalize difference vegetation index (NDVI) that uses the difference in near infrared reflectance between vegetation and the ground or water to estimate leaf area this method should be compared with the methods previously used. Currently GIS methods such as those found in , , save time when investigating spatial patterns in leaf area. It is possible that this method combined with lidar may give more accurate estimates.

A4.3 Resolution

Another issue that arises when attempting to combine GIS and ecohydrological data is determining the appropriate spatial and temporal resolution, because the data's quality and accuracy changes within degrees of magnitude between different scales of resolution. Additionally the time associated with processing larger files can be prohibitive. However, finding out how effectively and efficiently one data set is related to another is not always immediately obvious. It can be hard to preserve or apply temporal data to spatial data and maintain the benefits gained from each data set. The issue here is that the terrain or canopy is not always easily or accurately depicted by a single point measurement. For example, if solar radiation is used to represent the varying amount of solar radiation hitting each leaf to estimate carbon assimilation. It should take into account the aspect and slope of each leaf in reference to the sun. Although far from perfect this effect can be partially overcome by combining lidar data with a spatial data. The common lidar file contains millions of single point data, which can be used to interpolate and isolate discrete section of an ecosystem or stand. The ability isolated leaf and stem characteristic in the GIS database of may be of interest because a common method used to calculate water loss from an ecosystem in grams H_2O -m^2 –sec. It is here that leaf level process or can be scaled to the 1 to 10 m^2 gird cell, the footprint of the data in georefercened space.

A4.4 Stomatal Conductance:

Measurements of stomatal conductance and sap flux are the primary ways in which scientist quantify transpiration at the leaf level of a plant, assuming there is sufficient turbulent mixing of the air between the leaf and the atmosphere. For this reason plant physiologists and terrestrial ecosystem scientists are currently trying to develop empirical relationships that describe the influences VPD, soil moisture, and PAR have on stomatal function. It is recognized that there is also a biological component to stomatal regulation, however this mechanism has yet to be described in detail. The difficulties that arise when studying the environmental influences on stomatal regulation are isolating the influence of each environmental variable from one another. VPD is both dependent on temperature and the amount of water vapor in the air, two very dynamic factors. While soil moisture decreases as plant roots uptake water and transport it to the leaves to be used for photosynthesis and transpiration. Additionally, it is through measurements of stomatal conductance that we can estimate the amount of carbon being sequestered by a plant.

A big leaf approach has been utilized over the years to scale Gs to a canopy conductance Gc. However to accurately scale Gs to the canopy level a LAI > 3 or sap flow derived measurements of Gs from individual plants are needed. Tang et al. 2006 At Alligator River stomatal conductance was derived from sap flux measurements.

$$GS = (\gamma\ (T) \bullet \lambda(T) \bullet EL) / (CP \bullet \rho(T) \bullet D)$$

where g is the psychometric constant, λ is the latent heat of vaporization of water, Cp is the specific heat of the air, ρ is the density of liquid water, T is the temperature, D is the vapor pressure deficit of the canopy air, and EL is the canopy transpiration per unit of leaf area upscaled from sap flux measurements. Where Gs is the canopy stomatal conductance (mm s-1), EL is canopy transpiration per leaf area (g m-2 s-1), and D (kPa) is vapor pressure deficit in the canopy.

A4.5 Root to Soil:

When soil is at field capacity, gravitational potentials and opposing matrix potentials have equilibrated with one another and the soil water potential (Ψsoil) is theoretically around zero. However, in nature field capacity is often ephemeral, and quickly becomes slightly negative. In the SPAC pathway water must pass from the soil into the roots of the plants. This is a mostly passive system, as water moves from a slightly negative Ψsoil to the slightly more negative Ψroot. However, at this point it is important to mention that water must be transported actively across the hydrophobic Casparian strip of the root's endodermis. Scientists believe that the Casparian strip aids the plant by limiting water loss to the soil when Ψsoil becomes more negative then Ψroot. However, research on hydraulic redistribution suggests that plant roots can become conduits for passive water flow from wetter soils to dryer soils. Additionally, hydraulic redistribution is an important factor for terrestrial ecologists and ecosystem hydrologists to consider when determining the water balances of a drainage basin or when investigating the role vegetation plays in the timing and rate of discharge from a watershed. Other lines of research suggest aquaporons in the cell wall may facilitate the passive movement of water across the Casparian strip.

Soil-plant interactions at the Alligator River are best observed as interaction between the water table, the micro-topography and the vegetation. In the near future a plants tolerance to salt water maybe be a major selective force and the mechanisms plants employ to overcome adversity may be well worth studying. *Taxodium distichum* (bald cypress) is one species that has been studied because it has been noted to have a tolerance to salt.

A5 - Conclusion:

The need to change the global mindset in regards to how we produce and consume our basic resources (food, energy, and water) is dire, but this change does not have to limit economic growth or slow the forward progress of humanity as we move into a more connected digital age. The UN Millennial goals on the environment and human rights reflect the need to balance the growth of nations with the carrying capacity of the earth. Over the past year the global human population has reach an all time high of 7 billion with another 2 billion predicted by 2050. Carbon dioxide levels have risen above 400ppm, a higher level than any time before in human history. For reference, 350ppm is where scientists think positive feedback loops will begin to show large changes in weather patterns and ecosystem succession. A large part of this increase is because atmospheric carbon has been accumulating continuously over the past 100-years due to the extractive nature of energy production. Energy produced which mainly occurs through the combustion of dense carbon sources harnessed from under the earth that provides fuel to heat homes, run appliances, move cars and freight, and even to grow our food. Basically, all our energy has in some way been tied to the combustion of carbon-based molecules. Even human life is dependent on breaking down carbon-based sugars and starches to provide the energy we need to grow and function. For all these reasons the world has evolved an economy that reflects our dependence on carbon combustion and fuel extraction. However, humanity has reached a point in history that is unprecedented. The gradual warming of the globe due to the increase in greenhouse gasses in the atmosphere is affecting climate, ocean currents and weather patterns such as the intensity and frequency of precipitation events. The continual increase in greenhouse gasses, mainly carbon dioxide, is strongly correlated to global industrial and agricultural revolutions, including the combustion engine and the fossil fuel intensive Haber-Bosh process that is used to produce nitrogen-based fertilizers. For decades humans have been ignoring the signs that our activities are permanently altering the world we live in, while ignoring the fact that our current actions will affect future generations. Moreover, we are forcing ecosystems away from their native cover and communities, to which the environmental and economic burdens are only just being realized. A simplified way of thinking about how we are changing ecosystem compositions is that these changes often caused by an increased limitation to essential resources, such as water, nitrogen, phosphorus, and topsoil. Furthermore, when ecosystems are altered to the point that human resources become limited people get nasty. Wars are currently being fought over access to natural resources, including petroleum, coal, precious metals, fresh water, food, and radioactive materials for nuclear reactors. Many of the world's social and political problems are underscored by limited access to fresh water, food, education, and the lack of global upward mobility. Problems that in today's global society can be more efficiently overcome as technologies such as the internet give billions access to information and insight into new ways of thinking and living. However the will to make these changes has to be put in more realistic terms for the masses to get behind them. Solutions have to be able to be understood by everyone, not just the experts and they have be well thought out so naysayers can be quickly disproven.

It has been argued that the largest ecologically based problems facing human societies today are balancing food and energy production with the availability of fresh water and the limited amount of arable land. Global warming exacerbates problems such as these and humanity has to choose whether to grow food, fiber, or energy across the earth's terrestrial ecosystems. However, it seems that there is little economic will to find an effective way to internalize the unaccounted for externalities of a fossil fuel based economy, mainly pollution.

A major reason for the lack of innovation in this area is because of a conservative crusade on funding and research that could be used to develop extensive models to address all the issue specified above. However it is also because researchers neglect to include parameters in their models that explain how one could make money while accounting for environmental degradation, often categorized as externalities. However, one idea that has gained some traction over the last twenty years is the establishment of a carbon market or carbon tax. There has been much talk and more dismissal of a carbon market, largely due to a lack of understanding and unwillingness of corporations, governments and banks to invest in ideas that may limit their influence and their shareholder's profits. In modern terms it is the 1% dictating to the 99%, although this social structure has been the norm for much of human existence. However, at this time in world history, one must ask if profits to a few are more important than the survival of the global status quo in terms of quality of life, human well being, and world peace. Although if the carbon market is truly going to become a viable solution maybe profits are not the issue, maybe the issue really has more to do with the fear of losing influence, or a misunderstanding or misinterpretation about what the facts are telling us.

Global warming and cooling cycles on earth have been characterized by stable periods, where negative feedback loops regulate climate and the natural cycles of an ecosystem such as the water, carbon and energy balances as well as processes that regulate these cycles, including the weathering of rocks, the decomposition of organic matter, and the production of biomass. Historically, stable periods in the earth's climate, regulated by negative feedback loops, are interrupted by gradual alterations in geological, atmospheric, oceanic or terrestrial environments that eventually trigger positive feedback loops, which cause excessive warming or cooling cycles, tropical ages and ice ages respectively. Traditionally these warming and cooling cycles have been slow to start. Often occurring over geological time scales, until they reach a tipping point at which change happens at an exponential rate. Scientists, from a wide range of backgrounds and disciplines such as modelers, geologists, ecologists, hydrologists, terrestrial scientists as well as oceanic and atmospheric scientists, have all been studying these phenomenon's through their respective areas of expertise for the past several decades. A recent report put out by the American Association for the Advancement of Science (AAAS) states that 97% of all climate scientist have arrived at the same conclusions. While only 42% of Americans think scientist have come to an agreement. An agreement has more recently been solidified in the scientific community as technology has improved our understanding and ability to study earth and space from the quantum to the universal spatial scales and from the millisecond to geological time scales. These breakthroughs have allowed us to construct models that reconstruct many of the major earth changing events, from data gathered from air, rocks, soils, ice, and plants and develop theories that more precisely describe how the earth is changing using our improved understanding of biologic, chemical and physical processes.

The hard thing for many to wrap their heads around is the incredibly large amount of time that it took for each of these events to unfold. It is even harder still to understand how humans could accelerate this continually changing environment in just a few centuries, especially in a way that could compromise human survival on this planet in the near future. However this is the case, unless we start to examine what it is that made this planet habitable in the first place, and then use these principles to construct a more hospitable, sustainable and balanced approach to meet the energy, water, fuel, and economic needs of the 7 billion soon to be 9 billion humans on this earth. Honestly it is not that important whether humans have caused the changes in climate or not, the fact of the matter is that there are a lot of us on this earth and under the current trends in climate it appears that the resources needed for human survival are becoming more scarce. Furthermore, the technologies to overcome resource scarcity are either too expensive or simply not invented yet. Although, maybe just maybe this is not the case and the dots just have not been connected in the right order yet. However to the perceptive observer the answers may lay within plain sight and it is just our understanding of how these processes interact with one another that need to be unraveled further. Although once these processes are better-understood humanity also has to be willing to develop technologies and implement changes that can help us mitigate the most time sensitive environmental issues. To accomplish something of this nature we must first ask ourselves, what makes earth so unique, physically? Is it the fact that water exists in solid, liquid and vapor phases, is it the temperature range that allows metabolic processes to persist, or the balance of carbon dioxide, oxygen, water, and other elements in the atmosphere? The simple answer is, YES! It is all of these things.

Appendix B

Granier Sap Flux Method

Partitioning ecosystem water use is accomplished first by separating ecosystem wide evapotranspiration (ET) into canopy and understory fluxes. Then, these fluxes are further partitioned into evaporation and transpiration components of ET. This is accomplished by calculating the average transpiration of each dominate tree species, pond pine (4 trees), bald cypress (5 trees), red maple (5 trees) , and tupelo (5 trees) with Granier type sap flux probes. For each species the transpiration measurements are combined and averaged. These averages are then used to scaled up transpiration estimates to the site level based on the size and distribution of each species.

A sap flux probe is composed of two thermocouples**,** one heated probe (thermocouple) and one reference probe (thermocouple). The probes are inserted horizontally into the tree. The heated thermocouple is inserted at breast height and the reference thermocouple is inserted 10 cm directly below the heated probe. A Campbell scientific data logger records the temperature difference between these two probes every tenth of a second; these records are then compiled into half-hourly averages. Along with the sap flux probes the data logger is also recording eddy covariance and micro-metrological data above the canopy and in the understory. To calculate sap flow and scale these measurements across the ecosystems, empirical or allometric relationships concerning, plant water use under varying environmental conditions need to be developed for more accurate analysis and modeling of ecosystem behavior. The first step in processing the sap flux probe measurements is to follow Granier's method (below) to convert half hourly temperature differences into sap flow densities which has SI units of (g/m^2 s).

Sap Flux Equations and Environmental Variables needed.

T = the real time temperature difference between the headed and sensor probes at any point in time

Tmax = the maximum temperature difference between the probes for each day

K= (Tmax – T)/T = unitless and is part of the Granier Sap Flow Equation

Js= $119(K)^{1.231}$ = gram (H_2O)/m^2 sec = Sap Flux Density

As = Average Sapwood Depth for Site or Species x DBH for each individual tree

Al = Leaf Area

Ag= Ground Area

SAI = As/Ag = sapwood area index

LAI = Al/Ag = leaf area index

As:Al = Sapwood Area to Leaf Area = is the ratio between the site sapwood area the site leaf area and is equal to transpiration rate per unit of leaf area (El)

Esapwood = Js x As (for an individual tree) = the transpiration of an individual tree

Eleaf = Js x Al (for an individual tree) = the transpiration of an individual tree

Eground = Js x (As/Ag) or Js x (Al/Ag) = the transpiration per unit of ground area

Granier Procedure-

Step one:

Find **Tmax**: find the maximum temperature difference for each day. This value (Tmax) represents no sap flow or the lowest sap flow for that particular day. Then Tmax is entered into this equation along with the Tdiff to find K for each half hour during the day.

K= (Tmax - Tdiff)/ Tdiff,

K is unitless. Now that K has been calculated sap flux density (Js) can be calculated with the equation proposed by Granier.

Step two:

$$\mathbf{Js=119\ (K)^{1.231}}$$

Where **Js** measures of the amount of sap (water) moving across the thermocouples area ever second, this is measured in units of **grams H_2O /m^2 second**. Where g/m^2 s , measures the mass flow of water moving across the sensor area approximately 20mm x 2mm.

The units (g/m^2 sec) is useful because it links measurements of mass with measurements of length. This linkage allows scaling amounts (mass) of water to a specific area depending on research interests including: sapwood area, leaf area for an individual tree, or to scale to a plot or ecosystem level with **sapwood area/ground area** (sapwood area index), or **leaf area/ground area** (leaf area index).

Tree level transpiration **(Esapwood)** can be measured by multiplying the sap flux density **(Js)** by the sapwood area of a cross-section of the trunk. Since the amount of sapwood found within a tree trunk is both species and site dependent it is important to construct a reliable allometric relationship between the tree diameter at breast height (DBH) and the sapwood depth of the tree. From this relationship we can estimate the sapwood area with measurements of DBH with some accuracy.

Esapwood = Js x As

To scale up sap flux density or transpiration measurement to m^2 of ground area, estimates of the sap flux density (Js), or transpiration (E) must multiplied by the **sapwood area index (Area sapwood / Area ground) or the leaf area index (Area leaf/Area round)** which have units of m^2/m^2

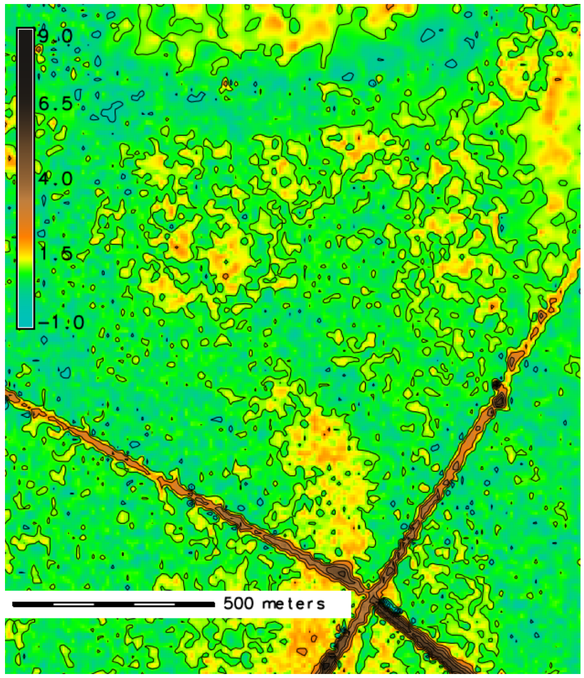
Sapwood Estimates

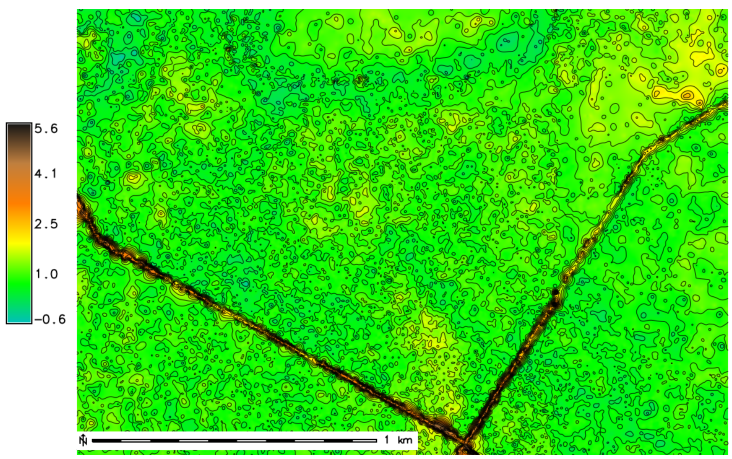
The proposed method for construction the allometric relationship between sapwood area and DBH is to increment bore 5 small, 5 medium, and 5 large trees, of each of the 4 species, as well as to measure the bark thickness and to measure DBH of each tree. From these measurements a linear regression describing the relationship between the sapwood to DBH of each species at each size class will be developed. With these allometric relationships and detailed sampling of species distributions scaling up to the plot level and to refuge should be straightforward.

Appendix C: GIS

Ground Area Analysis

Below are set of figures created in GRASS GIS from raw lidar data. With lidar data each time the laser hits a surface and returns to the sensor the point is stored that has an x-y-z coordinate. As single lidar file can have millions of points. The Alligator River elevation data for our site ranges from -14 to 140 ft in height. With lidar it is possible to extract ranges of elevation. So, knowing that the elevation is so flat and that the water table averages 3ft above sea level several different exactions where used to digital elevation maps (DEMs). The first extraction was made from all points below 9 ft. This DEM prominently displays the roads, wetter areas in blue and green along with pockets of higher elevation in orange and yellow. Although with close inspection it is recognized that the higher elevation areas are due to pockets of tall dense vegetation. So a low threshold was selected to generate a new DEM, the 3.6 inch contour intervals capture the complex topography.





Figures 10. GRASS GIS Contour Map

The maps above are two different looks at the side the upper image is a close up of the pine lens leading out site. The bottom image is the whole site with contour lines.

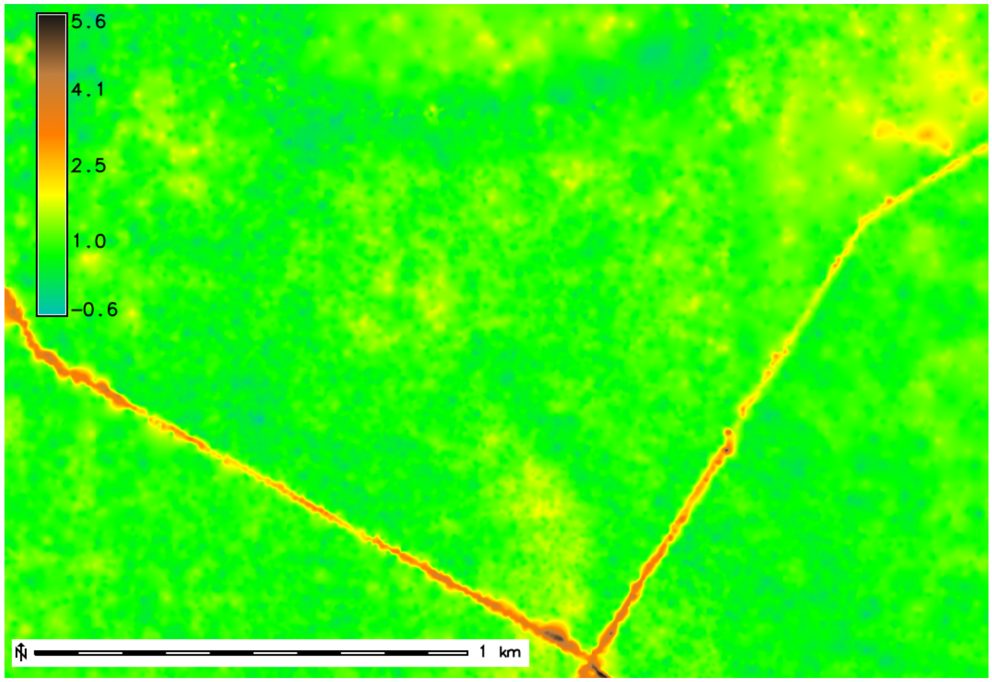


Figure 11. GRASS GIS Bare Earth DEM

This DEM was created from NCfloodmap's bare earth lidar data interpolated with a tension of 100, a smoothing parameter of 1 and a output cell size of 1ft x1ft. A high tension was used in an attempt to exaggerate the mound depression micro-topography of the site. This method ended up take a large amount of processing time because of the small cell size while not accentuating a whole lot new information from the data set and should probably be avoided in the future.

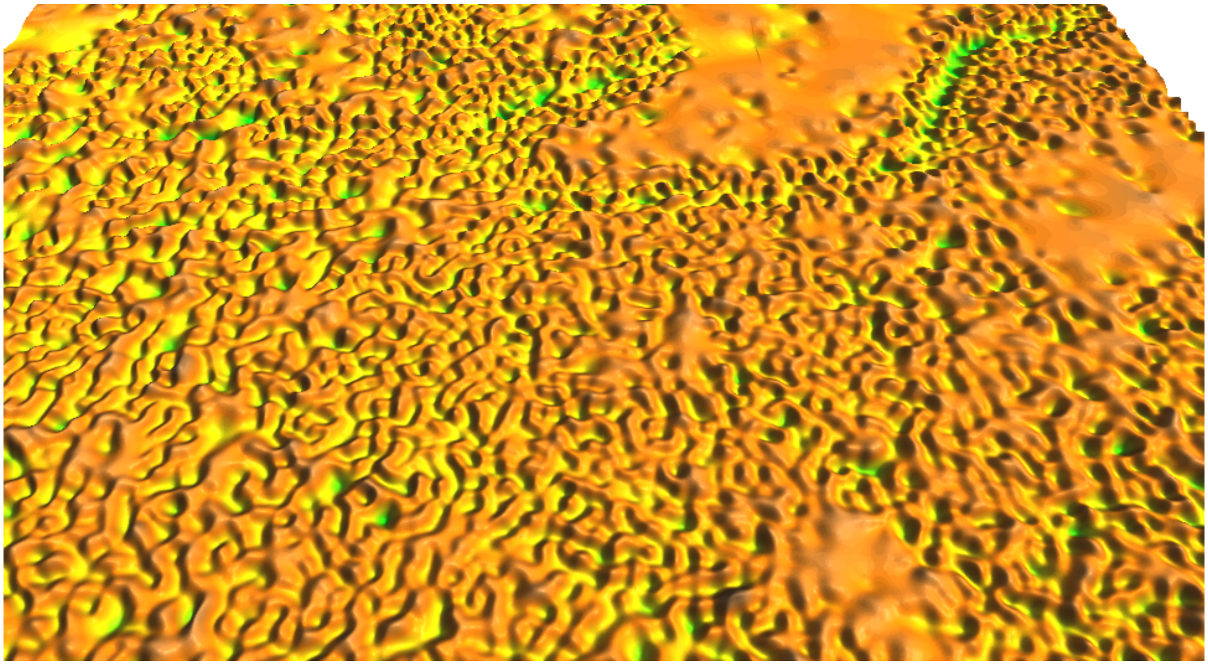


Figure 12. GRASS GIS 3-D Topography

This DEM is a 3-D illustration of topography with the elevation ranging from 0 to 1.8 ft. and the z-scale exaggerated. This image demonstrates the dendritic channels of water flow that are formed by the hill and mound micro -topography.

Tree Distribution

Lidar allows researchers the ability to separate out slope and aspect characteristics as well as elevation data. A discovery, when made using high tension values when conduction a spline analysis on the lidar data is that these spots arise. After looking at slope data is became apparent that high slope values accompanied these spots. A spine analysis is like take a large rubber sheet and stretching it over the surface the higher the tension the hard that sheet is being pulled. Since, ARNWR is so flat is was decided that this large slope must be due to vertical tree trunks. The ability to isolate are of high slope with different elevations may be an appropriate method for categorizing species distribution within differing forest shrub and estuary type wetlands. Additionally a NWI polygon shape file can be use to refine or compare wetland designations made through this method.

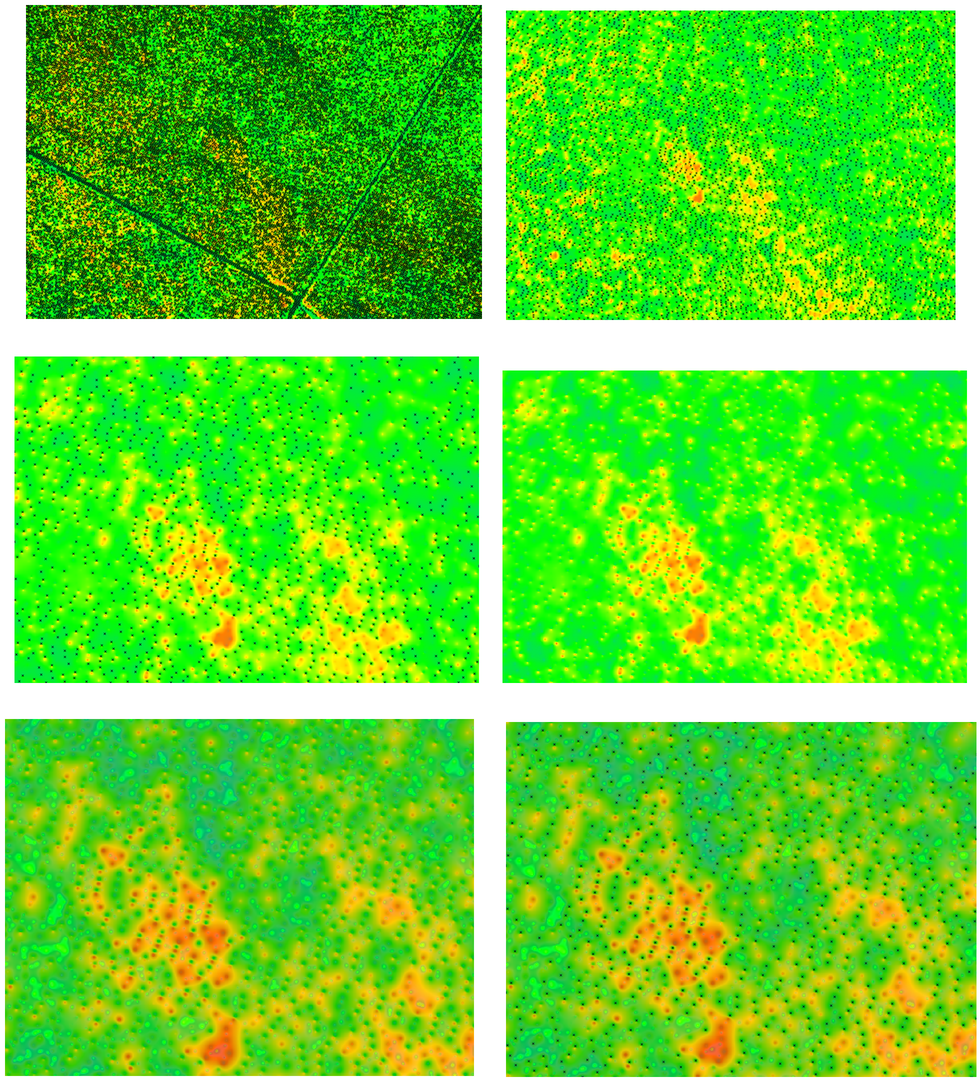


Figure 13: Theoretically Stem Distributions Model

This set of images illustrates the how a point-cloud of lidar data, a DEM, and a slope raster can be developed to possible identify stem distributions across the site.

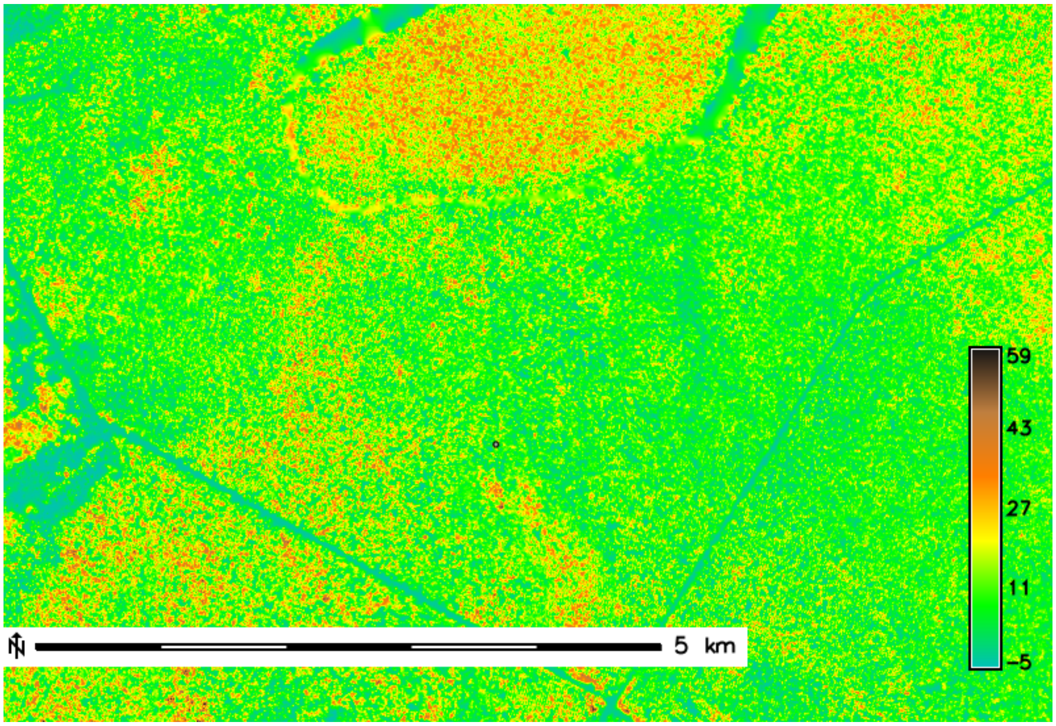


Figure 14: GRASS GIS Digital Surface Model

This DSM was created using USGS CLICK multiple return lidar data. It was created using a regularized tension spline with a tension of 100, smoothing of 2 and output cell size of 1ft x 1ft with GRASS GIS. Unlike the DEM made early this DSM at 1ft by 1ft raster cell size is helpful at developming canopy characteristic, that will become more apperent in the next set of images.

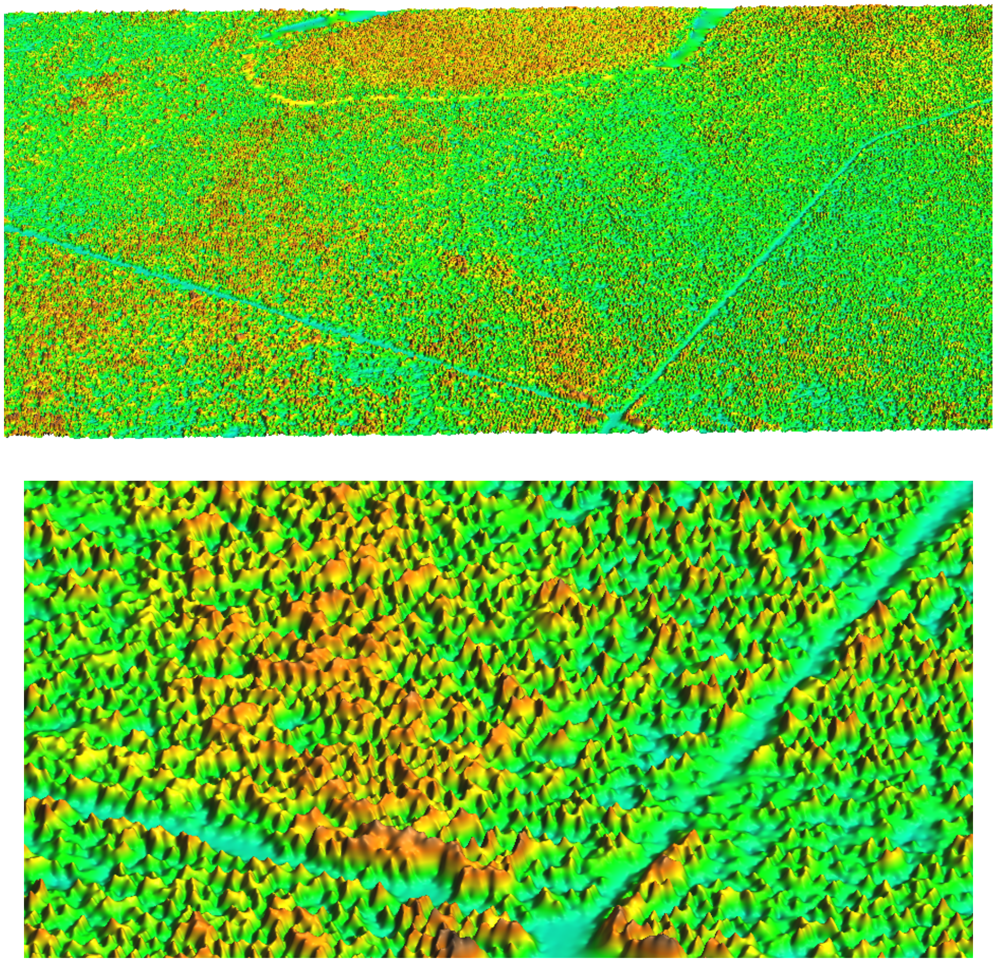


Figure 15: GRASS GIS 3-D DSM

The upper and lower images are DSM of the whole site and a close up of the clay lens displayed in 3-D. The brown represents areas of higher elevation and blue is the lowest. The river in top of the upper image can be seen in yellow.

Hydrology

Developing the hydrology of the site was the next stage of data creation. First part of the analysis was created a raster map using r.watershed and r.lake to unravel how water moves across the site. The first image is a flow accumulation map that was created in r.watershed and is displayed with a 50% transparency over the DEM for clarity.

Next is a series of maps developed in r.lake with different water table heights to demonstrate how water moves across the site. The seed point was located in the riverbed in the northeast corner of the map. These next sections of maps were developed to examine solar energy inputs and shadows across the DSM. The first two maps are close ups of beam and incident solar radiation maps displayed over the DSM in NVIZ. These final two images are global energy maps for my site on the summer solstice June 22 at 8am and 2pm, respectively

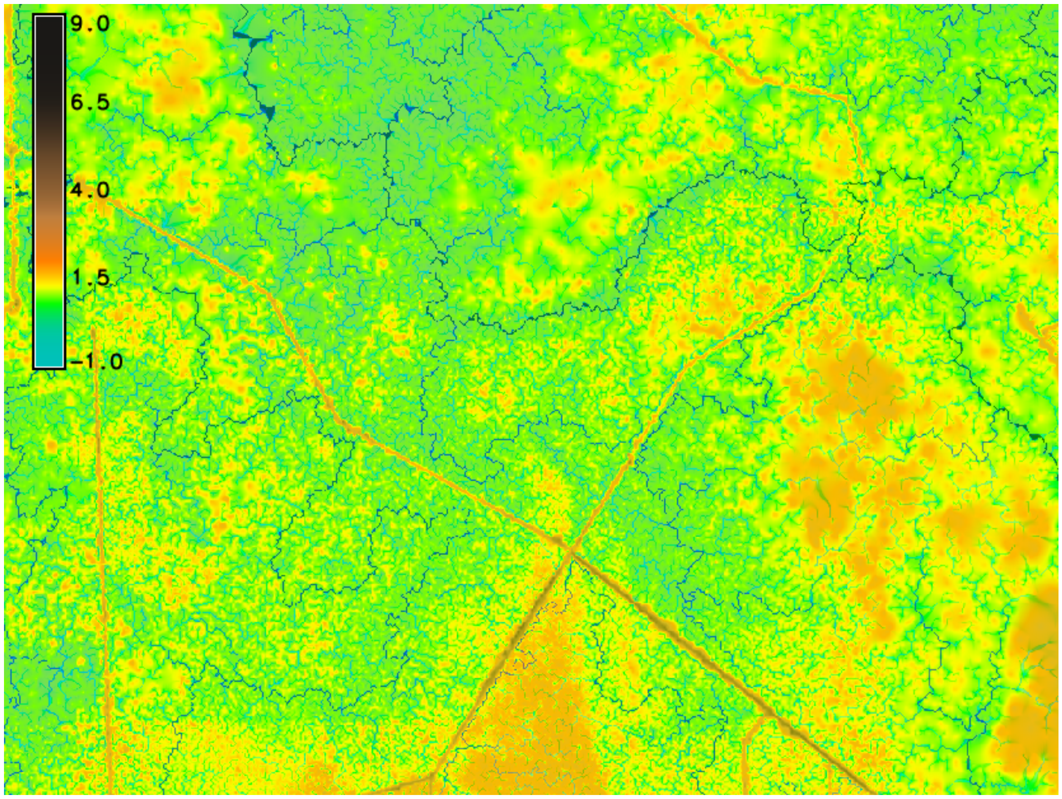


Figure 16. GRASS GIS Flow Accumulation Model

This is the flow accumulation combined with a DEM of the site.