An examination of net primary production in southern Appalachian wetlands

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Southern Appalachian wetlands have yet to be studied in terms of net primary production (NPP), thus few studies have been conducted to examine what environmental factors have relationships with NPP. To that end, this research investigates several facets of southern Appalachian wetland production. The research was divided into three studies. The first study was conducted to answer the question of what environmental factors have relationships with NPP. It appears that stream discharge and annual precipitation had the strongest relationships with NPP ($r = 0.91$, $p < 0.05$ and $r = 0.81$, $p < 0.05$, respectively), yet both factors showed multicolinearity ($r = 0.97$, $p < 0.05$). The strong relationships between hydrologic factors and NPP is similar to montane wetlands in the western United States. The second study was conducted to examine the relationship between water chemistry and NPP. Calcium (Ca), Magnesium (Mg), and pH were examined in order to determine if any of the aforementioned factors had a relationship with NPP. Neither Ca ($r = -0.34$, $p = 0.0835$) nor Mg ($r = -0.38$, $p = 0.0535$) had strong relationships with NPP, though pH ($r = -0.66$, $p < 0.05$) had a strong negative relationship with NPP. The acidity of the stream water, driven by the acid rain in the southern Appalachians, creates enhanced conditions for wetland plants to grow. The third study was conducted to establish which vegetation index was best for estimating NPP from proximally and remotely sensed data. The findings suggest that $\text{VARI}_{\text{Red Edge}}$ was best for examining NPP at the in situ level, NDVI was best for examining NPP at the airborne level, and the DVI was the best for examining NPP at the satellite level. NPP in southern Appalachian wetlands is driven by the chemistry, specifically the pH, of stream discharge and annual precipitation and can be monitored by NDVI using NAIP data or DVI using Landsat data. The examination of NPP in southern Appalachians in response to environmental factors and water chemistry along with the examination of vegetation indices at three levels of platforms will help to monitor and manage these rare and unique ecosystems in the future.

Key words: wetlands, southern Appalachians, environmental drivers, nutrient availability, remote sensing, proximal sensing, vegetation indices

DEDICATION

This work is dedicated to my wonderful and supportive wife, Chanda, for believing in me and pushing toward greater things.

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CHAPTER I

INTRODUCTION

There exists a large gap in scientific knowledge as it relates to montane wetland ecosystems in the Southeast United States, specifically the southern Appalachian Mountains. Studies have been conducted in montane wetland ecosystems in many regions of the United States (e.g. Dwire et al., 2006). However, montane wetland ecosystems in the southern Appalachians lack the same degree of research. Studying the environmental drivers of net primary production (NPP), a marker of ecosystem function, is important for all communities, scientific and otherwise, because of the lack of research in this area and the important ecological services that wetlands provide. Specifically, wetlands serve as flood buffers, maintain water levels, and maintain water quality (USGS, 2004). Change in function of the wetland would change the level and number of services that southern Appalachian wetlands provide. This research could serve as a guideline for managing wetlands in the southern Appalachians. Among the aforementioned environmental drivers of NPP are hydrologic characteristics, climate, geomorphological setting, and edaphic characteristics. The purpose of this dissertation was to study the effect of selected environmental factors and settings on NPP and better the methods used to study southern Appalachian wetlands by employing remote sensing.

Wetlands are sensitive ecosystems that can be used to indicate environmental variations and gradients, especially related to water quality (Allen-Diaz, 1991). Because of the sensitivity of wetlands, spatial variations in environmental characteristics have an influence on the health and productivity of wetland vegetation (Rea and Ganf, 1994a, b; Howard and Mendelssohn, 1995; Mann and Wetzel, 1999).

Environmental factors associated with vegetation health and productivity have been well studied since the second half of the twentieth century (e.g. Brinson et al., 1981). Previous work sheds light on the nature of these environmental factors, which heavily impact wetland ecosystems because wetlands serve as habitats for sensitive flora and fauna. The exploration of the interaction between plant communities and the environment began with Darwin and the study of plant geography (Cain, 1971; Ustin et al., 1999). Around the turn of the twentieth century, the field gained more focus by examining soil chemistry with studies conducted by Warming (1909) and Schimper (1898). Russian scientists introduced the field of geobotany, the link between plants and underlying geology, in the mid-twentieth century (e.g. Schennikov, 1964). Since then, other interactions that have been studied include the relationship between vegetation and soils (Chambers et al., 1999; Francl et al., 2004) and vegetation and hydrology (Allen-Diaz, 1991), among other factors. Currently, the relationship between environmental factors and primary production (e.g. hydroperiod, Schedlbauer et al., 2012) is being explored. Even with the increased level of research on wetland ecosystems, there are still many areas of uncertainty concerning wetland ecosystems. Examples of such areas include the role of soil texture and hydrology as these factors impact NPP as well as research on montane wetlands in the Southeastern United States.

Appalachian wetlands, which are primarily fens and bogs, are rare and experiencing habitat loss (Rossell and Wells, 1999). The number of fens and bogs left in the southern Appalachian mountains might be as small as 500 (Moorhead and Rossell, 1998). It is beneficial to determine how productive these types of ecosystems are in order to better understand the impact on the environment if these ecosystems are lost. Coastal wetland ecosystems in the Southeastern United States are also being lost (USGS, 2004), which has been made apparent to many in the scientific community as well as the general public. The same cannot be said for montane wetland ecosystem loss. In fact, freshwater wetlands have lost more acreage annually than coastal wetlands (440,000 acres annually for freshwater compared to 18,000 acres annually for coastal; Tiner, 1984).

The use of field collection in conjunction with remote sensing may provide a better and more efficient means to examine montane wetlands, which are not always easily accessible. Remote sensing allows for regional coverage of more areas which, in turn, permits a better understanding of ecological function. Advances in remote sensing technology and methodology now allow for more accurate estimations of NPP at regional scales. Many studies have focused on using remotely sensed data to derive NPP estimates (Cramer et al., 1999), though some work has been done at estimating NPP variables (biomass and chlorophyll) at finer scales (Mishra et al., 2012). However, few have extended the use of remotely sensed data to derive carbon sequestration estimates (e.g. Turner et al., 2004). Few studies have focused on examining wetland ecosystems for using remotely sensed data to calculate NPP.

The overarching goal of this research was to use an interdisciplinary approach, including integrating field measurements with remotely sensed data, to examine ecological functions of southern Appalachian wetlands. This study employed remote sensing, ground-based remote sensing, hydrologic analysis, sediment analysis, and nutrient analysis to establish wetland ecosystem function via NPP. The objectives of this study were to (1) examine the relationships between aforementioned environmental factors and NPP in southern Appalachian wetlands, (2) focus on the relationships between calcium (Ca), magnesium (Mg), and pH of surface water in southern Appalachian compared to NPP, and (3) compare field-gathered NPP data to vegetation indices using in-situ hyperspectral radiometers and remotely sensed data to determine the best vegetation index for estimating NPP.

This intellectual merit of this dissertation is substantial and the broader impacts are also notable. This research examines discharge as a relatively unstudied environmental factor associated with NPP in wetlands, adding a new theory that in floodplain wetlands discharge has the strongest relationship with NPP. This dissertation also compared the under-researched southern Appalachian wetlands to more heavily researched montane wetlands in the western United States. Secondly, this research was conducted in a geographic area, the southern Appalachians, that has been little studied. Most studies examining nutrients in water samples focus on nitrogen and phosphorus, however this dissertation looks at Ca and Mg, which have been little studied in their impact on NPP. This study also employs a new technology in improving remote sensing techniques for monitoring of NPP. Finally, the broader impacts of this dissertation are the possible use of this research in managing wetlands in the southern Appalachians. As an example, The Nature Conservancy of Shady Valley, Tennessee will use this research to better manage wetlands under their ownership.

CHAPTER II

ENVIRONMENTAL DRIVERS OF NET PRIMARY PRODUCTION IN SOUTHERN APPALACHIAN WETLANDS

2.1 About this chapter

The chapter is a journal article that has been submitted for publication in Wetlands.

2.2 Abstract

It has been established that southern Appalachian wetlands, and montane wetlands in general, are important for biodiversity, but the literature on net primary production (NPP) in southern Appalachian wetlands is lacking, if not absent. NPP is an important marker of ecosystem function. This study explored the relationship of environmental variables to NPP in southern Appalachian wetlands. NPP was determined from peak standing biomass for wetlands in Virginia, Tennessee, Georgia, and Alabama. At each of the seven sites soil moisture, soil depth, discharge data were collected along with soil samples for particle size analysis. Temperature and precipitation data were acquired from the National Climatic Data Center website for analysis. Across all field sites, discharge was the most highly correlated to NPP ($r = 0.91$, $p < 0.05$) and was able to explain 83% of variance in NPP. Similarly, precipitation was also highly correlated to NPP ($r = 0.81$, $p < 0.05$), yet showed multicolinearity to discharge ($r = 0.97$, $p < 0.05$). All

other factors exhibited weak relationships with NPP. Discharge and precipitation were the highest correlated variables to NPP. This study provides the seminal examination of southern Appalachian wetlands with regards to NPP and a guideline for southern Appalachian wetland management and preservation.

2.3 Introduction

Wetlands offer a number of important ecological services such as serving as flood buffers and habitats for commercially and recreationally important fauna (USGS, 2004), however montane wetlands are often overlooked. Perhaps montane wetlands are disregarded relative to coastal wetlands because of the perceived higher impact from climate change or because coastal wetlands are perceived as more important. Whatever the reason, research in montane wetlands, especially in the southern Appalachians, is generally sparse and should be bolstered, particularly with regards to net primary production (NPP). NPP serves as a marker of ecosystem function and is useful for comparison among wetlands. Thus, NPP could serve as a useful tool for comparing the little studied southern Appalachian wetlands to other wetlands, especially montane wetlands. Comparison can be a powerful tool in management of wetlands, by determining where the productive wetlands (higher NPP) are and what they have in common so that less productive (lower NPP) wetlands can be better managed. NPP can also be used as a way of denoting the importance of an ecosystem in the carbon (C) budget.

Wetlands are among the most productive types of ecosystems (Table 2.1; Leith and Whittaker, 1975), and thus can serve as a major C sink. Primary productivity is a measure of the ability of a plant to convert inorganic C in the atmosphere (CO_2) into part of the plant structure through photosynthesis, thus NPP can be used as a proxy for C storage. According to Leith and Whittaker (1975) swamps and wetlands are the second most productive type of ecosystem, with algal beds and reefs as the most productive type of ecosystem. High productivity means high C storage, adding to the importance of wetlands for ecological services, as well as ecosystems that maintain high biodiversity.

NPP in montane wetlands, which are a major source of biodiversity (e.g. Francl et al., 2004), has been shown to be affected by hydrologic factors, like many types of wetlands (Figure 2.1; Brinson, 1993; Mitsch and Gosselink, 1993; Stromberg et al., 1996; Thormann and Bayley, 1997; Yabe and Onimaru, 1997; Mann and Wetzel, 1999; Castelli et al., 2000; Dwire et al., 2004). In montane wetlands, aboveground biomass has been found to have a positive relationship with decreasing depth to water table (Thormann and Bayley, 1997; Dwire et al., 2004). The wetlands from the aforementioned studies were located in western montane wetlands, which are located at higher elevations with less precipitation. Surprisingly, not much has been reported in the academic literature about southern Appalachians, where little is known about the link between hydrology and NPP.

Southern Appalachian wetlands are a result of the hydrologic setting, which is strongly related to annual precipitation. Floodplain wetlands might be more dependent on precipitation, relative to groundwater fed sites, because of higher variability in water table depth compared to groundwater fed sites (Thompson et al., 2007). Floodplain wetlands also experience an inflow of nutrients and removal of toxins from flowing water (Brinson 1993; Craft, 2001). A general trait of climate in the southeast United States is occasional dry periods which do not have as much of an impact on the water table of groundwater fed systems (Thompson et al., 2007). These dry periods are one reason that southern Appalachian wetlands are sometimes considered a unique type of fen (Warren et al., 2004).

It is believed that southern Appalachian wetlands behave like northern fens and bogs with acidic and nutrient poor soils with bryophyte vegetation cover, thus these unique wetlands have been termed southern Appalachian fens (Kivinen and Pakarinen, 1981; Chadde et al., 1998; Cooper and Jones, 2004; Warren et al., 2004). However, the aforementioned dry periods are one of the reasons for the lack of a thick peat layer, which is characteristic of northern bogs (Clymo, 1984; Wieder et al., 1989, 1994; Winston, 1994; Moorhead and Rossell, 1998; Warren et al., 2004). The lack of a peat layer changes the amount of water retention the soil is capable of, putting more of an emphasis on soil texture in hydrologic processes.

Soil texture plays a role in water retention and the amount of water available to plants (Saxton and Rawls, 2006) as well as the retention of nutrients (Odum et al., 1971; Howard-Williams, 1985), especially in stream fed wetlands. Given that stream fed wetlands experience an inflow of nutrients (Brinson, 1993), it is important for NPP that the water flow is fast enough to bring in nutrients (Brown, 1981) but slow enough for soil to be able to retain that water so the plant has time to absorb the nutrients.

The importance of this study is three-fold. Primarily this study adds a new component to wetlands research by adding a new component (discharge) that has been largely absent from studies examining NPP. Secondarily, this study focuses on southern Appalachian wetlands, which are underrepresented in the wetland literature. This study also has importance in that the results from this study could be used in the management of southern Appalachian wetlands, by outlining what factors help to maintain a productive and healthy wetland in this environment. The Nature Conservancy in Shady, Valley (TN-1 and TN-2) is a prime example of an agency that participated in this research that will benefit from this research.

While there have been efforts to characterize southern Appalachian wetlands (e.g. Francl et al., 2004), the function of the ecosystem as a result of the environment needs to be investigated in this setting. The objectives of this study were to (1) examine the hydrologic characteristics, including discharge, storage, and precipitation, of selected southern Appalachian fens and the effect on NPP, (2) determine if any relationship exists between edaphic characteristics and NPP, and (3) examine climatic factors and the impact on NPP, specifically focusing on growing season length. Among all the factors in this study, it was hypothesized that hydrologic characteristics would have the greatest impact on NPP as has been determined for montane wetlands in other settings (e.g. Dwire et al., 2004).

2.4 Methods

2.4.1 Site Description

Montane wetland sites in the southern Appalachian Mountains (Virginia, Tennessee, Georgia, and Alabama; Figure 2.2) were selected based on a series of qualifications. The primary qualification was the location within the southern Appalachian Mountains, classified as the portion of the Appalachians from Virginia south to the end of the Appalachians in Alabama. A secondary geographic characteristic was that the sites lie within the bounds of a government agency, such as a national park or forest to limit the amount of disturbance to the wetland. The Nature Conservancy of Shady Valley, Tennessee was the only non-governmental organization that owned a wetland included in this study. This exception was made because of their efforts to restore and manage the wetlands in their care. Third, the presence of emergent wetland vegetation, as identified on the Wetlands Mapper website (operated by the U.S. Fish and Wildlife Service) using the National Wetland Index (NWI) code, was used to select sites with emergent vegetation. The NWI codes freshwater emergent vegetation wetlands as PEM1x, where P signifies palustrine (freshwater), EM1 signifies emergent and persistent (the vegetation is an herbaceous hydrophyte that stands from the end of the growing season the start of the next growing season), and x, which we have simply placed because this letter in the code signifies the hydrologic regime which can range from A (temporarily flooded) to F (semipermanently flooded) in the cases of montane wetlands in this study. Two sites had tree cover, though it was not enough to serve as a light limiting factor. While sites had similar dominant vegetation, underlying bedrock, elevation, and surface hydrology varied (Table 2.1).

Site characteristics, such as elevation, were initially compiled using geologic and topographic maps as well as aerial imagery. The presence, or absence, of a surface water body and the influence of that water body was initially established by examining topographic maps and aerial imagery on the Wetlands Mapper website. Elevation was initially recorded using United States Geological Survey (USGS) topographic maps and later verified with GPS coordinates. Each site in this study brings distinct characteristics that allow for what was felt to be an accurate and complete representation of the variety of settings in which southern Appalachian wetlands occur.

Site VA-1 represents an uncommon setting for wetlands in the southern Appalachians. This site lies within a depression with no obvious surface flow and is situated near the top of a ridge, because this site lies on the Catoctin Formation, a resistant Cambrian meta-basalt (Virginia Division of Mineral Resources, 1993; NRCS, 2013). VA-1 lies atop Baile stony silt loam, which typically occurs in depressions and consists of alluvium (NRCS, 2013). This unit has a high available water capacity and is composed of a thin layer of silt loam, an underlying layer of gravelly silty clay loam, and a loam at the base (NRCS, 2013).

Site VA-2 represents a more common, although important, setting for southern Appalachian wetlands. VA-2 lie within the floodplain a main valley creek (Reed Creek) and is underlain by sedimentary bedrock. This site lies on the Brallier Formation, which consists of Devonian shale, siltstone, and sandstone (Virginia Division of Mineral Resources, 1993). Site VA-2 has no soil data (NRCS, 2013).

Sites TN-1 and TN-2 represent sites that lie within the floodplain of a first order creek (Milam Branch and Brickyard Branch, respectively) and sites that lie on karst bedrock (Tennessee Department of Environment and Conservation, 1966). Both sites lie on the Shady Dolomite, which is composed of Cambrian dolomite, limestone, and clay or mud (Tennessee Department of Environment and Conservation, 1966). The soil for sites TN-1 and TN-2 is Dunning silt loam, which is composed of clayey alluvium derived from limestone (NRCS, 2013). This unit has high available water capacity and is composed of a layer of silt loam underlain by clay (NRCS, 2013).

Site GA-1 represents wetlands that lie within the floodplain of a river (Etowah River) and sites that lie on metamorphic bedrock (Lawton et al., 1976). GA-1 lies on Precambrian-Paleozoic mica schist (Lawton et al., 1976). The soil for site GA-1 consists of Congaree and Starr soils, which consist of alluvium (NRCS, 2013). Both units have a high available water capacity (NRCS, 2013). Congaree soils are composed of silt loam underlain by loam, whereas Starr soils are composed of fine sandy loam and sandy clay loam (NRCS, 2013).

Site GA-2 represents sites within the floodplain of a first order creek (Mose Branch) that flows into a major river (Chattooga River). GA-2 lies on Precambrian-Paleozoic metagraywacke and mica schist (Lawton et al., 1976). The soil for site GA-2 consists of Toccoa fine sandy loam, which typically occurs on floodplains and consists of alluvium (NRCS, 2013). This unit has a moderate available water capacity and is composed of a thin layer of fine sandy loam, underlain by sandy loam (NRCS, 2013).

Site AL-1 represents sites within the floodplain of a non-flowing surface water body (Guntersville Lake). lies on Monteagle Limestone, which is Mississippian in age and consists of limestone and dolomite (Szabo et al., 1988). The soil for site AL-1 consists of Melvin fine sandy loam, which consists of loamy alluvium that originated from sedimentary rock (NRCS, 2013). This unit has a high available water capacity and is composed of a thin layer of fine sandy loam, underlain by silt loam and sandy loam (NRCS, 2013).

Climate was established by using National Climatic Data Center (NCDC) Global Historical Climatology Network (GHCN) data (Menne et al., 2012). Stations were selected based on proximity (<20 km from the site) and elevation. Elevation was important because of differences in temperature and precipitation that can occur between two points with highly different elevation. For all sites except VA-1 and VA-2, differences in site and station elevation were roughly 100 m or less. Virginia sites were different because of high elevations, which could cause fog to be more of a factor in precipitation. Virginia sites might also exhibit acid rain. Growing season was established through determining the day of that year at which air temperature exceeded biological zero (5º C; Soil Survey Staff, 1975) until the date of field work when biomass samples were collected. After growing season was established, precipitation amount during the growing season was summed for a growing season precipitation amount.

2.4.2 Field Methods

Hydrology was established through a series of methods including field-based methods and GIS methods. Channel characterization (width and depth profile) before and after the stream passes through or adjacent to the field site (Brown, 1981). Channel characterization consisted of initially measuring the width of the surface water body at the surface of the water. Then, depth of the surface water body at the surface of the water to the channel bottom was measured at 30 cm increments to establish a profile. After field work, these data were plotted in GIS by generating an empty shapefile and entering x (point along the transect where depth was measured) and y (depth) points within the attribute table. The points were then projected and the area of the shapefile was measured. Field measurements of water velocity took place through observation of the flow of an object between two points of known distance (EPA, 1997). A 50 mL plastic sampling vial was selected because it floated but only half of the vial was above the water. Using the surface velocity data along with the profile area generated in GIS, a discharge in m^3/s was calculated.

NPP data were derived from aboveground biomass collected at peak standing biomass in mid- to late summer (August and September; Cronk and Fennessy, 2001). It was imperative to collect samples within this time frame to achieve peak standing biomass while limiting decay during the dry periods associated with the southeastern US climate. 10-m transects were established in each site. The number of transects depended on the species richness and size. One transect was used for smaller wetlands with lower species richness (Virginia and Tennessee sites; monospecific sites averaging 0.02 ha in size). Two transects were used for moderately sized wetlands with moderate species richness (GA-2; 5 species and 0.2 ha). Three transects were established for some sites to account for larger wetlands with higher species richness (GA-1 and Alabama sites; averaging 12 species per site and 0.5 ha in size). This method was used because of the relationship between species richness and wetland size (Risvold and Fonda, 2001). It was also thought that larger wetlands might exhibit higher variability in NPP so more data points were necessary to capture that variability. For sites with a flowing surface water body (Table 1), the transect ran perpendicular from stream edge to 10 m away with a sampling points at 0 m (stream edge), 5 m from the stream edge, and 10 m from the stream edge. Biomass samples were collected to represent NPP at each point along the transect, where possible. Ideally, three samples would have been collected per transect but factors, such as size (as limited by tree canopy or disturbance) of the site, limited sampling. It has been found that there is a significant difference in plant height at stream edge and 5 m from the stream edge (DeLaune et al., 1979). If there was no flowing surface water body present, the 10-m transects were set up at random points in the middle of the wetland to avoid the fringes of the wetland. Transects were set to run parallel with the longest axis of the wetland (most of the wetlands studied had an ovular shape). Aboveground biomass, live and dead, was clipped at ground level within a 0.09 m^2 quadrat (Mishra et al., 2012) at 0 m, 5 m, and 10 m along the transect. Biomass samples were refrigerated to minimize decay and dried for 12 hours at 50º C (Mishra et al., 2012). Total and dry masses were taken, with dry mass representing NPP. The value from the 0.09 m2 quadrat was multiplied to get a 1 m^2 value for NPP.

Soil data were collected at the same points where biomass was collected. Soil samples were collected at a depth of 10 cm with a soil auger, measuring 1.9 cm in diameter. Soil samples were analyzed for particle size following the methods of Gee and Bauder (1979). Soil depth was also analyzed in order to characterize storage capacity. In order to record soil depth data, as a means of determining water storage potential, a piece of 0.625 cm thick rebar was hammered into the soil until the bedrock was reached.

2.4.3 Data Analysis

In order to provide proper evidence for inferences made on the relationships between environmental factors and NPP, several statistical analyses were conducted. The initial analysis involved generating a Pearson correlation matrix in SAS 9.4 (SAS Institute, Cary, NC) to compare NPP with those variables with quantitative values (elevation, precipitation, discharge, soil depth, and growing season length). Data were entered in a dataline command and analyzed by a covariance and Pearson correlation matrix command with the output set as a correlation matrix and variables set as "Discharge Precipitation Elevation Depth Season NPP." Specifically, correlation values greater than 0.6 and less than -0.6 (moderately strong relationships) were targeted as threshold values for importance. While Pearson correlation assumes a normal distribution and does not imply causation, it can identify variables which could be linked to variance in NPP. The variables were assumed to have a normal or near-normal distribution, thus the Pearson's parametric correlation analysis was used. Though the relationship between precipitation and NPP appeared to be logarithmic, the bounds of the precipitation fell within the bounds of the near linear relationship between NPP and precipitation.

Once the initial portion of the quantitative data analysis was completed, simple linear regressions were generated for all of the aforementioned quantitative variables. Analysis of the scatter plots revealed what appeared to be linear relationships between NPP and the environmental variables examined. Generating simple linear regressions for all variables allows for more of a visual analysis as well as a means to examine how much each of the quantitative variables in this study were able to explain the variance in NPP. Simple linear regression analysis also allows for a linear model to be generated if the condition of a linear relationship between the dependent and independent variable is met. Scatter plots were examined to ensure that the relationships did not appear non-linear. The models generated in this study could be applied to other study areas to see if the model can transcend the southern Appalachian wetlands in this study.

Basic comparisons between NPP and soil texture were made by examining NPP average over each soil texture. NPP values were averaged across all sites for each specific soil texture for comparison. Linear regressions were also generated to determine the amount of variance that could be explained by amounts of sand, silt, and clay.

2.5 Results

2.5.1 NPP Data

Examination of NPP data per site reveals that there was a high amount of variability (range = 1105 g/m^2/yr) among the sites but also a fair amount of variability within each site (Figure 2.4). The site with the highest NPP was TN-1 (1101 g/m^2/yr, standard deviation = 470 g/m^2/yr, n = 2). The site with the lowest NPP was GA-2 (96 g/m^2/yr, standard deviation = 64 g/m^2/yr, n =5).

2.5.2 Environmental Factors

Of all the quantitative environmental factors examined, hydrologic factors (discharge and precipitation) were the only ones to have strong relationships with NPP (Table 2.2). Discharge had a very strong positive relationship with NPP ($r = 0.91$, $p < 0.05$). Where NPP was highest (TN-1) with an average value of 1101 g/m^2/yr was also where discharge was the highest at 19.7 m^3/s. The lowest NPP values at GA-2 with an average value of 96 g/m^2/yr was also where discharge was lowest at 3.4 m^3/s.

Through simple linear regression analysis of the relationship between discharge and NPP (Figure 2.3), it was clear to see the high amount of variance in NPP that could be explained by discharge ($r^2 = 0.83$). Discharge was able to explain 83% of variance in NPP. Discharge also had a very strong positive relationship with precipitation ($r = 0.97$, $p < 0.05$).

Precipitation was the only other factor to have a very strong correlation with NPP ($r = 0.81$, $p < 0.05$). Where NPP was highest is where the highest amount of precipitation fell. For example, the three most productive samples with NPP values of 1433, 777, and 768 g/m^2/yr experienced precipitation amounts of 839.4, 551.4, and 839.4 mm, respectively. Conversely, the three least productive samples (all from GA-2) with NPP values of 39, 54, and 90 g/m^2/yr experienced 280.2 mm of precipitation. For further analysis, a linear regression was plotted for precipitation and NPP (Figure 2.5).

The simple linear regression analysis for precipitation revealed that it was the second strongest variable in explaining variance in NPP ($r^2 = 0.66$). This result indicates that precipitation was able to explain 66% of the variance in NPP. Precipitation had a moderately strong positive relationship with elevation ($r = 0.61$, $p < 0.05$).

The relationship between elevation and NPP was weak ($r = 0.49$, $p < 0.05$). The three most productive samples with NPP values of 1433, 777, and 768 $g/m^2/yr$ were located at elevations of 850, 1077, and 850 m above sea level, respectively. However, the least productive samples (GA-2) were located at 497 m above sea level. The site at the lowest elevation (AL-1) had an average NPP value of 185 $g/m^2/yr$.

Elevation was not able to explain as much variance in NPP as were discharge and precipitation ($r^2 = 0.31$; Figure 2.6). This result indicates that elevation was only able to explain 31% of the variance in NPP. As expected the relationship between elevation and season was negative, though it was weak ($r = -0.11$, $p = 0.6095$).

The relationship between soil depth and NPP was negative and weak ($r = -0.37$, $p = 0.0622$). The three most productive samples with NPP values of 1433, 777, and 768 $g/m^2/yr$ were located over soils with depths of 51.1, 71.7, and 121.9 cm, respectively. However, the least productive samples (GA-2) with NPP values of 39, 54, and 90 $g/m^2/yr$ were all located over soils with a depth of 121.9 cm. The site at the lowest elevation (AL-1) had an average NPP value of 185 $g/m^2/yr$.

Soil depth was revealed to be a poor indicator of NPP variance through linear regression ($r^2 = 0.14$, Figure 2.7). This result indicates that soil depth was only able to explain 14% of the variance in NPP. Relationships between soil depth and all other factors were weak.

Growing season length had a weak negative relationship with NPP ($r = 0.11$, $p = 0.6171$). The sites with the longest growing season of 153, 150, and 140 days had average

NPP values of 537, 185, and 1101 g/m^2/yr, respectively. Alternatively, the sites with the shortest growing season of 96, 97, and 98 days had average NPP values of 595, 469, and 96 g/m^2/yr, respectively.

Among all of the quantitative variables in this study, growing season length was the weakest in both the Pearson correlation and linear regression ($r^2 = 0.01$; Figure 2.8). This result suggests that growing season length was only able to explain 1% of the variance in NPP.

Soil texture varied little with high amounts of sand and was able to explain little variance in NPP (Figure 2.9). Twenty-seven of the soil samples collected were sandy loam with the remaining samples composed of fine sand (VA-2) and loamy sand (one sample from VA-1). Sand content ranged from 57.9% of the soil composition (AL-1) to 94.4% of the soil composition (VA-2). Silt content ranged from 2.5% of the soil composition (VA-2) to 32.5% of the soil composition (AL-1). Clay content ranged from 3.1% of the soil composition at multiple sites to 13.1% of the soil composition (AL-1).

2.6 Discussion

2.6.1 Southern Appalachian Wetlands in Context

Prior to this study, there have been no NPP studies in the southern Appalachians to serve as benchmarks for comparison of wetlands among regions. Of particular interest might be comparing wetlands located in the humid Southeastern US to wetlands in the drier conditions of the western US, which are also situated at higher elevations. It is debatable whether the wetlands in this study are peatlands and should be compared to peatlands or are simply montane wetlands and should be compared to other montane wetlands, excluding peatlands.

Wetlands in the southern Appalachians share similarities in NPP values and NPP variability with the selected studies that were conducted in mountain ranges in western North America (Szumigalski and Bayley, 1996; Thormann and Bayley, 1997; Dwire et al., 2004). Site-averaged NPP values from this study fall mostly within the range of the gradient of wetlands studied by Thormann and Bayley (1997). In Alberta, Canada it was found that bogs were the sites with the lowest herb NPP (34 g/m^2/yr) and lacustrine marshes were the sites with the highest NPP (757 g/m^2/yr), with floating sedge fens, lacustrine sedge fens, riverine marshes, and riverine sedge fens falling in between (Thormann and Bayley, 1997). Along a similar gradient in Alberta, Szumigalski and Bayley (1996) found bogs to exhibit higher NPP (264–297 g/m^2/yr) than Thormann and Bayley (1997), however fens were less productive compared to the same study (214–360 g/m^2/yr). In montane riparian meadows in eastern Oregon, Dwire et al. (2004) discovered NPP values ranging from 513 g/m^2/yr to 809 g/m^2/yr. The range in NPP in this study was much larger than the range in NPP found by Dwire et al. (2004; 1105 g/m$^{/2}$/yr) and the average NPP in this study (363 g/m^2/yr, n = 30) fell within the ranges of Szumigalski and Bayley (1996) and Thormann and Bayley (1997) . Dwire et al. (2004) and Thormann and Bayley (1997) were examining the change in NPP with environmental gradients, specifically the changing of water table depth or available water.

Using NPP as a proxy for C storage, wetlands in the southern Appalachians, and montane wetlands in general, greatly underperform compared to the swamps and wetlands measured by Leith and Whittaker (1975). One reason for the large disparity could be that montane wetlands might have shorter growing seasons relative to wetlands in other settings (i.e. wetlands at lower latitudes and altitudes, especially on the coast).

Other possible reasons could be differences in areal extent, species, or settings that are simply more conducive to higher NPP values.

2.6.2 Association of Environmental Factors with NPP

It was hypothesized that hydrologic characteristics would have the greatest relationship with NPP as it has in many previous studies in montane wetlands (e.g. Dwire et al., 2004). Discharge had the greatest relationship with NPP ($r = 0.91$, $p<0.05$) and if precipitation ($r = 0.81$, $p<0.05$) is included as part of the hydrologic setting, then two elements had very strong relationships with NPP. At a 95% confidence level ($\alpha = 0.05$), the hypothesis that hydrologic variables would have a significant relationship with NPP cannot be rejected.

Discharge was included in this study because the relationship between discharge and NPP has not been studied in montane wetlands prior to this study. Thus, the cause for this relationship is not well understood. In broader terms, higher discharge could increase NPP for floodplain vegetation for a couple of reasons. First, discharge can serve as a way of maintaining water table depths in wetlands where the source of water is the flowing surface water body in losing stream settings. In losing stream settings, discharge was more highly correlated with NPP than discharge and NPP for all sites ($r = 0.98$ $p = 0.11$). High discharge could also indicate high water table levels in floodplains where the wetland is the source of the surface water in gaining stream settings. In gaining stream settings, discharge was more highly correlated with NPP than discharge was for all sites ($r = 0.98$, $p <0.05$). If water table levels are important for NPP, then montane wetlands in both the western mountain ranges and eastern mountain ranges would both be affected by water table depth. Future work could examine water table depth and its impact on NPP in southern Appalachian wetlands to be certain. Because the vegetation in southern Appalachian wetlands is hydric or mesic, higher amounts of water relieve the stress that the plant might undergo, allowing the plant to store higher amounts of C. Secondly, the flowing water could bring in nutrients and remove toxins (Brinson, 1993; Craft, 2001). An important part of maintaining high discharge in the southeastern US, as indicated in this study among others, is precipitation.

The difference in the correlation between discharge and NPP and precipitation and NPP might be accounted for by a couple of explanations. The discharge could serve as a better marker of water table levels, which might be more important for NPP than either discharge or precipitation, though both are important for maintaining water table levels. During precipitation events, some water is lost to overland flow and therefore unavailable to the vegetation and serves no purpose for NPP.

While precipitation is generally not associated with hydrology, it is an important part of surface and subsurface processes that are mainly associated with hydrology and Southeastern hydrology in general. Generally, precipitation is important for NPP in ecosystems and C storage (Figure 2.10). Precipitation and NPP values generally fit in well with the results in Figure 2.10. Toward the end of the summer and beginning of fall, a dry period occurs in many parts of the Southeastern US when droughts are generally common (Menne et al., 2012) and so it was determined that precipitation was too important of a hydrologic factor to leave out of this study. Wetlands in the Southeastern US are affected by this pattern, as it affects water table levels, and wetlands occurring in floodplains, as most of the wetlands in this study were, are more impacted by changes in precipitation than wetlands in other settings (Thompson et al., 2007; NRCS, 2013).

The relationship between elevation and precipitation was moderately strong positive ($r = 0.61$, $p < 0.05$), though elevation was included in this study mainly because of the anticipated relationship with growing season length. Elevation did not have a strong relationship with NPP, though the relationship between elevation and NPP was unexpected. It was not expected that elevation would have a positive relationship with NPP. Generally, increases in elevation delay the onset of important phenological processes and shorten the growing season (Caprio, 1966, 1967).

Growing season length was expected to have a positive relationship with NPP because more days allows for more biomass accumulation and C storage, however the relationship between NPP and growing season length was negative and weak. It was anticipated that there would be a difference in the start of the growing season, where the southern-most sites in Georgia and Alabama would have an earlier start on the growing season compared to the northern sites in Virginia and Tennessee. However, using biological zero as a start for the growing season (Soil Survey Staff, 1975), the growing season for all sites started at the end of April. The only difference in the sites was when the collection of samples took place. This might indicate a few points to consider. First, while the anticipation that the southern-most sites would have a longer growing season, all of the sites fall into the humid subtropical climate zone (Koppen, 1936). Second, perhaps more focus should go toward the leaf out phase of the phenological cycle than simply using climatic indicators, such as temperature. Finally, this weak relationship might serve as validation for collecting biomass in late summer or early fall (Cronk and Fennessy, 2001).

It was expected that soil would have an impact on NPP, however all sites had very similar soil in terms of texture. While this result does not help to indicate anything about NPP, the similar soil texture does indicate that wetlands in the southern Appalachians occur on a similar soil texture. The absence of major variations in soil texture also point to the fact that almost all the wetlands in this study were located in a floodplain.

2.6.3 Relationships among Factors

The strongest relationship between two factors in this study was discharge and precipitation. Precipitation is the driver of many parts of the hydrologic settings in the southern Appalachians and the Southeastern US. Groundwater flow is the intermediary step between these two parts of the hydrologic cycle. However, given that soil texture was similar throughout the study sites, it is logical that precipitation and discharge would have such a strong relationship.

There was a moderately strong positive relationship between precipitation and elevation. This relationship is most likely due to a rain shadow effect where wetlands at higher elevations receive more precipitation because of the removal of the atmospheric moisture through forced vertical motion. Such motion leads to adiabatic cooling of the rising air and condensation of the moisture, forming precipitation along the windward edge of the mountain range and warmer, drier conditions along the leeward edge and subsequent valley. In the southern Appalachians, declines in precipitation have been found to be between 5% (Swift et al., 1988) and 30% (Hibbert, 1966) by decreasing elevation 100 m and 30 m, respectively.

It was anticipated that growing season length would shorten with an increase in elevation. However, as previously discussed, the growing season started at the same time of the year according to biological zero (Soil Survey Staff, 1975). While there was a negative relationship between elevation and growing season, it was weak (r = -0.34). This relationship should not be judged according to this study, however, since the growing season for all sites started in late April, and growing season length was determined by the date of the collection of biomass.

2.6.4 Limitations

There was a problem with the methodology related to the sampling scheme. The sample scheme was inhibited by small wetland size. Only in the largest wetlands were samples taken from all three points along the transect. In many cases, only two points along the transect were sampled and in a few locations, only one point was able to be sample due to disturbance or limited wetland size.

2.7 Conclusions

This study provides the definitive examination of the relationship between environmental factors and NPP in southern Appalachian wetlands. Specifically, NPP in southern Appalachian wetlands seems to be most correlated with discharge. Precipitation in the humid Southeastern US was moderately important to NPP and was very important to discharge, and should be considered in future work conducted on wetlands in similar climates along with discharge. Higher amounts of water reduce the stress that the hydric and mesic plants undergo and allow for higher amounts of C storage by plants.

This study also provides focus on a region that is sparsely examined as far as montane wetlands. Southern Appalachian wetlands are unique wetlands that are seeing habitat loss. Studying these ecosystems and reporting on what important environmental factors are needed in order to maintain current productivity is vital for future management. In turn, the function of these ecosystems serves the residents of the southern Appalachians in terms of water storage and water quality.

Future work should address some questions that were raised by this study. Flowing surface water could bring in fresh nutrients, thus surface water should be investigated for nutrient levels. The role of precipitation in water table levels of surface water bodies in southern Appalachian wetlands should be investigated. Future work should also examine the relationship between water table depth and NPP. Any future investigations that include climatic variables should consider this study and consider adding phenological data to more precisely determine the start of the growing season.

2.8 Acknowledgments

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Table 2.1 Adapted from Leith and Whittaker (1975). Global C storage for different types of ecosystems.

Ecosystem Type	**Area (10^6 km^2)**	**Mean NPP (g/m^2/yr)**	**World NPP (10^9tons/yr)**	**Mean Biomass (kg/m^2)**	**World Biomass (10^9 tons)**
Tropical Rain Forest	17.0	2,200	37.4	45	763
Tropical Seasonal Forest	7.5	1,600	12.0	35	260
Temperate Evergreen Forest	5.0	1,300	6.5	35	175
Temperate Deciduous Forest	7.0	1,200	8.4	30	210
Boreal Forest	12.0	800	9.6	20	240
Woodlands & Shrublands	8.5	700	6.0	6	50
Savanna	15.0	900	13.6	4	60
Temperate Grasslands	9.0	600	5.4	1.6	14
Tundra & Alpine	8.0	140	1.1	0.6	5
Desert & Semi-Desert	18.0	90	1.6	0.7	13
Extreme Desert & Ice	24.0	3	0.07	0.02	0.5
Cultivated Land	14.0	650	9.1	1.0	14
Swamp & Wetland	2.0	2,000	4.0	12.3	30
Lake & Stream	2.0	250	0.5	0.02	0.05
-- Total Continental	149	773	115	12.3	1837
Open Ocean	332.0	125	41.5	0.003	1.0
Upwelling Zones	0.4	500	0.2	0.02	0.008
Continental Shelf	26.6	360	9.6	0.01	0.27
Algal Bed & Reef	0.6	2,500	1.6	2.0	1.2
Estuaries	1.4	1,500	2.1	1.0	1.4
-- Total Marine	361	152	55.0	0.01	3.9
---- Grand Total	510	333	170	3.6	1841

Table 2.2 Summary of study sites with locations and site characteristics.

Site	Owner	Elevation (m)	Surface Hydrology
VA-1	Shenandoah National Park	1077	No Surface Flow, Depression
VA-2	Jefferson National Forest	737	Main Valley Creek Floodplain
TN-1	The Nature Conservancy	850	First Order Creek Floodplain
TN-2	The Nature Conservancy	847	First Order Creek Floodplain
GA-1	Chattahoochee National Forest	452	River Floodplain
GA-2	Chattahoochee National Forest	497	Branch Floodplain
AL-1	Lake Guntersville State Park	185	Lake Floodplain

Table 2.3 Correlation matrix for the environmental factors studied.

	Discharge	Precipitation	Elevation	Depth	Season	NPP
Discharge	1.00000	0.96710	0.90615	-0.32526	0.79061	0.90985
p-value		<.0001	0.0003	0.4651	0.0065	0.0003
Precipitation	0.96710	1.00000	0.61614	-0.14181	0.28759	0.81109
p-value	<.0001		0.0010	0.4967	0.2325	<.0001
Elevation	0.90615	0.61614	1.00000	-0.02281	-0.10737	0.48864
p-value	0.0003	0.0010		0.9138	0.6095	0.0132
Depth	-0.32526	-0.14181	-0.02281	1.00000	-0.04534	-0.37828
p-value	0.4651	0.4967	0.9138		0.8296	0.0622
Season	0.79061	0.28759	-0.10737	-0.04534	1.00000	0.10511
p-value	0.0065	0.2325	0.6095	0.8296		0.6171
NPP	0.90985	0.81109	0.48864	-0.37828	0.10511	1.00000
p-value	0.0003	<.0001	0.0132	0.0622	0.6171	

Soil depth is noted by 'depth' and growing season length is noted by 'Season.' p-values for each correlation are listed under the correlation value.

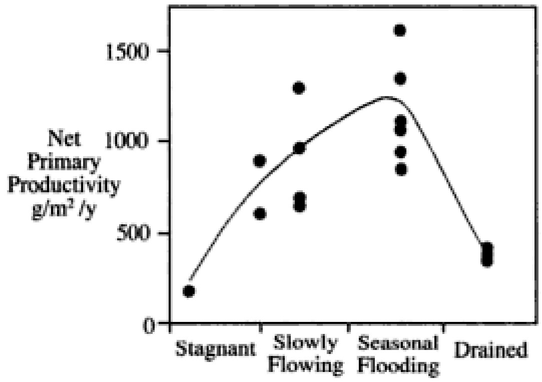

Figure 2.1 Relationship between hydrologic setting and NPP for forested wetlands adapted from Conner and Day (1982).

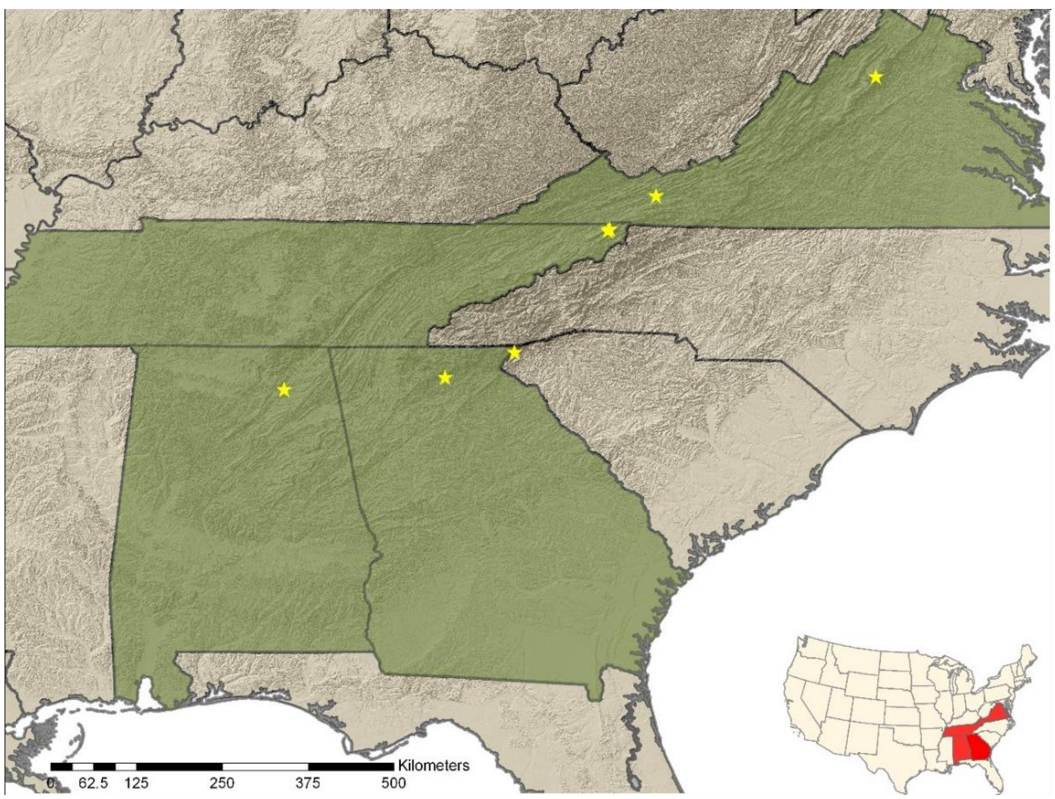

Figure 2.2 Site map for southern Appalachian wetlands in the study.

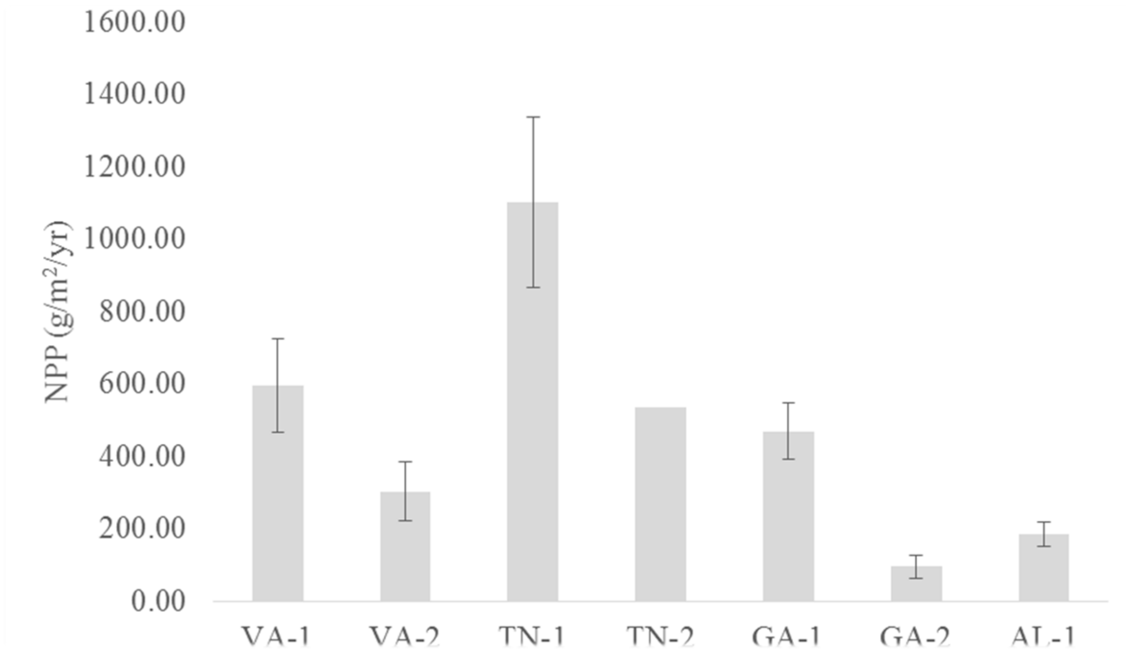

Figure 2.3 Average NPP values per site.

Error bars represent one standard deviation. TN-2 is missing an error bar because NPP for TN-2 was derived from one sample.

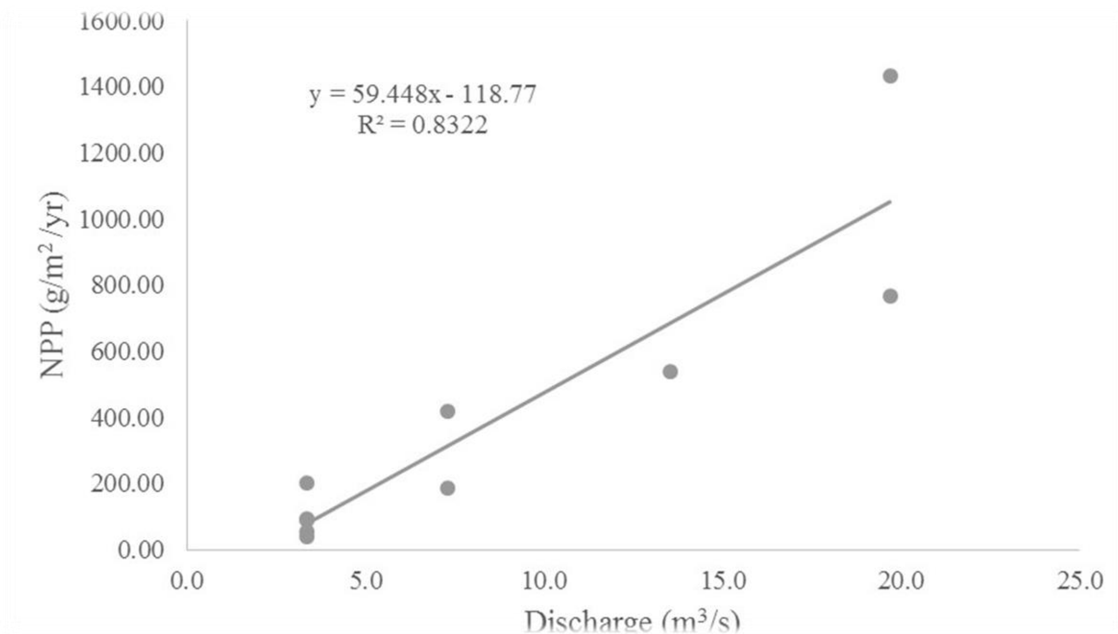

Figure 2.4 Linear regression between discharge (m^3/s) and NPP ($g/m^2/yr$).

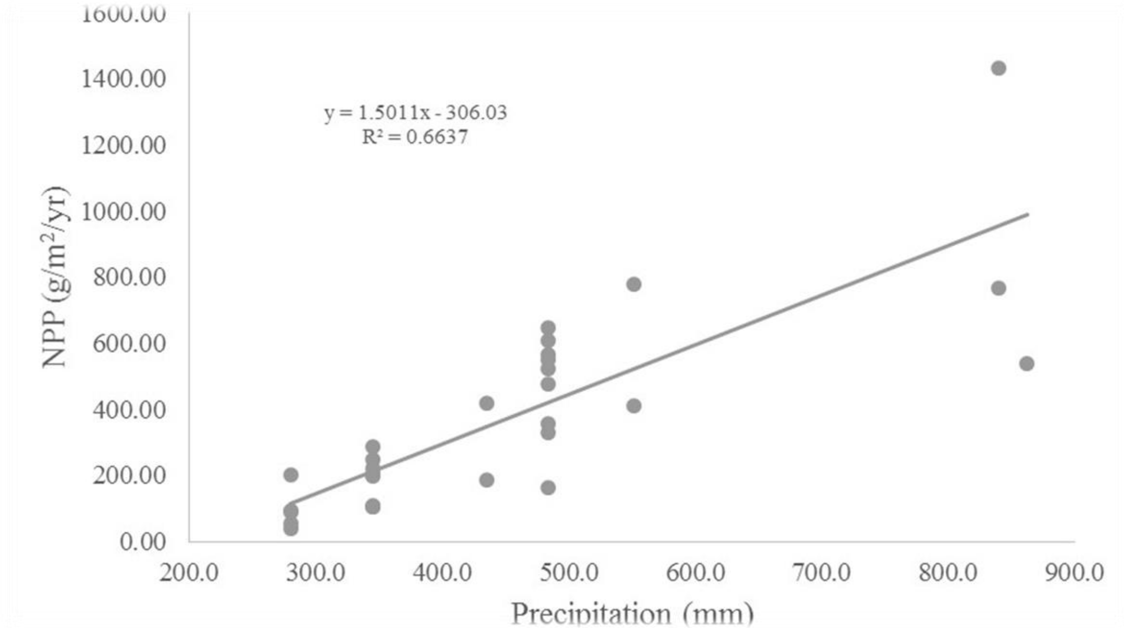

Figure 2.5 Linear regression between precipitation (mm) and NPP ($g/m^2/yr$).

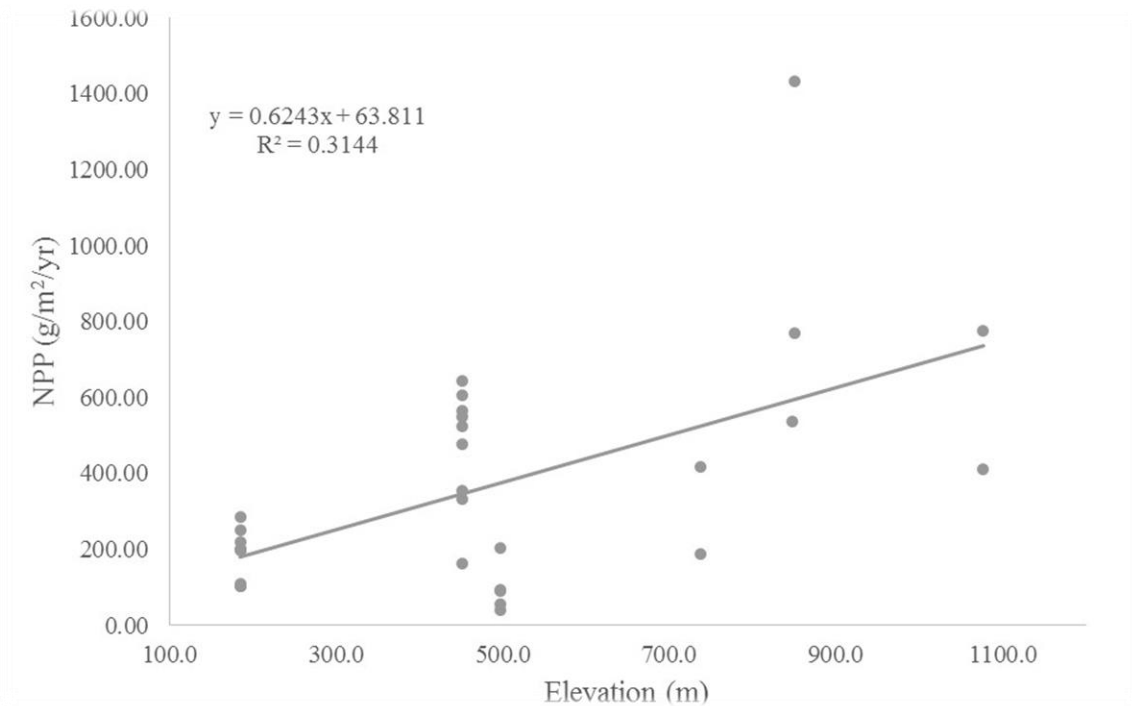

Figure 2.6 Linear regression between elevation (m) and NPP ($g/m^2/yr$).

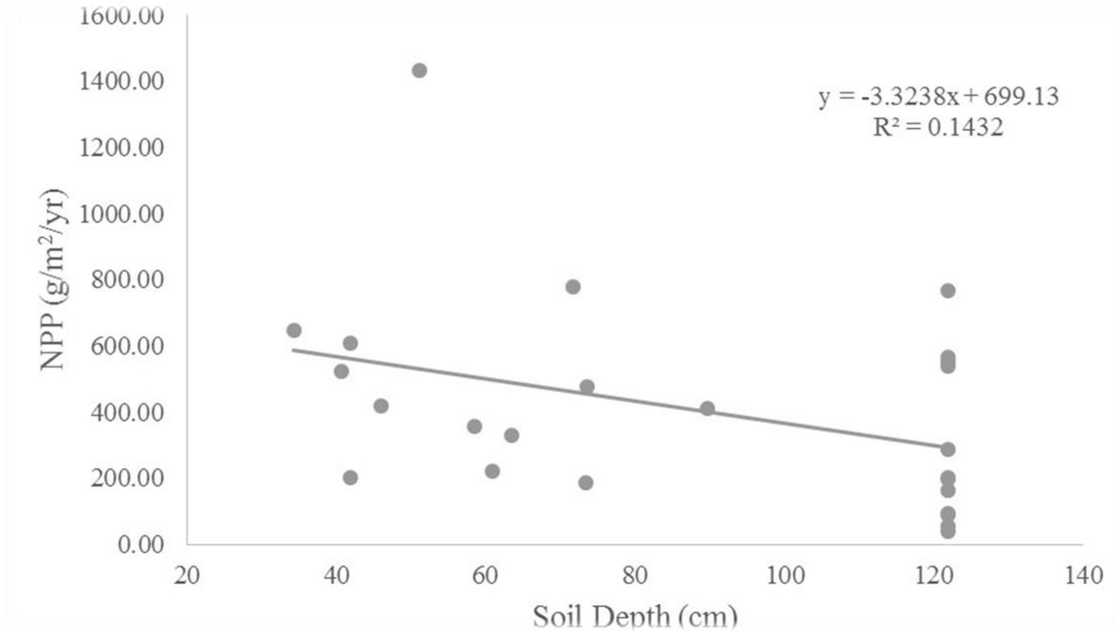

Figure 2.7 Linear regression between soil depth (cm) and NPP (g/m^2/yr).

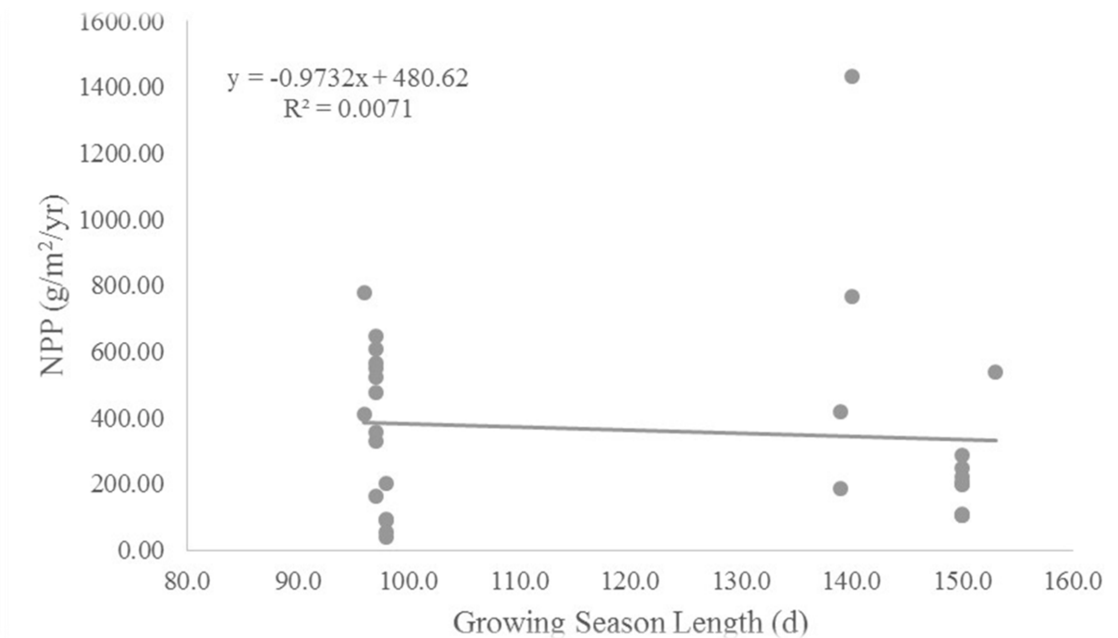

Figure 2.8 Linear regression between growing season length (d) and NPP (g/m^2/yr).

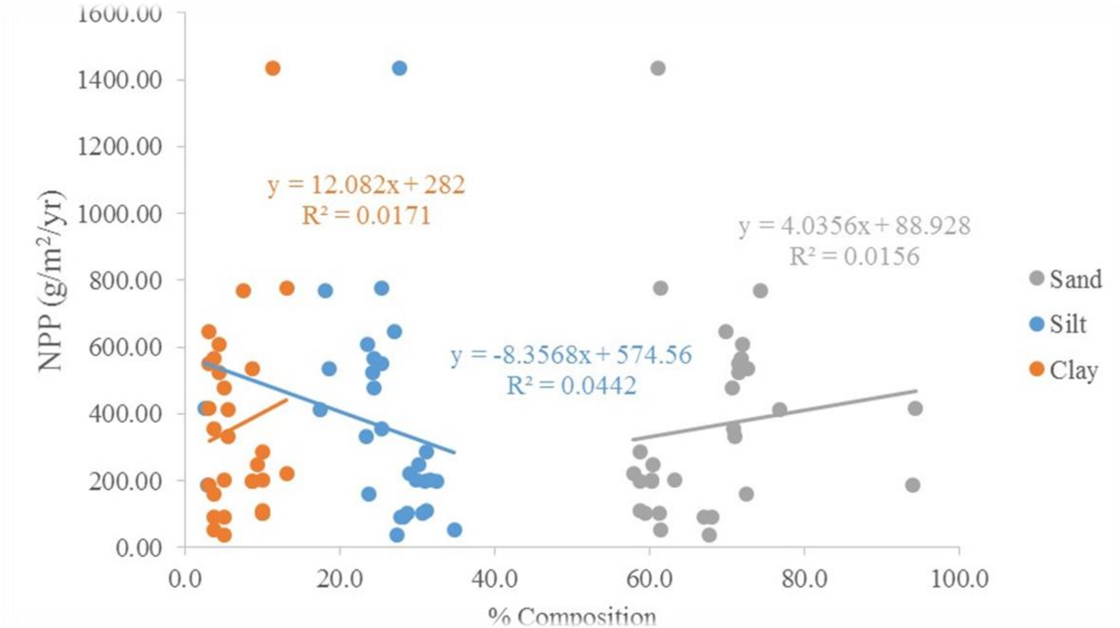

Figure 2.9 Linear regressions for sand, silt, and clay percentages compared to NPP ($g/m^2/yr$).

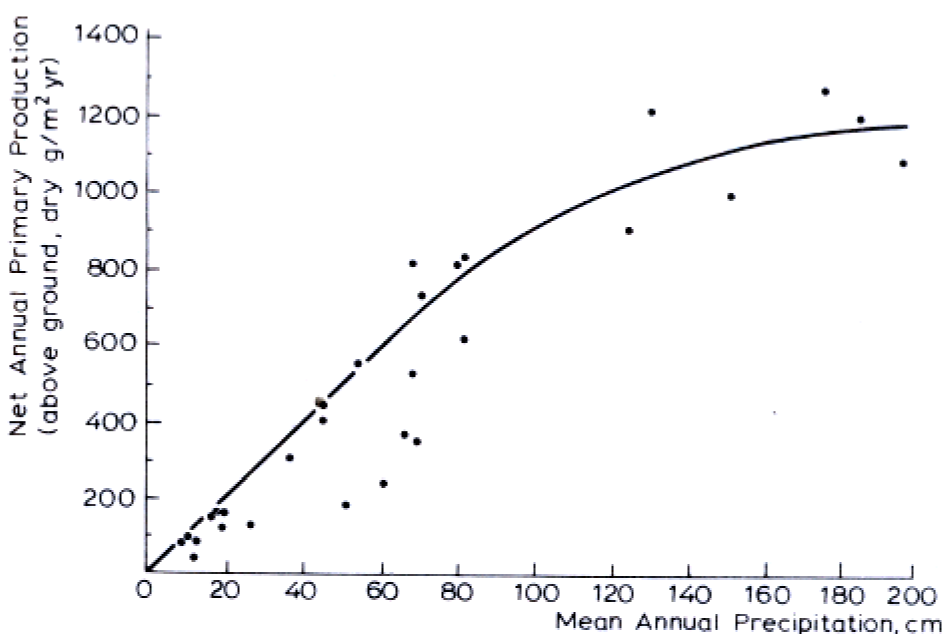

Figure 2.10 NPP ($g/m^2/yr$) compared to annual precipitation (cm) adapted from Whittaker (1970)

CHAPTER III

CALCIUM, MAGNESIUM, AND PH WITHIN SOUTHERN APPALACHIAN WETLAND ENVIRONMENTS

3.1 About this chapter

The chapter is a journal article that will been submitted for publication in Castanea.

3.2 Abstract

This study explored the relationship of water chemistry, underlying bedrock, and species richness in southern Appalachian wetlands, a wetland environment that is not well understood. Peak standing biomass was used to determine NPP for wetlands in Tennessee, Georgia, and Alabama for comparison to magnesium (Mg^{2+}), calcium (Ca^{2+}), and pH from grab samples of surface water. Species richness and underlying bedrock were also determined for comparison to all other variables. A correlation matrix and linear regressions were generated for all variables to compare to NPP. A cluster analysis was also conducted to examine if any clusters between Ca^{2+} and Mg^{2+} existed in the context of NPP. pH was the only variable of water chemistry to have a strong relationship with NPP ($r = -0.66$, $p < 0.05$), explaining 44% of variance in NPP. Large differences were seen in NPP between karst and crystalline bedrock. The relationship between NPP, water chemistry, and bedrock suggests the importance of the local differences in southern

Appalachian wetland productivity. Given that Ca^{2+} and Mg^{2+} were not individually significantly related to NPP, it is not clear at this time why the rock types produced wetlands with different NPP values. Yet this research makes it clear that other factors not associated with bedrock may play an important role in southern Appalachian wetland NPP than the availability of Ca^{2+} and Mg^{2+}.

3.3 Introduction

Montane wetlands are important for maintaining high biodiversity (e.g. Francl et al., 2004), yet southern Appalachian wetlands are seeing a high amount of habitat loss (Moorhead and Rossell, 1998). Compounding the problem of habitat loss is that the nature of these sensitive habitats is that little is known about southern Appalachian wetlands. Research is needed to better understand these unique ecosystems if they are to be protected and maintained. Specifically, more research on the nature of net primary production (NPP), a value denoting ecosystem function, and water chemistry is needed.

Few studies have examined the relationships between nutrient availability, pH, and growth of plants in peatland environments (Brigham et al., 1996). From what has been reported, nitrogen (N), which limits many freshwater wetlands (Bowden, 1987), is an important nutrient. However, N also has a variety of species, including nitrite (NO_2^-), nitrate (NO_3^-), and ammonium (NH_4^+), which creates difficulties in examining N. The more comprehensive studies on nutrient availability in wetlands were conducted in The Netherlands (e.g. Koerselman and Meuleman, 1996; Bedford et al., 1999). Simply applying those relationships to North American wetlands, especially montane wetlands, would not be useful for comparison due to differences in setting, such as soil, climate, and nutrient cycling. Instead, it would be more beneficial to focus on studying a few nutrients, like calcium (Ca^{2+}) and magnesium (Mg^{2+}) in southern Appalachian peatlands that have been tied to differences in rich fens, poor fens, and bogs in other settings (e.g. Bridgham et al., 1996).

The effect of Mg^{2+} on NPP in other environments has been established, however Mg^{2+} was examined with other nutrients (Bernard and Bernard, 1977; Twilley et al., 1985). The findings of both studies were that Mg^{2+}, along with most other nutrients, had a strong relationship with standing crop (NPP; Bernard and Bernard, 1977; Twilley et al., 1985). Both studies examined emergent herbaceous vegetation, with Bernard and Bernard (1977) examining *Carex lacustris* and *C. rostrata*, while Twilley et al. (1985) examined *Justicia americana (L.)* as well as *Nuphar luteum*, a floating-leafed species. The aforementioned species are all found in the southern Appalachian wetlands, thus the relationships should emerge in this study. In both of the aforementioned studies, Ca was also a nutrient with a strong relationship to standing crop (Bernard and Bernard, 1977; Twilley et al., 1985).

Ca^{2+} has been identified as a limiting nutrient in peatlands (Bridgham et al., 1996), but the impact depends on the type of vegetation and species (Bridgham et al., 1996; Chapin et al., 2004). Bog vegetation has exhibited growth in most treatments when Ca^{2+}, in the form of $CaCO_3$ (lime), was added (Chapin et al., 2004). This relationship was significant for bryophytes and shrubs in the bog, while having an insignificant and sometimes negative relationship on graminoids in the bog and fen (Chapin et al., 2004). Ca^{2+} can also act as a phosphate inhibitor or even a toxicant (Clymo and Hayward, 1982; Bridgham et al., 1996). Clymo and Hayward (1982) found decreases in production for all bryophyte species and sharp decreases in production for some bryophyte species when

Ca^{2+} concentrations increased from 0.5 to 5.0 mmol dm^{-3}. Increases in Ca^{2+} generate increases in alkalinity, which increases pH (Chapin et al., 2004).

pH, like Ca^{2+}, is another environmental variable that can impact production either positively or negatively, depending on the type of plant and species composition. The addition of the lime in the Chapin et al. (2004) study increased alkalinity along with pH, and relieved the stress of the plants in the strongly acidic bog. Chapin et al. (2004) reported the increased production in bryophytes was contrary to the findings of previous studies such as Clymo and Hayward (1982), where bryophyte cover decreased with increasing pH. Swanson and Grigal (1991), a study that included trees and shrubs as well as mosses, found an inverse relationship between biomass and pH. This study is only concerned with the relationships of these environmental variables and herbaceous vegetation, however. Examining net primary production (NPP) as a product of standing crop is important, though biodiversity is also an important ecological factor.

Biodiversity, as noted in species richness in this study, is another important factor for analysis in montane wetlands. Southern Appalachian wetlands exhibit a high amount of biodiversity (Francl et al., 2004) and differences between rich fens, poor fens, and bogs, are partly based on biodiversity (Sjors, 1950; Bridgham et al., 1996). Species richness has been shown to have a negative relationship with plant height (Bowles et al., 2005) and biomass (Dwire et al., 2004, 2006). The relationship between biodiversity and nutrient availability as it relates to surface water is another area to be explored, though NPP and discharge have been shown to be strongly related (Chapter 2).

Surface water was selected because the results from Chapter 2 suggest that discharge had a very strong positive relationship with NPP ($r = 0.91$, $p < 0.05$). This study will aid in determining why the relationship between discharge and NPP in southern Appalachian wetlands had the strongest relationship with NPP. It was thought that this relationship might exist because flowing surface water can serve as a source of fresh nutrients for vegetation in the wetland (Brinson, 1993). Nutrient availability can be, in part, determined from the interaction between water and the underlying bedrock (Nelson et al., 2011). Alternatively, this study explores the variability in environmental settings among southern Appalachian wetland habitats.

Underlying bedrock can serve as an influence on nutrients and other traits of water chemistry (Nelson et al., 2011). Sedimentary bedrock can produce higher Ca^{2+} and Mg^{2+} concentrations in water relative to crystalline (igneous and metamorphic) bedrock (Nelson et al., 2011). Ca^{2+} concentrations in water can be as much as 2.6 times higher in sedimentary bedrock compared to crystalline bedrock, with Mg^{2+} at 1.8 times higher in sedimentary bedrock relative to crystalline bedrock. pH can also be 0.4 units higher in sedimentary bedrock relative to crystalline bedrock.

The objective of this study was to examine the surface water chemistry of southern Appalachian wetlands, with a focus on Ca^{2+}, Mg^{2+}, and pH. Given that the distinction between rich fens, poor fens, and bogs relies on the close correlations between pH, alkalinity, and cation concentration with community composition (Sjors, 1950; Bridgham et al., 1996), it was hypothesized that montane wetlands in the southern Appalachians have different chemistries given differences in underlying bedrock geology. Further, these water chemistry differences may help explain variability in wetland NPP.

3.4 Study Area

3.4.1 Geography

The sites in this study were selected by using geographic, biologic, and geologic criteria. The main selection criterion was that the sites be located in the southern Appalachian Mountains (from Tennessee south to Alabama; Figure 3.1) and the secondary criterion for site selection was ownership. Preference of ownership of the site was given to government agencies, such as national or state parks or national forests. The only exception that was made was The Nature Conservancy of Shady Valley, Tennessee. The ownership criterion was set in place to minimize the amount of human disturbance. Exceptions were made for the Shady Valley sites (TN-1 and TN-2) because of the efforts that are made by The Nature Conservancy to preserve the wetlands it owns. Variations in underlying geology were also preferred (Table 3.1) because of the hypothesized variations in water chemistry associated with changes in underlying geology. Virginia sites were excluded from this study because VA-1 has no surface water associated with the wetland and VA-2 was not accessible for the second field season when water samples were collected.

3.4.2 Vegetation

The final criterion was the dominant vegetation cover. Preference was given to emergent (herbaceous) vegetation cover for this study. In order to select sites, the Wetlands Mapper website (owned and operated by the U.S. Fish and Wildlife Service) was used. The Wetlands Mapper website is a GIS database that has multiple layers, including a National Wetland Index (NWI) layer, complete with information on NWI codes and wetland size. Sites were selected based on the code PEM1x, where P (palustrine) signifies a freshwater wetland, EM1 (persistent emergent vegetation) signifies herbaceous vegetation that stands from the end of one growing season to the beginning of the next growing season, and x is a hydrologic regime qualifier that can range from A (temporarily flooded) to F (semipermanently flooded) in the case of many southern Appalachian wetlands. While there was some tree cover in most sites, it was not enough to serve as a light limiting factor.

3.4.3 Geologic Setting

Geologic setting varied throughout the southern Appalachians between sedimentary and metamorphic parent material. Both Tennessee sites (TN-1 and TN-2) lie on the Cambrian dolomite, limestone, and clay or mud (Tennessee Department of Environment and Conservation, 1966). GA-1 lies on Precambrian-Paleozoic mica schist and GA-2 lies on Precambrian-Paleozoic metagraywacke and mica schist (Lawton et al., 1976). The Alabama site, AL-1, lies on Mississippian limestone and dolomite (Szabo et al., 1988).

3.5 Methods

3.5.1 Vegetation Sampling

NPP is often used to characterize ecosystem function. Herbaceous vegetation are being examined for NPP. Herbaceous plants are important for biodiversity of Appalachian wetlands (Francl et al., 2004) and have been used in many studies (e.g. Dwire et al., 2004) to examine environmental characteristics.

Vegetation sampling was dependent on wetland size, species richness, and hydrologic setting. The methodology is based on the findings of Risvold and Fonda

(2001), where species richness and wetland size had a significant positive relationship. 10-m transects were established to quantify wetland NPP relative to size and variability of the wetland. The number of 10-m transects established and sampled in each site was dependent on the size of the wetland and diversity of flora in the wetland. Sites in Tennessee (TN-1 and TN-2) were small (average = 0.02 ha) and monospecific, thus only one transect was sampled for each site. Only stream edge was sampled for both Tennessee sites due to human disturbance (mowing). GA-2 was larger than the Tennessee sites (0.2 ha) with higher species richness (5 species), thus two transects were used for this site. GA-1 and AL-1 were both large sites (average = 0.5 ha) with the highest amount of species richness (average = 12 species), thus three transects were used for these two sites. Additionally, these sites were proximal to surface water, not adjacent, so transects were set in the middle of the wetland to avoid any boundary wetland species. 10-m transects were established parallel to the longest axis of the wetland (generally both these wetlands were ovular or rectangular) and samples were taken from 0 m, 5 m, and 10 m along the transect. For sites that were located adjacent to a flowing water body, 10-m transects were set up perpendicular to the edge of the water and the transect was sampled at 0 m (edge of the surface water body), 5 m, and 10 m. Vegetation was sampled at peak standing biomass in mid- to late summer (Cronk and Fennessey, 2001) by clipping vegetation at the ground level within a 0.09 m^2 plot for collection (Mishra et al., 2012). The biomass was assumed to be a representation of NPP. In order to minimize decay, biomass samples were refrigerated before being dried for 12 hours at 50º C (Mishra et al., 2012). Before and after drying, biomass samples were massed. The value from the dry mass within the 0.09 m^2 quadrat was multiplied to get a 1 m^2 mass. Samples were identified for species composition by Dr. Victor Maddox of the Plant and Soil Sciences department at Mississippi State University.

3.5.2 Surface Water Sampling

Surface water samples were collected at a point where the stream was flowing directly adjacent to, or in one case through, the wetland where samples were collected. One grab sample of surface water sample was collected for each site (Dwire, personal communication, May 22, 2014). Polypropylene bottles were rinsed with deionized water before sample collection (Nelson et al., 2011). Samples were refrigerated until analysis was conducted (Nelson et al., 2011), which was no more than three weeks after collection. Before laboratory analyses, samples were filtered by vacuum through 0.45-µm filter paper, transferred into clean polypropylene bottles, and frozen (Greenberg et al., 1992).

3.5.3 Laboratory Analyses

Water samples were analyzed for Ca^{2+} and Mg^{2+} by atomic absorption spectrometer (Perkin-Elmer AAnalyst700, Perkin-Elmer Corp. Norwalk, CT; Greenberg et al., 1992). Before analysis, samples were thawed for ~2 h and prepared with a 10% Strontium Chloride ($SrCL_2$) solution to limit phosphate interference (Greenberg et al., 1992). The $SrCL_2$ solution was added to pure sample to create 10 mL of 10:1 ($SrCL_2$: sample) diluted solution. Standards were prepared through serial dilution to establish a standard curve for Ca^{2+} (1.0 – 5.0 mg/L) and Mg^{2+} (0.1 – 0.5 mg/L). The atomic absorption spectrometer was prepared with a blank and standards before samples were run. Samples were run through the atomic absorption spectrometer, which generated two values for concentration and then the average was calculated by the atomic analysis program. Once the output was generated by the atomic analyzer, concentrations were generated by using the equation:

$$C_1V_1 = C_2V_2 \quad 3.1$$

where C_1 is the concentration of the sample, V_1 is the volume of the sample, C_2 is the concentration of the sample plus $SrCl_2$, and V_2 is the volume of the sample plus SrCl2. Some samples, such as AL-1, were diluted further with deionized water because the values fell outside the detection range of the atomic analyzer. pH was also determined for samples after thawing by an Accumet model15 pH meter (Fisher Scientific, Pittsburgh, PA).

3.5.4 Data Analysis

Multiple data analyses were conducted in order to get a better idea of the interactions of vegetation, water chemistry, and geologic setting. First, quantitative data (NPP, Ca^{2+} concentration, Mg^{2+} concentration, and pH) were analyzed in a correlation matrix generated by SAS 9.4 (SAS Institute, Cary, NC) in order to examine relationships between NPP and water chemistry. Data were entered in a dataline command and analyzed by a covariance and Pearson correlation matrix command with the output set as a correlation matrix and variables set as "Mg Ca pH Richness NPP." A correlations matrix was chosen because of the relationships revealed by correlating each variable with all other variables and determining p-values for the user to determine the significance of the relationships revealed. Pearson correlations assume normal distributions but are an effective way to demonstrate association among variables, though correlation does not imply causation.

Simple linear regressions were then generated to explore the relationships between NPP, Ca^{2+}, Mg^{2+}, pH, and species richness. Linear regression analyses helped provide insight into the relationships between southern Appalachian wetland environmental settings and NPP. NPP values were obtained from Chapter 2.

Cluster analyses were used to explore site variability with regards to water chemistry. Of particular interest was the nature of the relationship between Ca^{2+} and Mg^{2+}. Ca^{2+} and Mg^{2+} were plotted with Mg^{2+} as the x variable and Ca^{2+} as the y variable. Points were labeled by site and clusters were established by noting any cluster of value which was then separated by a large gap from other values. It was assumed that clusters of Ca^{2+} and Mg^{2+} concentrations would fall within a fairly narrow range (~1 mg/L).

Given the results from Chapter 2, pH, Ca^{2+}, and Mg^{2+} were examined in order to determine whether water chemistry was related to stream discharge. The variables of water chemistry were compared to discharge by simple linear regression. Because discharge was not able to explain all variance in NPP (Chapter 2) pH. Ca^{2+}, and Mg^{2+} were also compared to residuals from the equation generated from the discharge linear regression with NPP. Residuals were calculated as observed NPP – predicted NPP and squared for comparison to water chemistry variables.

3.6 Results

3.6.1 Nutrient Availability

Mg^{2+} exhibited some variability among all sites, though the majority of Mg^{2+} concentrations fell below 1 mg/L (Figure 3.2). Among those sites was TN-1 (0.23 mg/L

Mg^{2+}), GA-1 (0.66 mg/L Mg^{2+}), and GA-2 (0.38 mg/L Mg^{2+}). Mg^{2+} had two concentrations above 3 mg/L at TN-2 and AL-1 (3.56 mg/L and 3.37 mg/L, respectively). Mg^{2+} had a range of 3.33 mg/L, with TN-2 as the maximum and TN-1 as the minimum.

Mg^{2+} had two relationships out of four that were either moderately strong or very strong. The strongest relationship Mg^{2+} had with any other factor was with Ca^{2+} (Table 1; $r = 0.93$, $p < 0.05$). The relationship between Mg^{2+} and Ca^{2+} was also the strongest relationship between any two factors in this study. The relationship between Mg^{2+} and pH was moderately strong ($r = 0.75$, $p < 0.05$). The relationship between Mg^{2+} and NPP was negative and weak ($r = -0.34$, $p = 0.0835$).

Simple linear regression analysis of the relationship between Mg^{2+} and NPP (Figure 3.3) yielded a low amount of variance in NPP that was explained by Mg^{2+} ($r^2 = 0.13$, $p = 0.09$). Mg^{2+} was only able to explain 13% of variance in NPP. The relationship between Mg^{2+} and Ca^{2+} was very strong, however.

Ca^{2+} exhibited more variability than Mg^{2+} among all sites, though the majority of Ca^{2+} concentrations fell below 1 mg/L. Among those sites were TN-1 (0.02 mg/L Ca), GA-1 (0.56 mg/L Ca), and GA-2 (0.44 mg/L Ca). Ca^{2+} had two concentrations above 1 mg/L at TN-2 and AL-1 (7.4 mg/L and 35.2 mg/L, respectively). Ca^{2+} had a range of 35.18 mg/L, with TN-2 as the maximum and TN-1 as the minimum.

Ca^{2+} had two relationships out of four that were either moderately strong or very strong. The strongest relationship Ca^{2+} had with any other factor was with Mg^{2+}. The relationship between Ca^{2+} and pH was moderately strong ($r = 0.75$, $p < 0.05$). The relationship between Ca^{2+} and NPP was negative and weak ($r = -0.38$, $p = 0.0535$).

Simple linear regression analysis of the relationship between Ca^{2+} and NPP (Figure 3.4) yielded a low amount of variance in NPP that was explained by Ca^{2+} (r^2 = 0.17, $p < 0.05$). Ca^{2+} was only able to explain 17% of variance in NPP. Ca^{2+} and Mg^{2+} exhibited some clustering with regards to NPP.

Cluster analysis revealed three clusters of NPP values by plotting Ca^{2+} and Mg^{2+} values. Three sites clustered in the low range of Ca^{2+} and Mg^{2+} concentrations (<1 mg/L; Figure 3.5). Sites that fit into the low concentration cluster of both nutrients were TN-1, GA-1, and GA-2, which all had different underlying geologies. NPP displayed no obvious signs of clustering among Ca^{2+} and Mg^{2+} concentrations as the highest NPP value (TN-1) clustered with the lowest NPP value (GA-2). TN-2 fell within a cluster of moderate concentrations of Ca^{2+} (1-10 mg/L) and a high concentration of Mg^{2+} (>3 mg/L). Although TN-1 and TN-2 lie on the same underlying geology, the amount of Ca^{2+} and Mg^{2+} varied greatly. This might indicate a lack of association between geology and water chemistry. AL-1 was located within a cluster of high concentrations for both Ca^{2+} (>10 mg/L) and Mg^{2+} (>3 mg/L).

3.6.2 pH

The pH of surface water was acidic for all sites and had a small amount of variability (Figure 3.6). The majority of pH values fell into the range between 6 and 7. Among those values were TN-2 (6.15), GA-1 (6.19), GA-2 (6.04), and AL-1 (6.60). The only pH value to fall out of this range was the minimum value at TN-1 (5.21). The range in pH values was 1.39 units with the maximum pH value of 6.6 at AL-1.

pH had a moderately strong relationship with all other variables except species richness. pH had moderately strong positive relationships with both Mg^{2+} (r = 0.75, p

<0.05) and Ca^{2+} ($r = 0.79$, $p < 0.05$). pH was the only variable to have a moderately strong relationship with NPP, though the relationship was negative ($r = -0.66$, $p < 0.05$).

Simple linear regression analysis of the relationship between pH and NPP (Figure 3.7) revealed that pH was able to explain the most amount of variance in NPP among all variables in this study ($r^2 = 0.44$, $p < 0.05$). pH had the strongest relationship with NPP and was able to explain 44% of variance within NPP.

Given the results of Chapter 2, with stream discharge able to explain 83% of variance in NPP, it may be the pH of the stream water that is the chemical factor of the water that accounts for the variance in NPP. Simple linear regression revealed that pH was able to explain 84% of the variance in squared residual NPP that was not explained by discharge (Figure 3.8).

3.6.3 Relationships between Water Chemistry and Discharge

An examination of discharge and water chemistry suggested that pH exhibits multicolinearity with discharge ($r = -0.84$) with discharge able to explain 71% of variance in pH ($r^2 = 0.71$, $p < 0.05$; Figure 3.9). Neither Mg^{2+} ($r = 0.19$) nor Ca^{2+} ($r = 0.16$) were as highly correlated with discharge as was pH. Discharge was only able to explain 3% ($r^2 = 0.03$, $p = 0.67$; Figure 3.10) of variance in Mg^{2+} and 3% ($r^2 = 0.03$, $p = 0.72$; Figure 3.11) of variance in Ca.

3.6.4 Species Richness

Like all variables already discussed, species richness had variability among sites and, like NPP, there was a smaller variability within sites (Figure 3.12). The two northern-most sites in Tennessee were monospecific, while sites in Georgia and Alabama had a higher amount of species richness. Species richness was highest in GA-1 (14) and lowest in TN-1 and TN-2 (1 each), with GA-2 (5) and AL-1 (10) falling in between that range.

Pearson correlations revealed no strong relationships between species richness and any other variable. The strongest relationship between species richness and any other variable was with pH ($r = 0.47$, $p < 0.05$). The weakest relationship species richness exhibited with any other variable was with Mg^{2+} ($r = 0.08$, $p = 0.7083$). The relationship between species richness and NPP was negative ($r = -0.08$, $p = 0.7037$) and nearly as weak as the relationship between species richness and Mg^{2+}.

Simple linear regression analysis of the relationship between species richness and NPP (Figure 3.13) revealed that species richness was able to explain the least amount of variance in NPP among all variables in this study ($r^2 = 0.04$, $p = 0.74$). Species richness had the weakest relationship with NPP and was only able to explain 4% of variance within NPP.

3.6.5 Geologic Influences

A simple comparison of NPP among sites underlain by crystalline bedrock and sites underlain by sedimentary bedrock revealed that the difference was relatively large. NPP in sites from Tennessee and Alabama with sedimentary bedrock were 1.7 times higher than in sites with crystalline bedrock. Within sedimentary sites, the NPP for the site with dolomite and limestone from TN-1 and TN-2 was 4.9 times higher NPP values compared to the limestone and dolomite from AL-1. A comparison of NPP in sites with crystalline bedrock material revealed that NPP in the site with mica schist was 4.9 times higher values for NPP compared to metagraywacke.

Examination of water chemistry and species richness relative to underlying bedrock revealed large differences. There was a large disparity in Ca^{2+} and Mg^{2+} concentrations (mg/L) when comparing sedimentary bedrock to crystalline bedrock, with average Mg^{2+} and Ca^{2+} concentrations (mg/L) 4.7 times and 15. 6 times higher, respectively, in sedimentary bedrock compared to crystalline bedrock. There was also a difference in pH between the sedimentary and crystalline bedrock, however the difference was smaller than that of Mg^{2+} and Ca^{2+} (0.13 units). The difference in species richness between sedimentary and crystalline bedrock was 5.5, with crystalline bedrock averaging 9.5 species (n = 14) and sedimentary averaging 4 species (n = 12).

3.7 Discussion

3.7.1 NPP in the southern Appalachians

NPP in the southern Appalachians showed a high amount of variability among sites. Sites also exhibited some intra-site variability. In general, sites further north (Tennessee) exhibited higher NPP values. This study captures key environmental characteristics of southern Appalachian wetlands by examining wetlands throughout this portion of the mountains.

3.7.2 Relationships between Water Chemistry and NPP

Wetlands in the southern Appalachians are typically bogs and fens (Warren et al., 2004), which are generally acidic and nutrient-poor (Kivinen and Pakarinen, 1981; Chadde et al., 1998; Cooper and Jones, 2004; Warren et al., 2004), thus examining relationships between NPP and water chemistry variables was important for determining the role of the nutrients and pH studied. It was hypothesized that variations in water chemistry, possibly due to variations in underlying bedrock, would explain variance in NPP. Ca^{2+} and pH were expected to have strong positive relationships with each other, which Chapin et al. (2004) found to be sometimes negative for graminoid growth in a Minnesota bog.

pH was the variable in this study that was best able to explain variance in NPP and the only variable with a strong relationship with NPP. The relationship between NPP and pH was negative and significant at the 95% confidence level ($r = -0.66$, $p < 0.05$). Thus, the hypothesis that pH would have a strong negative relationship with NPP cannot be rejected. Further examination of the relationship between pH and NPP with the removal of the variance explained by discharge suggested that pH is the chemical factor of the stream water that is influencing NPP in southern Appalachian wetlands.

While Chapin et al. (2004) found that increased pH, as a product of increased alkalinity, reduced the stress on bog vegetation, the findings of this study are more in line with Swanson and Grigal (1991), where pH and biomass had an inverse relationship. There could be a few explanations for the inverse relationship between pH and NPP. Southern Appalachian wetlands are generally acidic due to the nature of peatland soils (Warren et al., 2004), thus the plants that are able to survive in acidic environments might be more stressed in a neutral or even alkaline environment. Different species have different ranges of pH tolerance, and the species that can tolerate more acidic soils and water might be more productive and grow larger. A third explanation, that also points to differences in species tolerances, is that the species of herbaceous plants that can survive in more acidic conditions are few and can grow larger due to lack of competition. The relationship between biomass and competition is murky, though a study by Twolan-Strutt and Keddy (1996) suggested an inverse relationship between biomass and competition intensity. The two aforementioned explanations could also be used for Ca^{2+} and Mg^{2+}, for which plants have certain tolerances (Chapin et al., 2004).

Ca^{2+} has been determined to be a nutrient which can control species composition (Bridgham et al., 1996), though the relationship between Ca^{2+} and NPP has been inconclusive. Ca^{2+} can be a positive nutrient for bryophytes and shrubs (Chapin et al., 2004) and even a limiting nutrient in peatlands (Birdgham et al., 1996). However, Ca^{2+} can act as a phosphate inhibitor or toxicant (Clymo and Hayward, 1982; Bridgham et al., 1996). In this study, Ca^{2+} exhibited a weak and negative relationship with NPP, thus the hypothesis that Ca^{2+} would have a strong negative relationship with NPP is rejected. While the relationship between Ca^{2+} and NPP was negative, the relationship was not strong enough to indicate that the Ca^{2+} was negatively impacting NPP at a significant rate.

Mg^{2+} was expected to have a strong positive relationship with NPP and a strong negative relationship with species richness, given the findings of previous studies on the relationships between Mg^{2+}, NPP, and species richness (Bernard and Bernard, 1977; Twilley et al., 1985; Bowles et al., 2005). However, Mg^{2+} only had strong relationships with Ca^{2+} ($r = 0.93$, $p < 0.05$) and pH ($r = 0.75$, $p < 0.05$). While the hypothesis concerning the relationships between Mg^{2+}, NPP, and species richness must be rejected, the hypothesis concerning the relationships between Mg^{2+}, Ca^{2+}, and pH at the 95% confidence level cannot be rejected. Mg^{2+} did not have a significant relationship with NPP at the 95% confidence level however Mg^{2+}, Ca^{2+}, and pH all positively correlated with one another.

While NPP was not shown to have strong relationships with Ca^{2+} or Mg^{2+}, the findings are important for future work in the southern Appalachians. The strong relationship between Ca^{2+}, Mg^{2+}, and pH might support the use of all three of these variables as classifiers of fens and bogs (Sjors, 1950; Bridgham et al., 1996). However, these three variables combined could be not be used to predict ecological indicators, such as NPP or species richness, in the southern Appalachians.

3.7.3 Role of Bedrock

A comparison of averaged NPP of wetlands overlying sedimentary and crystalline bedrock types revealed large differences both between the major bedrock types and within each bedrock type. Differences were larger within each bedrock type compared to the differences between sedimentary and crystalline bedrock. The large difference between the two karst bedrocks was unexpected, given that both bedrocks are composed of both dolomite and limestone. Perhaps the influence of the dolomite over the limestone was an important difference, though. This result could also point to the fact that bedrock was not an influence on NPP for these two sites. Similarly, the two crystalline sites both had the influence of mica schist, yet had largely different NPP values. Again, the difference in the main bedrock member might make a difference in NPP or NPP could be unaffected by bedrock. Bedrock did have an effect on water chemistry and species richness, though.

Differences between sedimentary and crystalline bedrock for Ca^{2+} and Mg^{2+} in this study were large. Ca^{2+} and Mg^{2+} concentrations were 15.6 and 4.7 times higher, respectively, in sedimentary bedrock sites compared to crystalline bedrock sites. Both of the aforementioned ratios are much higher than the same ratios of Ca^{2+} and Mg^{2+}

compared to sedimentary and crystalline bedrock sites in Nelson et al. (2011). Nelson et al. (2011) found that Ca^{2+} was 2.6 times higher and Mg^{2+} was 1.8 times higher in the interbedded shale, claystone, fine-grained sandstone, and limestone compared to the schist and biotite-hornblende gneiss associated with quartz diorite in the southern Rockies wetlands in their study.

Both this study and the Nelson et al. (2011) compared sedimentary bedrock with limestone to crystalline bedrock with schist and found similar trends, albeit with much higher numbers in this study. With the karst sedimentary bedrock, it is logical that Ca^{2+} levels would be higher for both sedimentary bedrock sites relative to the crystalline bedrock sites. The chemical formulae for limestone and dolomite are $CaCO_3$ and $CaMg(CO_3)_2$, respectively. The bedrock in the sedimentary sites is also more likely less resistant to physical and chemical weathering which would release the components of the underlying bedrock more easily relative to crystalline bedrock.

3.7.4 Relationships among Discharge, pH, and NPP

pH exhibited multicolinearity with stream discharge, which also exhibited multicolinearity with annual precipitation. As stream discharge increases, the stream water becomes more acidic, which positively affects NPP. The acidity of the stream discharge is most likely related to the acidic precipitation that occurs in the southern Appalachian wetlands, particularly at higher elevations (Sullivan et al., 2004). Thus, the more water that falls in southern Appalachian wetlands, the more acidic the water, which is beneficial for the naturally acidic peatlands of the southern Appalachians in terms of function and NPP (Warren et al., 2004).

There exists the possibility that the precipitation which is acidic and potentially driving the acidic discharge is the mechanism by which wetlands are kept acidic, however the correlation between pH and precipitation ($r = -068$, $p = 0.08$) is not as strong as the correlation between pH and discharge (-0.84, $p < 0.05$). The aforementioned scenario is likely, given the high correlation between precipitation and discharge (Chapter 2). Specifically, the acid rain could have a higher impact on wetlands that are in a gaining stream setting where the water is entering the wetland from the upland or through precipitation.

3.8 Conclusions

This study provides more insight into NPP in southern Appalachian wetlands by examining nutrients and water chemistry, as well as geologic characteristics. The work from this study builds on existing nutrient literature (e.g. Twilley et al., 1985) in a different setting, while shifting focus to nutrients that are generally lesser studied. This study also aids in pressing the work done by the likes of Warming (1909) and Schimper (1898) on soil chemistry in the role of plant function as well as works in geobotany (e.g. Schennikov, 1964). This work employs an interdisciplinary approach for examining southern Appalachian ecology, which is needed in a time of high specialization in research.

Work in southern Appalachians needs to continue to further shift focus toward montane wetlands which are important for ecological processes and seeing habitat loss. This study highlights a region in which little work has been done on wetland function. More studies need to delve into what is needed to maintain wetland health in the southern Appalachians, in order to help protect and maintain these unique ecosystems.

Future work can build off of the outcomes of this study, by continuing to examine water chemistry in its role on NPP in southern Appalachian wetlands. New techniques, especially those employing geospatial technology, could be developed in order to lessen the impact of field work and preserve function in southern Appalachian wetlands.

3.9 Acknowledgments

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Table 3.1 Description of site characteristics for Chapter 3.

Site	Owner	Elevation (m)	Underlying Geology
TN-1	The Nature Conservancy	850	Dolomite/Limestone
TN-2	The Nature Conservancy	847	Dolomite/Limestone
GA-1	Chattahoochee National Forest	452	Mica Schist
GA-2	Chattahoochee National Forest	497	Metagraywacke/Mica Schist
AL-1	Lake Guntersville State Park	185	Limestone/Dolomite

Table 3.2 Correlation matrix for the water chemistry variables, species richness, and NPP.

	Mg	**Ca**	**pH**	**Richness**	**NPP**
Mg	1.00000	0.93210	0.74606	0.07705	-0.34587
p-value		<.0001	<.0001	0.7083	0.0835
Ca	0.93210	1.00000	0.74819	0.12681	-0.39958
p-value	<.0001		<.0001	0.5370	0.0431
pH	0.74819	0.74705	1.00000	0.47273	-0.66341
p-value	<.0001	<.0001		0.0147	0.0002
Richness	0.07705	0.12681	0.47273	1.00000	-0.07834
p-value	0.7083	0.5370	0.0147		0.7037
NPP	-0.34587	-0.39958	-0.66341	-0.07834	1.00000
p-value	0.0835	0.0431	0.0002	0.7037	

Species richness is noted by ‘Richness.’ p-values for each correlation value are listed below the correlation value.

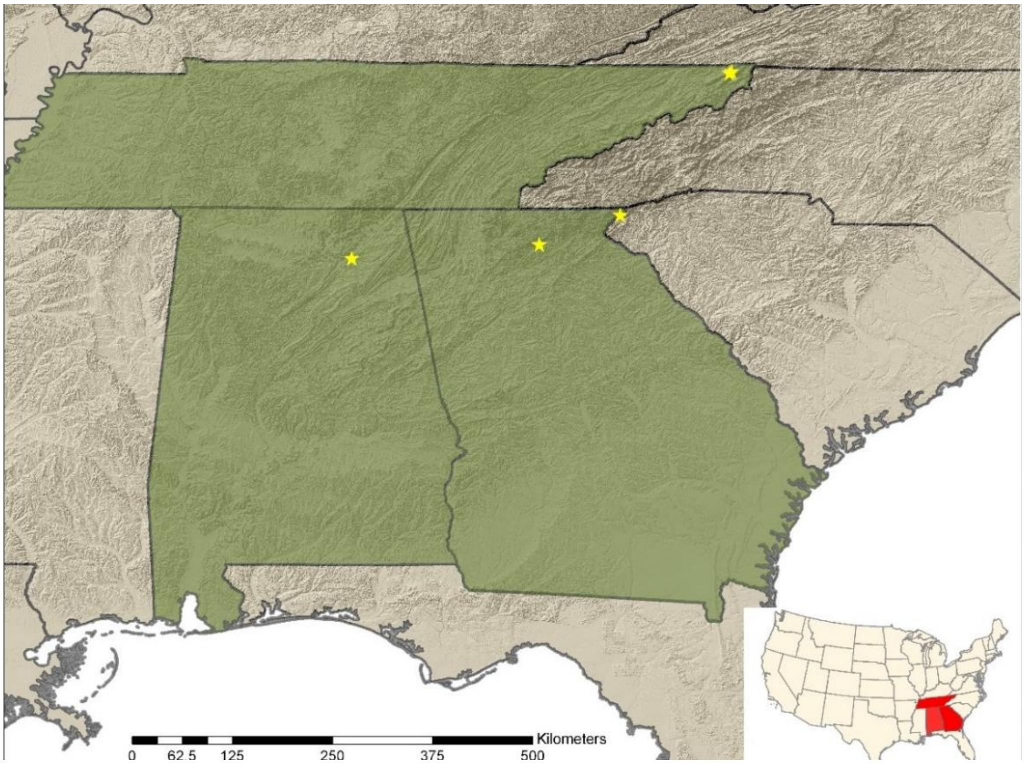

Figure 3.1 Site map for southern Appalachian wetlands in this study.

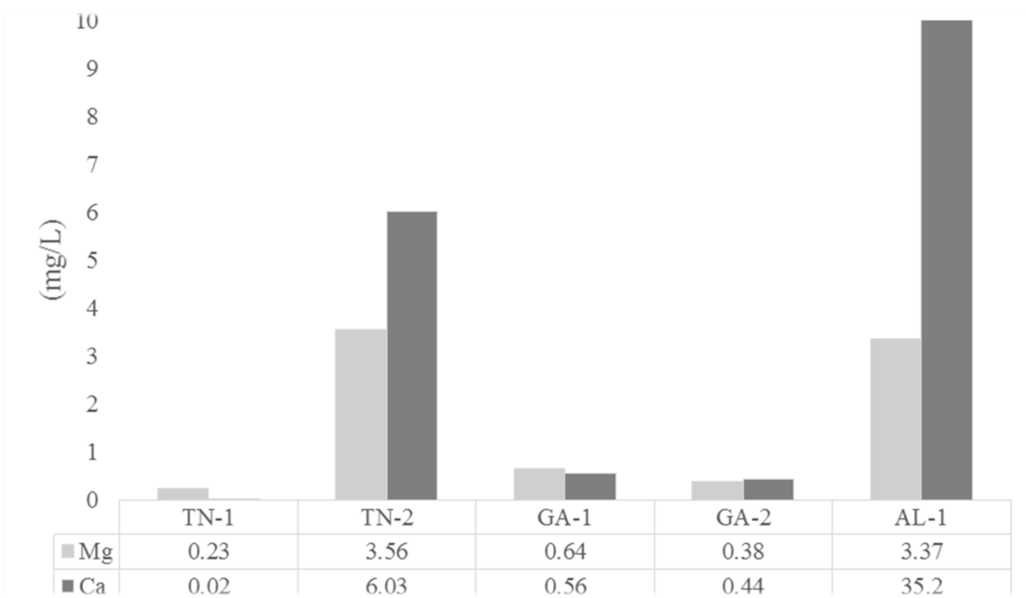

Figure 3.2 Comparison of Mg^{2+} (mg/L) and Ca^{2+} (mg/L) among sites.

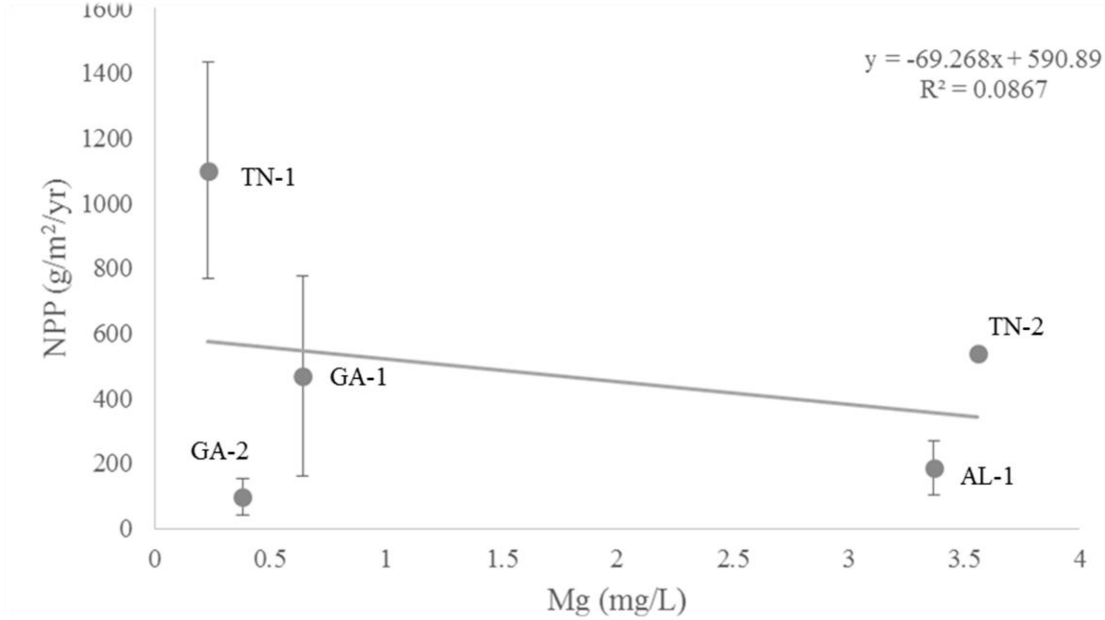

Figure 3.3 Simple linear regression between Mg^{2+} (mg/L) and averaged NPP ($g/m^2/yr$).

Error bars represent the minimum and maximum NPP values ($g/m^2/yr$). The data point with no error bars (TN-2) was derived from one biomass sample.

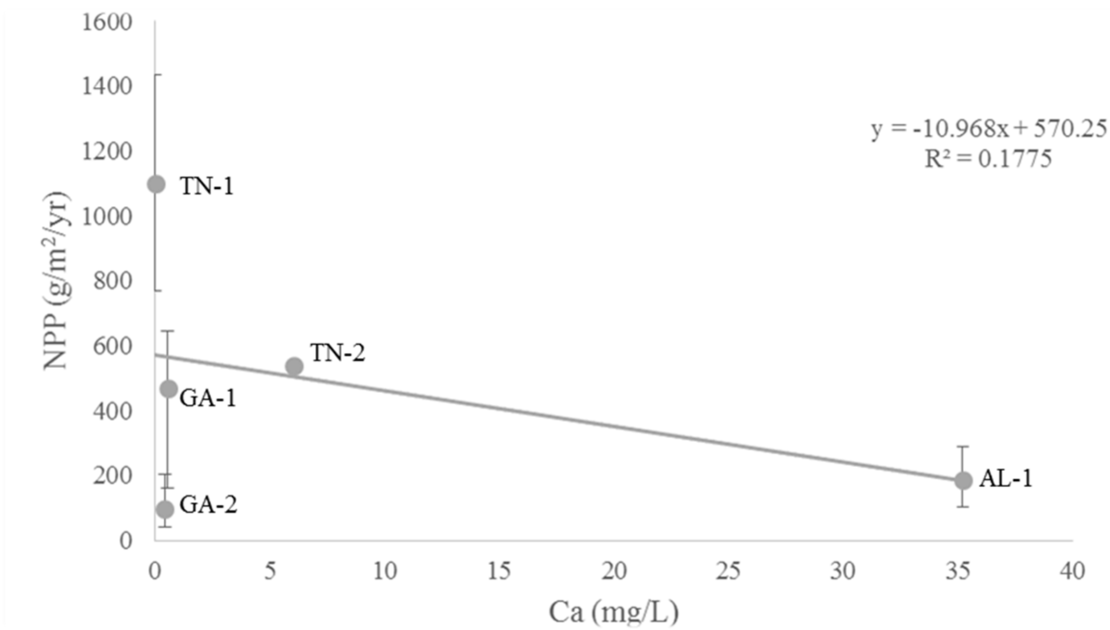

Figure 3.4 Simple linear regression between Ca^{2+} (mg/L) and NPP ($g/m^2/yr$).

Error bars represent the minimum and maximum NPP values ($g/m^2/yr$). The data point with no error bars (TN-2) was derived from one biomass sample.

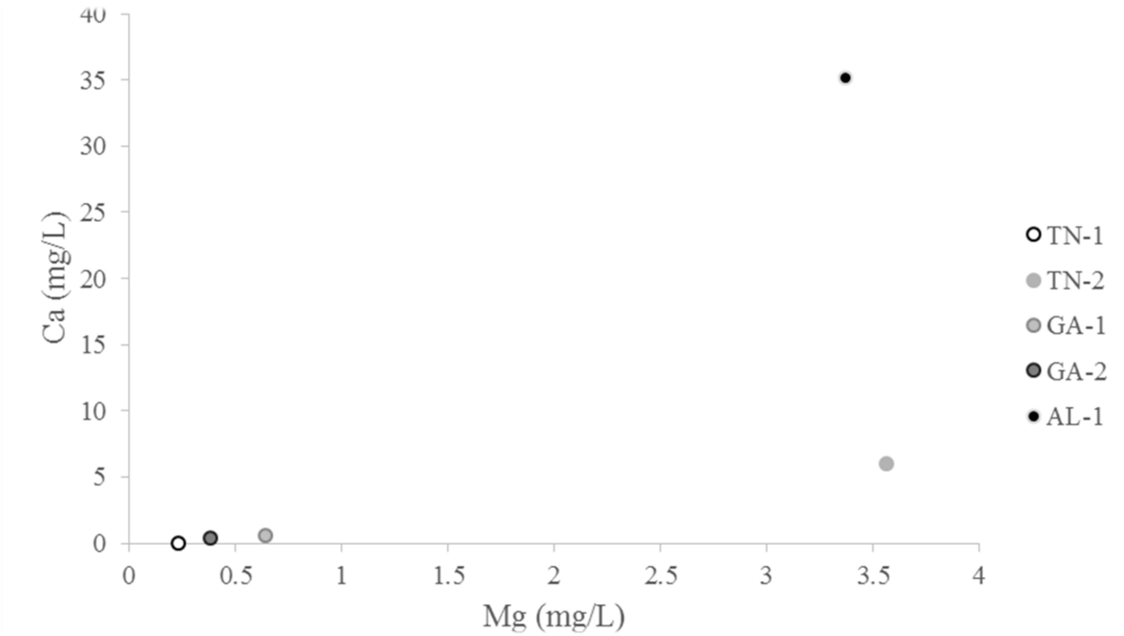

Figure 3.5 Cluster analysis of Ca^{2+} and Mg^{2+} using sites as identifiers.

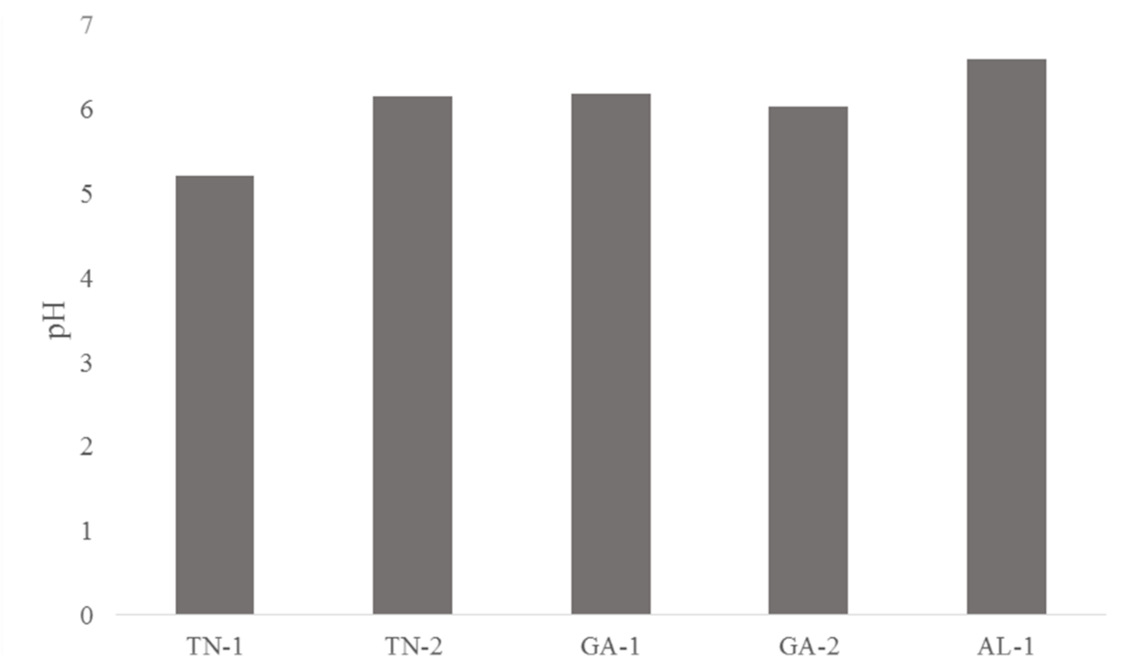

Figure 3.6 Comparison of pH among sites.

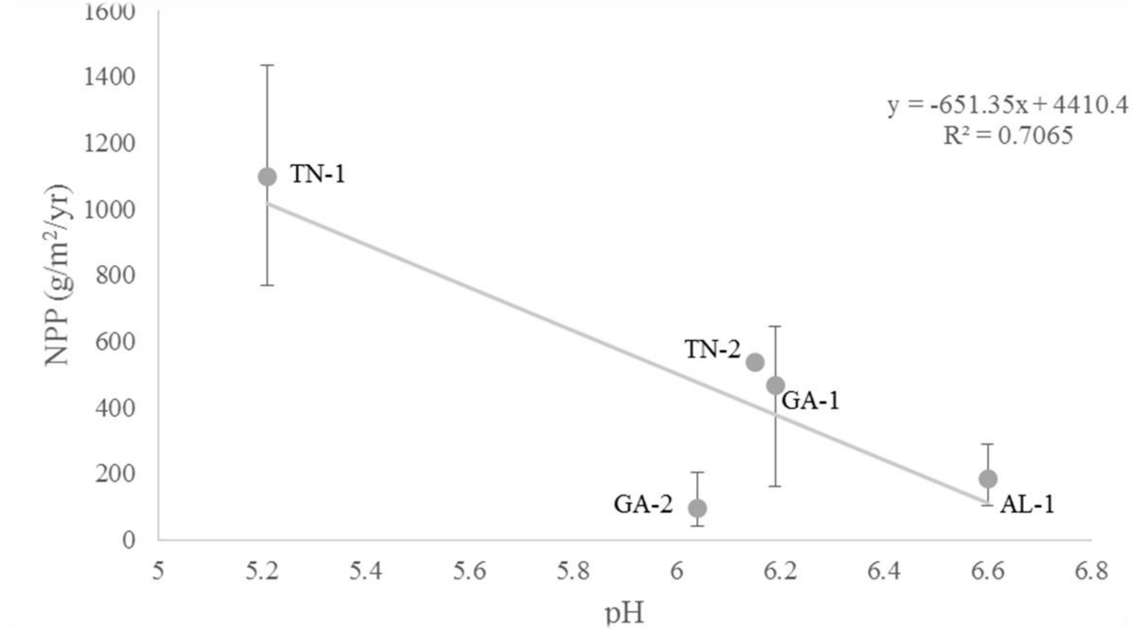

Figure 3.7 Simple linear regression between pH and NPP (g/m^2/yr).

Error bars represent the minimum and maximum NPP values (g/m^2/yr). The data point with no error bars (TN-2) was derived from one biomass sample.

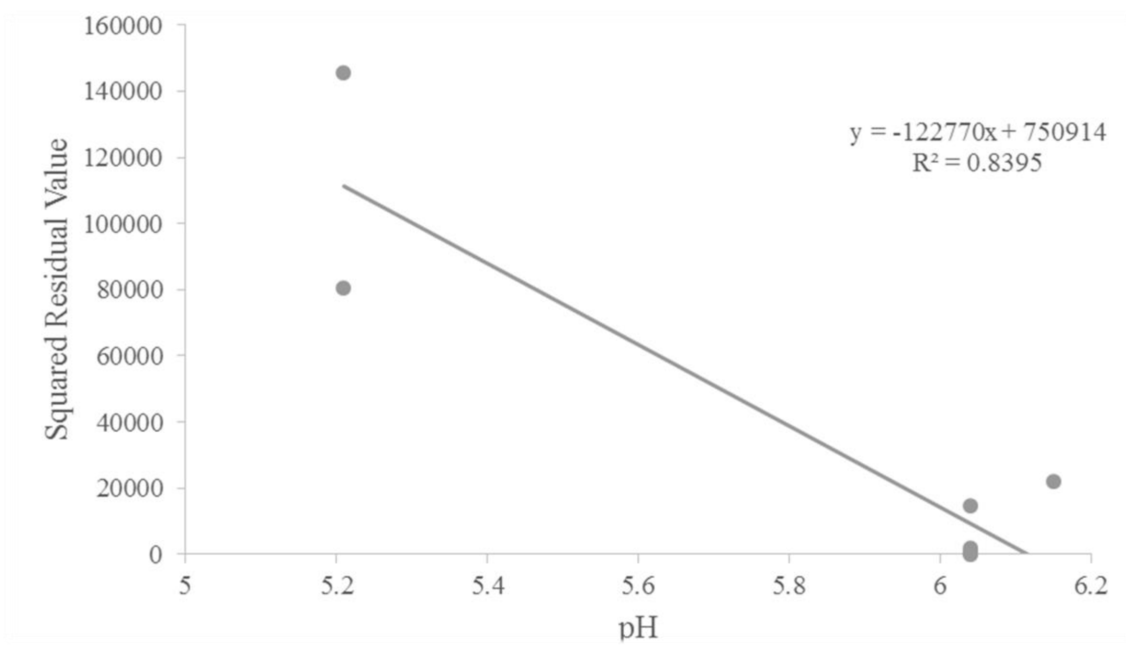

Figure 3.8 Linear regression between pH and residual NPP from the equation generated from the linear regression between discharge and NPP.

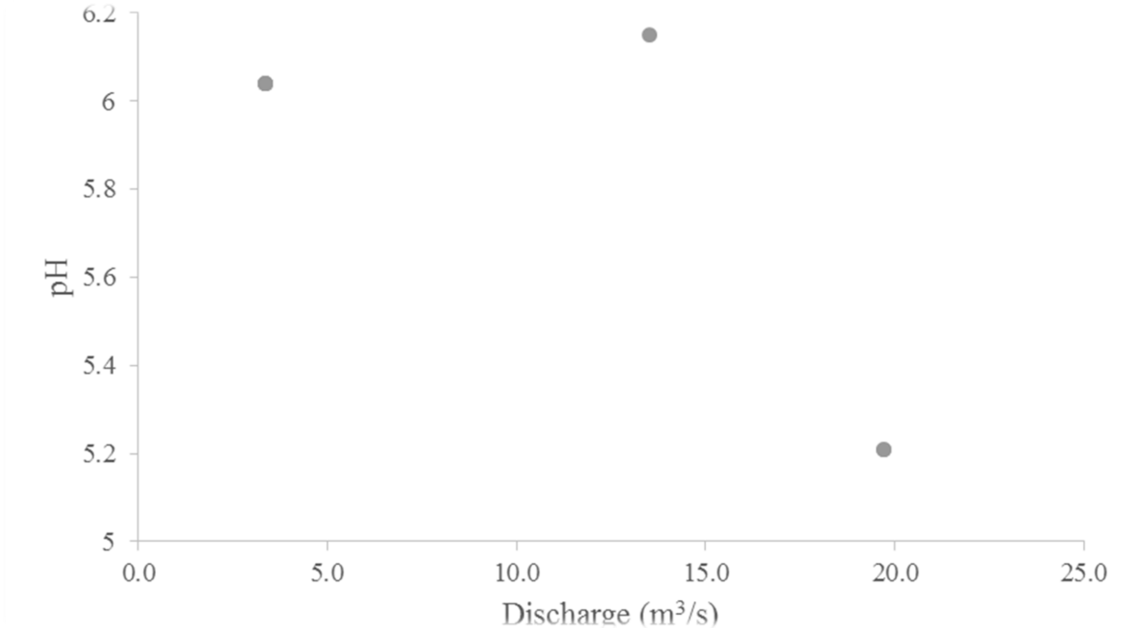

Figure 3.9 Simple linear regression between discharge (m^3/s) and pH.

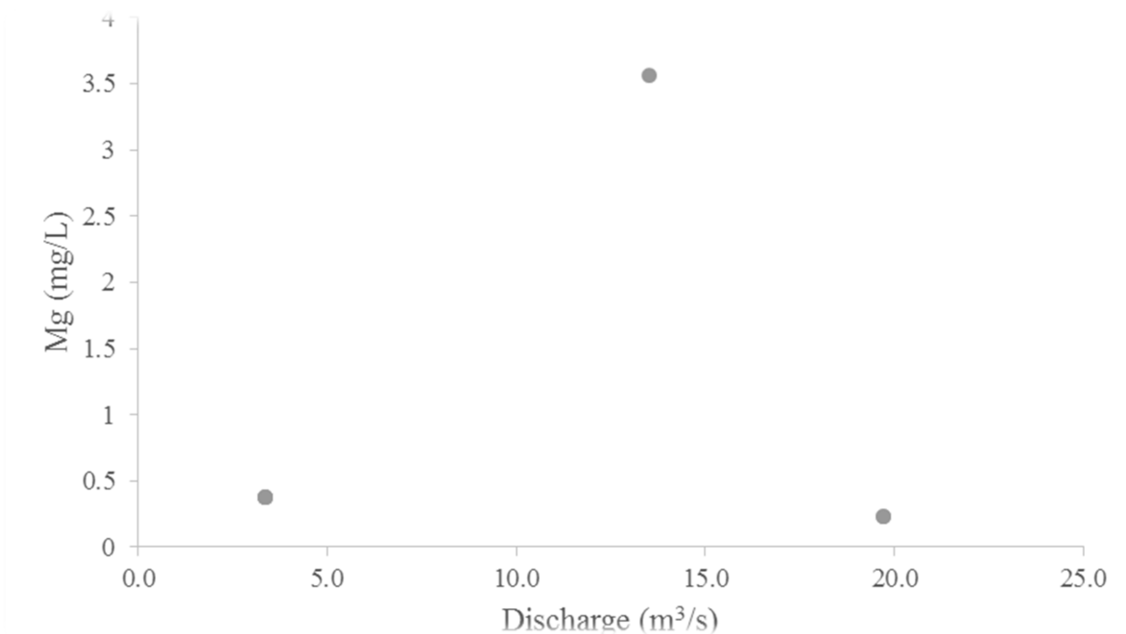

Figure 3.10 Simple linear regression between discharge (m^3/s) and Mg^{2+} (mg/L).

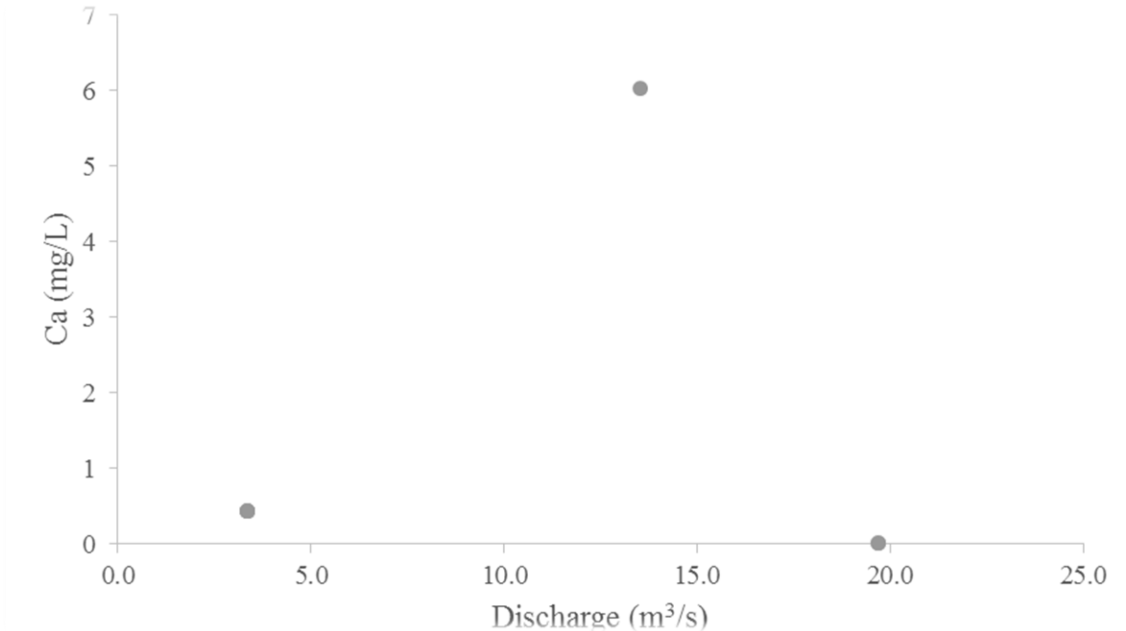

Figure 3.11 Simple linear regression between discharge (m^3/s) and Ca^{2+} (mg/L).

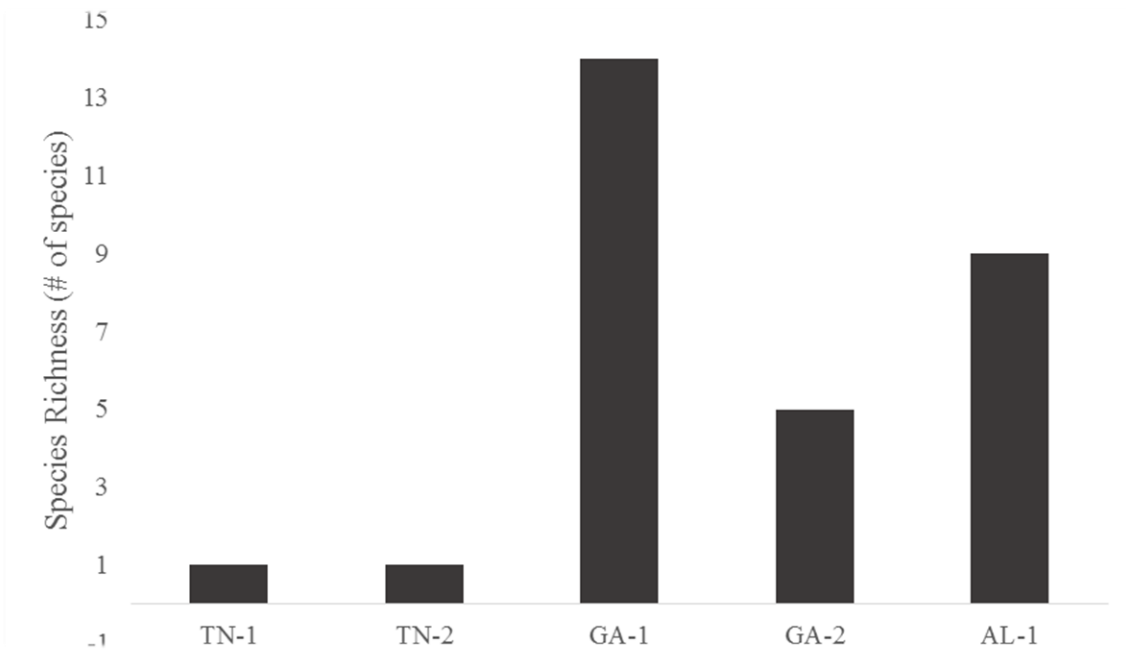

Figure 3.12 Comparison of species richness (number of species) among sites.

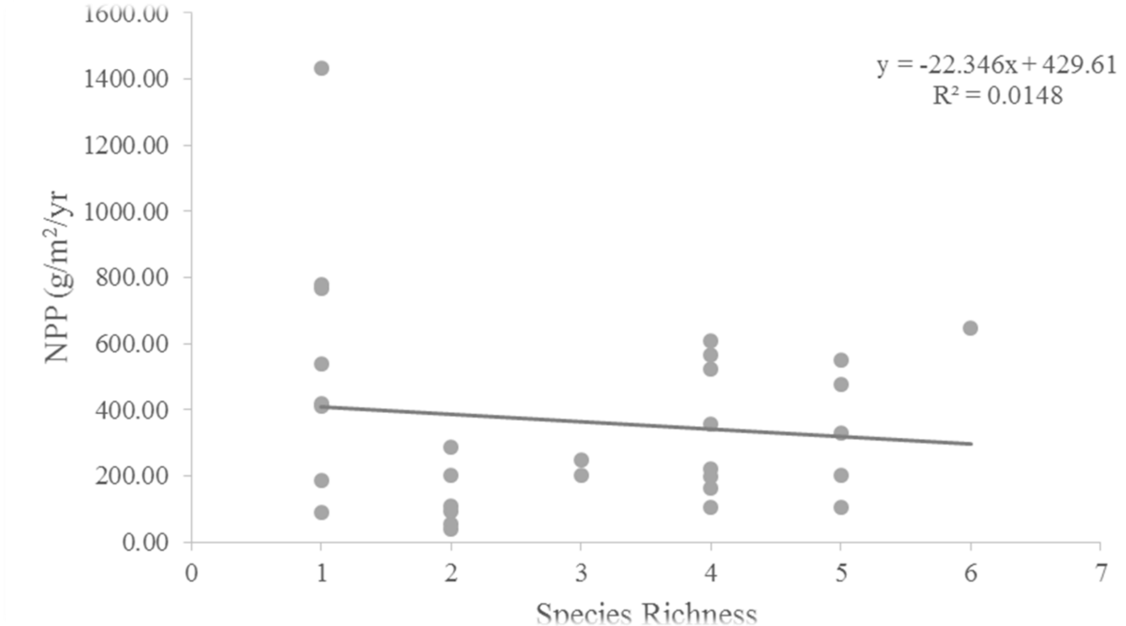

Figure 3.13 Simple linear regression between species richness and NPP (g/m^2/yr).

CHAPTER IV

ASSESSING NET PRIMARY PRODUCTION IN SOUTHERN APPALACHIAN WETLANDS FROM PROXIMAL AND REMOTE PLATFORMS

4.1 About this chapter

The chapter is a journal article that has been submitted for publication in Remote Sensing of Environment.

4.2 Abstract

Remote sensing is a powerful tool in the examination and monitoring of vegetated areas. In order to best monitor southern Appalachian wetlands, it was necessary to examine several vegetation indices in order to determine the most sensitive vegetation index. Three levels of platforms (in situ, airborne, and satellite) for sensors were also examined in conjunction with vegetation indices. Based on previous studies, the normalized difference vegetation index (NDVI), difference vegetation index (DVI), wide dynamic ranging vegetation index (WDRVI), renormalized difference vegetation index (RDVI), soil adjust vegetation index (SAVI), modified simple ratio (MSR), visible atmospherically resistant index-red edge ($VARI_{Red\ Edge}$), and visible atmospherically resistant index-green ($VARI_{Green}$) were selected. NPP data were gathered from sites in southern Appalachian wetlands along with spectral data from hyperspectral radiometers. Leaf area index (LAI) data were also gathered to provide ancillary data to two of the

vegetation indices. Along with the in situ radiometers, National Agricultural Imagery Program (NAIP) data, and Landsat 8 Operational Land Imager (OLI) data were gathered in order to calculate vegetation indices at three platforms. The most sensitive vegetation index varied with changes in platform. At the in situ level, $VARI_{Red\ Edge}$ was the most sensitive vegetation index in terms of NPP ($r^2 = 0.65$, $p < 0.05$). At the airborne level, the NDVI was the most sensitive vegetation index to NPP ($r^2 = 0.35$, $p = 0.11$). At the satellite level, the DVI was the most sensitive vegetation index to NPP ($r^2 = 0.37$, $p = 0.10$). For most indices there was a drop in the coefficient of determination with NPP when the platform altitude increased. The only exception to that decrease was NDVI when increasing altitude from in situ to airborne. Managers can use the findings from this research to better monitor southern Appalachian wetlands.

4.3 Introduction

The use of remote sensing in vegetation-related studies is a rising trend as it allows for the estimation of vegetation characteristics (chlorophyll content and net primary production, NPP) over large areas (e.g. Cramer et al., 1999). Because of the benefit of wetland analysis in a relatively small amount of time, more area can be studied with the implementation of remote sensing at a low cost. Proximal sensing, the use radiometers in the field, is becoming a larger part of the field of remote sensing than it has been previously with studies like Gitelson et al. (2003), Rundquist et al. (2004), Gitelson et al. (2006), and Mishra et al. (2012), among others.

In all of the aforementioned in-situ remote sensing studies, two inter-calibrated hyperspectral radiometers were used. This methodology was employed because the use of two radiometers allows for one to capture incoming radiation while the other captures the ground reflectance simultaneously (Rundquist et al., 2004; Gitelson et al., 2006). This practice allows for smaller errors when estimating irradiance because irradiance is being captured while the upwelling radiance is also captured, resulting in more accurate reflectance values (Rundquist et al., 2004; Gitelson et al., 2006). Computing radiance is also possible during times of inconstant irradiance (Gitelson et al., 2006), which might be a difficulty with remote sensing.

Remote sensing allows for the estimation of vegetation characteristics over large areas in a short amount of time, though error is encountered due to interactions of light in the atmosphere (e.g. scattering). Differences in platform (plane vs. satellite) might determine the amount of the aforementioned error due to the amount of atmosphere with which light must interact. Thus, using data from a plane platform for comparison to proximally sensed data might serve as an intermediate step between comparing proximally sensed and satellite data.

The National Agricultural Imagery Program (NAIP) generates plane platform data that served the purpose of this comparison. NAIP was selected among the varieties of remotely sensed data for a few reasons. The spatial resolution of NAIP data is 1 m of ground distance with ground control points within 6 m (USDA, 2013). High spatial resolution was a top priority for this study given the size of the wetlands in this study (average = 0.17 ha, n = 7) as well as the quadrats within the wetlands (0.09 m^2; Mishra et al., 2012). The other priority for remotely sensed data were the spectral resolution, specifically focusing on the need for green, red, and near infrared (NIR) bands. NAIP data records visible bands (red, green, and blue) for all states with some states having NIR data recorded as well. The NIR band is important for most, if not all, of the vegetation indices that have been generated (e.g. Gitelson et al., 2003). However, NIR is not available for all states and NAIP has low temporal resolution relative to many satellite sensors, like Landsat 8 Operational Land Imager (OLI).

While Landsat 8 OLI has limitations associated with spatial resolution (30 m) for visible and NIR bands, imagery from Landsat 8 is available at 16 day intervals (USGS, 2014). Landsat 8 OLI also offers 11 bands, including three bands covering the visible portion of the electromagnetic spectrum (band 2- blue, band 3- green, band 4- red) and NIR (band 5; USGS, 2014). With high temporal and spectral resolution, Landsat 8 OLI is provides useful imagery for management of sensitive areas, such as southern Appalachian wetlands.

Attempts to estimate biomass from remotely sensed data have been numerous (Adam et al., 2010). Over forty vegetation indices have been developed (Bannari et al., 1995) but the primary vegetation index used in remote sensing is the normalized difference vegetation index (NDVI). However, NDVI has been criticized and found to have non-linear relationships with aboveground vegetation characteristics (Myneni et al. 1995, 2002, Huete et al. 2002; Gielson, 2004). For that reason, efforts have been made to improve NDVI and develop other vegetation indices (Gitelson, 2004). The difference vegetation index (DVI) has shown the ability to explain a high amount of variance in biomass estimates ($r^2 = 0.8546$; Tan et al., 2003; Adam et al., 2010). The DVI is calculated as:

$$DVI = \rho NIR - \alpha(\rho Red) \quad 4.1$$

where ρNIR is the reflectance of NIR, ρRed is the red reflectance, and $\alpha = 0.96916$ (Richardson and Everett,, 1992; Lyon et al., 1998). The wide dynamic range vegetation index (WDRVI) was found to have the best correlation ($r^2 = 0.52$) with biomass in the coastal marsh study conducted by Mishra et al. (2012). According to Gitelson (2004), the WDRVI is calculated as:

$$WDRVI = (a * \rho NIR - \rho Red)/(a * \rho NIR + \rho Red) \qquad 4.2$$

where a serves as an estimation of the vegetation fraction (VF) and can range from 0.05 to 0.2. Other vegetation indices that have been found to have linear relationships with aboveground vegetation characteristics are the modified simple ratio (MSR; Chen and Cihlar, 1996; Gitelson, 2004), calculated as:

$$(\rho NIR/\rho red - 1)/(\rho NIR/\rho red + 1)^{1/2} \qquad 4.3$$

and the Renormalized Difference Vegetation Index (RDVI; Roujean and Breon, 1995; Gitelson 2004), which is calculated as:

$$(\rho NIR - \rho red)/(\rho NIR + \rho red)^{1/2} \qquad 4.4$$

All vegetation indices have benefits and drawbacks (Table 4.1). Methods for examining ecosystems, NPP in particular, have evolved and will continue to evolve as knowledge and technology expand.

NPP is an important indicator of ecosystem function. Gross primary productivity (GPP) is the amount of carbon (C) converted from inorganic forms in the atmosphere to part of the plant body through the process of photosynthesis. NPP is the GPP minus the amount of C lost to the environment through cellular respiration in the root system and herbivory. NPP is important because it serves as a marker of C storage as well as an indication of ecosystem function, where more productive systems will result in higher

NPP values. Thus, NPP is important as a measure of both C sequestration and ecological function. The importance of this study is, in part, tied to the importance of NPP.

The importance of this research lies in the study of NPP in montane wetlands, an ecosystem that is little studied, as well as the methods used in this study. As already discussed, NPP is an important factor to study and the development of a model that can estimate NPP in southern Appalachian montane wetlands using vegetation indices would provide a useful tool in management of montane wetlands with less disturbance. In order to create this model, we employed a methodology using proximally sensed data to help improve the accuracy of remotely sensed data for the model. The model developed in this study could be employed in other settings to also improve management, while limiting disturbance.

The objective of this study was to create a model using vegetation indices generated from remotely sensed data in order to estimate NPP to best serve in the management of southern Appalachian wetlands. Many vegetation indices were tested to provide the best estimate for NPP throughout southern Appalachian wetlands.

4.4 Study Area

Three wetland sites in the southern Appalachians, one in Alabama and two in Tennessee (Figure 4.1) were selected based on the presence of emergent wetland vegetation and the lack of forest using the Wetlands Mapper website operated by the U.S. Fish and Wildlife Service. Among the sites used in previous research (Chapters 2 and 3 of this dissertation), Tennessee and Alabama sites provided the least amount of surrounding forest cover, which was desirable for the remote sensing portion of this research. Tree cover would limit the capture of images by creating shadows or by being captured within a pixel for Landsat 8 OLI. GA-1 near Dahlonega, Georgia also met this qualification, however imagery was not available for NAIP and the Landsat data were missing brightness values, which were needed for the calculation of vegetation indices.

4.5 Methods

4.5.1 Vegetation Sampling

Leaf area index (LAI) data were collected along with peak standing aboveground biomass, which was assumed to be NPP, for each quadrat (Mishra et al., 2012). Vegetation was sampled within a 0.09 m^2 quadrat along 10-m transects for each wetland site (Mishra et al., 2012). The biomass collected from each quadrat was assumed to be NPP and NPP values were generated for each quadrat. Biomass samples were refrigerated until further analysis. For biomass sample analysis, samples were oven-dried for 12 hours at 50ºC (Mishra et al., 2012). Biomass samples were massed before and after drying. One above canopy and four below canopy LAI values were taken for each quadrat (Mishra et al., 2012). LAI served as an ancillary value for WDRVI as well as another aboveground biophysical characteristic.

4.5.2 Proximally Sensed Data Collection

Generating a spectral signature involved collecting top of canopy reflectance using OceanOptics JAZ hyperspectral radiometers (OceanOptic Inc., Dunedin, FL, USA) following Mishra et al. (2012). Each of the radiometers was calibrated for white, using a Spectralon white reference board (ASD Inc., Boulder, CO), and dark by covering the end of the radiometer. Radiance and irradiance were collected from the two calibrated hyperspectral radiometers, which were operated at least 1 m above the canopy (Rundquist et al., 2004; Mishra et al., 2012). One of the radiometers was pointed toward the sky in order to collect one sample of incoming irradiance (Mishra et al., 2012). The other radiometer was pointed toward the ground with 25º field of view (FOV) to collect one sample of upwelling radiance (Mishra et al., 2012). One signature was collected for each biomass sample by collecting one sample of irradiance and one sample of radiance from the vegetation.

After field collection of radiometer data, a reflectance value was generated for each proximally sensed data sample. Radiance and irradiance data were downloaded from the radiometers and a reflectance value was generated by dividing the radiance by the irradiance. The reflectance value generated was a measure of the percentage of irradiance that was radiated back by the vegetation (radiance) for each band, unless vegetation indices dictated otherwise (e.g. $VARI_{Green}$). Reflectance values generated from the radiometers were averaged over the bandwidths of NAIP radiometers. For example, the red band for NAIP captured by an ADS radiometer is 607-662 nm, thus the values for the reflectance of radiometers were averaged over the same range in order to generate a red reflectance for the radiometers for comparison to NAIP data.

4.5.3 Remotely Sensed Data Collection and Calibration

NAIP data were collected by downloading data from the USDA Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/). The year of the field work was used for the data collection. If the year of the field work was not available, the closest year was used. Local governments proximal to each site were contacted to inquire about data collected closer to field work dates. GPS coordinates were used to find the pixel associated with the NPP sample collection point and reflectance values for red, green, and NIR were recorded for vegetation index calculations.

NAIP imagery was calibrated using ERDAS Imagine (Hexagon Geospatial, Norcross, GA). NAIP images were calibrated using the empirical line calibration (ELC). Images were calibrated by band by using a spectral library (ASTER). Ground cover types were selected (e.g. grass, asphalt) that occurred near the site and five points were taken of each ground cover within the image. The spectral signatures for the ground points were run against the spectral library signatures for that band. A new image was generated from the ELC. Brightness values were taken from that image for vegetation indices.

Landsat 8 OLI images were downloaded from the USGS Earth Explorer website (http://earthexplorer.usgs.gov/). Imagery was downloaded for the date closest to the date of field work before field work was conducted. 40% cloud cover was the maximum cloud cover; if an image exceeded 40% cloud cover for the collection date, the image from the previous collection period was used. GPS coordinates were used to locate the pixel for each quadrat. Brightness values were recorded for blue, green, red, and NIR for each pixel in order to calculate vegetation indices.

4.5.4 Vegetation Indices

After reflectance values were generated from radiometer and brightness values were recorded from NAIP data, vegetation indices were calculated for all NPP sites using combinations of green, red, and NIR reflectance data, depending on the vegetation index equation. NDVI was employed because it is the most common vegetation index and generally accepted as the best vegetation index for estimating biomass. The MSR (eq. 3), RDVI (eq. 4), DVI (eq. 1), and WDRVI (eq. 2) were also used because success has been found in estimating biomass from these indices (Gitelson, 2004; Mishra et al., 2012). LAI was used in order to estimate for VF to calculate WDRVI. LAI values were put into 15 categories to account for the 15 values (0.05-0.2) within the range of the VF value used by Gitelson (2004) with the lowest LAI category representing 0.05 and the highest LAI category representing 0.2.

4.5.5 Data Analysis

The objectives of this study were to determine which vegetation index best identifies variance in NPP and to improve remotely sensed data using proximally sensed data. Linear regressions of the vegetation indices calculated for each sample point for in situ and NAIP data and compared to NPP will determine which of the vegetation indices was best able to explain variance in NPP. Because Landsat has coarser spatial resolution than in situ and NAIP imagery, NPP values that fell within one Landsat pixel were averaged (Mishra et al., 2012) and the vegetation index for the pixel was compared to the average NPP value within the pixel via scatter plot.

4.6 Results

4.6.1 Variability within NPP

There was a large amount of variability in NPP among sites in this chapter as well as a smaller amount of variability in NPP within each site (Figure 4.2). The range in NPP among all sites was 915 g/m^2/yr, with an NPP maximum of 1101 g/m^2/yr (sd = 470 g/m^2/yr, n = 2) at TN-1 and an NPP minimum of 185 g/m^2/yr (sd = 66 g/m^2/yr, n =9) at AL-1. TN-1 and AL-1 were also the sites in this study with the highest and lowest amount of intra-site variability, respectively.

4.6.2 NPP and Vegetation Indices

4.6.2.1 Vegetation Indices from In Situ Radiometer Data

Vegetation indices calculated from in situ radiometer data were able to explain a moderate amount of variance in NPP in southern Appalachian wetlands (Figure 4.3). The $VARI_{Red\ Edge}$ showed the most sensitivity to NPP and was able to explain the most amount of variance in NPP ($r^2 = 0.65$, $p < 0.05$), though all of the index values were negative and there appeared to be an outlier. After removing the outlier, it appears as though $VARI_{Red\ Edge}$ is not as sensitive to NPP (Figure 4.4). The SAVI was able to explain 39% of variance in NPP and the $VARI_{Green}$ index was able to explain 32% of variance in NPP. Five of the eight vegetation indices used to estimate NPP were able to explain less than 30% of variance in NPP.

4.6.2.2 Vegetation Indices from NAIP Data

Most of the vegetation indices calculated from NAIP data were unable to explain more than 10% of variance in NPP in southern Appalachian wetlands (Figure 4.5). The NDVI was able to explain 35% of variance in NPP, ranking as the most sensitive vegetation index for NAIP. The WDRVI and MSR were able to explain 8% of variance in NPP and the SAVI was able to explain 6% of variance in NPP. The DVI and RDVI were the least sensitive vegetation indices and were able to explain the least amount of variance in NPP.

4.6.2.3 Vegetation Indices from Landsat 8 OLI Data

The amount of variance in NPP by vegetation indices from Landsat 8 OLI were the lowest among all vegetation indices tested in this study (Figure 4.6). The DVI was able to explain the most amount of variance in NPP ($r^2 = 0.37$, $p = 0.10$) among vegetation indices calculated from Landsat 8 OLI. The MSR was able to explain 5% of variance in NPP. All other vegetation indices calculated from Landsat 8 OLI were not able to explain more than 2% of variance in NPP.

4.6.2.4 Trends among Vegetation Indices by Platform Level

In examining NPP by vegetation indices at three platform levels, a trend was noted for most of the vegetation indices along a change in height of the platform (Figure 4.7). Generally the highest coefficients of determination between NPP and vegetation indices were noted for the in situ radiometer. As the platform level moves from the in situ radiometer to airborne (NAIP), there is a sharp decline in coefficients of determination for all vegetation indices except NDVI, which increased from 0.28 to 0.35. The coefficient of determination for NDVI dropped sharply when the platform increased in elevation from airborne to satellite. The coefficients of determination for all other vegetation indices, except for the DVI, decreased with an increase in elevation from airborne to satellite platforms.

4.7 Discussion

4.7.1 Performances of the Vegetation Indices

There was a disparity in the ability of vegetation indices to explain variance in NPP at all levels, though no vegetation index was best able to explain variance consistently at all levels. The difference in the ability of vegetation indices to explain variance in NPP is due in part to differences in the indices themselves, but also is related to the type of vegetation and ecosystems in which the indices were employed. No vegetation indices have been developed to specifically study montane wetland NPP. Another cause for the lack of a vegetation index that was able to explain NPP variance at all three levels is that the data is different for all three levels. At the in situ level, hyperspectral radiometers were employed and thousands of bands were used at a high spatial resolution. At the airborne level, NAIP data are limited in the context of spectral resolution, though spatial resolution is still high. At the satellite level, spatial resolution is low, though spectral resolution is higher than NAIP.

At the in situ level, the $VARI_{Red\ Edge}$ was best able to explain variance in NPP, though it was only applicable to the in situ radiometers because the $VARI_{Red\ Edge}$ requires hyperspectral data. The $VARI_{Red\ Edge}$ is a useful vegetation index that was developed by Gitelson et al. (2006), which estimated canopy chlorophyll content well for maize (r^2 = 0.93). However, $VARI_{Red\ Edge}$ was not as strong at estimating NPP in this study (r^2 = 0.65).

The viability of $VARI_{Red\ Edge}$ is limited to agencies or institutions with hyperspectral radiometers and the time to conduct field work. While hyperspectral radiometers are powerful tools, the money and time associated with the equipment and data collection, respectively, makes them an unrealistic option for land management. While the in situ data generated indices that were best able to explain variance in NPP, it might not be a viable option for smaller agencies or institutions. All the other vegetation indices can be used with sensors that are equipped to measure red and NIR reflectance, though some, like the SAVI and WDRVI, require ancillary information for constants.

The SAVI was the second best vegetation index for estimating NPP at the in situ level, however the SAVI, like the $VARI_{Red\ Edge}$, requires field work to establish an L value which is based on soil exposure. The SAVI was the fourth and fifth best vegetation index for explaining variance in NPP at the airborne and satellite levels, respectively. Thus, SAVI is sensitive to NPP variations when radiometers are used in the field but it is not as sensitive at remote platforms. While the SAVI, which was developed by Huete (1988), is useful for examining reeds (Poulin et al., 2010), especially when vegetation cover is low and soil exposure is high (Zhang et al., 1997), it was not as effective in estimating NPP in this study concerning emergent vegetation. While SAVI was more sensitive to NPP than WDRVI at the in situ level, the WDRVI was the more sensitive index at the airborne and satellite levels.

The WDRVI, developed by Gitelson (2004), was most sensitive to NPP at the in situ level like most of the other vegetation indices, however it was the second most effective at the airborne level. Like the SAVI, the WDRVI also requires ancillary data and like the $VARI_{Red\ Edge}$, the WDRVI was developed for monitoring agricultural vegetation. The WDRVI requires a constant, a, which can range depending on vegetation fraction. The WDRVI was sensitive to coastal marsh vegetation biomass ($r^2 = 0.52$; Mishra et al., 2012) compared to other vegetation indices, but was not sensitive to NPP at any platform in the montane setting. It was hypothesized that the WDRVI would be the most sensitive to NPP in this study, however we reject that hypothesis given that WDRVI was not the most sensitive vegetation index at any platform. Differences in performance of the WDRVI at the coastal and montane settings might be related to the differences in the setting or the quality of the imagery. The DVI is calculated with a constant like the SAVI and WDRVI, though the constant is not based on ancillary data.

The DVI was the most sensitive vegetation index when using Landsat 8 OLI data. Similarly, Tan et al. (2003) found a high amount of variance in wetland biomass ($r^2 = 0.85$) was explained by the DVI calculated from Landsat 7 ETM+ (Adam et al., 2010). The DVI would be useful for Landsat 8 OLI data, which is available at a high temporal resolution (16 days). For constant monitoring of montane wetland vegetation, the use of the DVI calculated from Landsat 8 OLI data would serve as the best tool. The NDVI is also a good tool given a more sparsely vegetated land cover (Gitelson et al., 2003).

The NDVI, which is one of the main vegetation indices used for examining or monitoring vegetation, was the most sensitive vegetation index for NAIP data. Outside of the airborne level, the NDVI did not show sensitivity to NPP. The NDVI was one of the original vegetation indices developed by Rouse (1973) and Rouse et al. (1974; Bannari et al., 1995) and has since been modified to better estimate vegetation characteristics (e.g. WDRVI; Gitelson, 2004). The NDVI serves as a point against which to measure any new vegetation index. The NDVI serves well in any land management where vegetation biomass or LAI is low before the NDVI is saturated (Gitelson et al., 2003). Other than the problem of saturation, the NDVI would provide a useful tool for wetland management if NAIP data were used. The RDVI is a simple modification of the NDVI.

The MSR ranked as the fourth, third, and second most sensitive vegetation index at the in situ, airborne, and satellite levels, respectively. Like most of the other vegetation indices, the MSR was the most sensitive at the in situ level and decreased with increased altitude above the vegetation being examined. The MSR might be considered as an option for vegetation examination at any of the levels, especially in cases where biomass is higher. However, there are better options at every platform level.

4.7.2 Limitations

There were some limitations associated with this research. More specifically, there was a lack of sample size to examine the associations between field NPP estimates and the estimates gathered from vegetation indices. There were limitations associated with the congruence of dates between the field work and the collection of remotely sensed data. Also, there might be some differences in the season in which the biomass was collected and when the imagery was collected. For imagery with lower spatial resolution (i.e. Landsat 8 OLI), there may exist a difference in the NPP from field samples and the ecosystem NPP. There might also exists differences between scales concerning NPP and imagery.

4.8 Conclusions

This study provided valuable tools for wetland managers in the southern Appalachians and contributes to the scientific community with intellectual merit. By conducting an examination on vegetation indices and NPP, the people in charge of southern Appalachian wetlands can now make better informed decisions on how to monitor wetlands with remote sensing data. The results of this study also contribute to the scientific community by further testing vegetation indices in an environment where few, if any, similar studies have been conducted.

The choice in vegetation index depends on the platform that is being used to examine southern Appalachian wetlands. At the in situ level, the $VARI_{Red\ Edge}$ was most sensitive to changes in NPP, with SAVI and $VARI_{Green}$ also showing sensitivity toward NPP. At the airborne level, most vegetation indices saw a drop in coefficient of determination with NPP. The exception was the NDVI, which was more sensitive to NPP at the airborne level than the in situ level. All other vegetation indices were insensitive to changes in NPP. At the satellite platform, the DVI was the most sensitive vegetation index, though the DVI was more sensitive at the in situ level than at the satellite level.

Table 4.1 Summary of vegetation index needs.

Vegetation Index	Bands Needed	Ancillary Data Needed?	Can be Used with Multispectral Data?
NDVI	Red, NIR	No	Yes
DVI	Red, NIR	No	Yes
WDRVI	Red, NIR	Yes	Yes
RDVI	Red, NIR	No	Yes
SAVI	Red, NIR	Yes	Yes
MSR	Red, NIR	No	Yes
$VARI_{Red\ Edge}$	Red Edge, NIR	No	No
$VARI_{Green}$	Blue, Green, Red, NIR	No	Yes

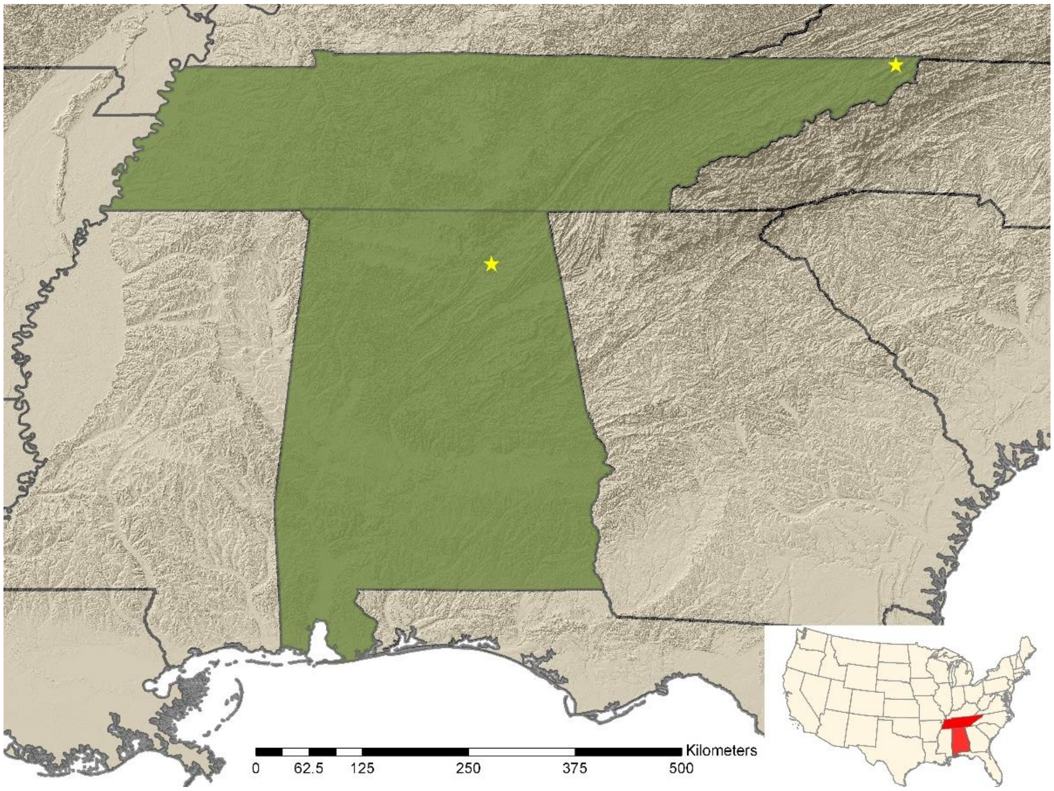

Figure 4.1 Site map for southern Appalachian wetlands in this study.

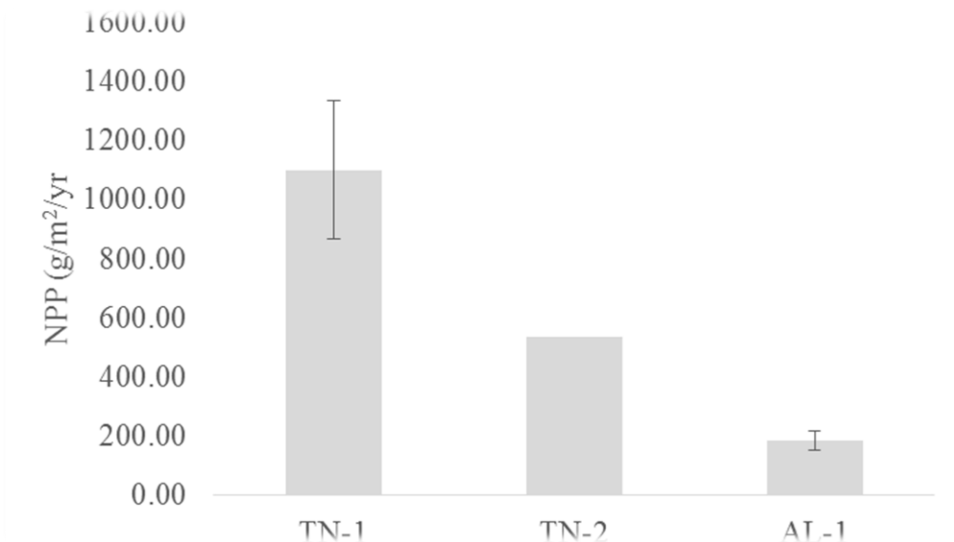

Figure 4.2 Variability in NPP among sites.

Error bars represent one standard deviation.

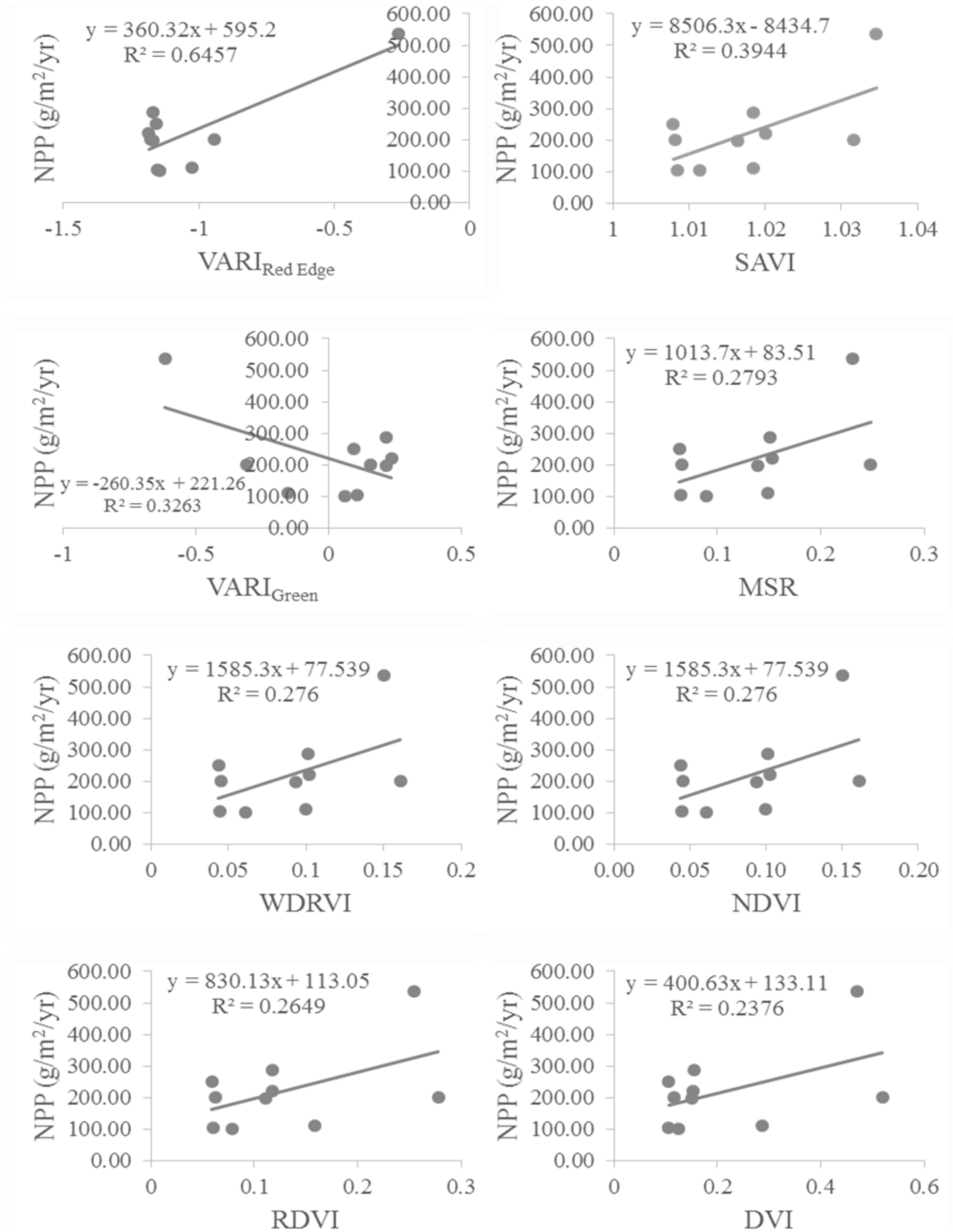

Figure 4.3 Linear regressions between NPP and the vegetation indices calculated from in situ radiometers.

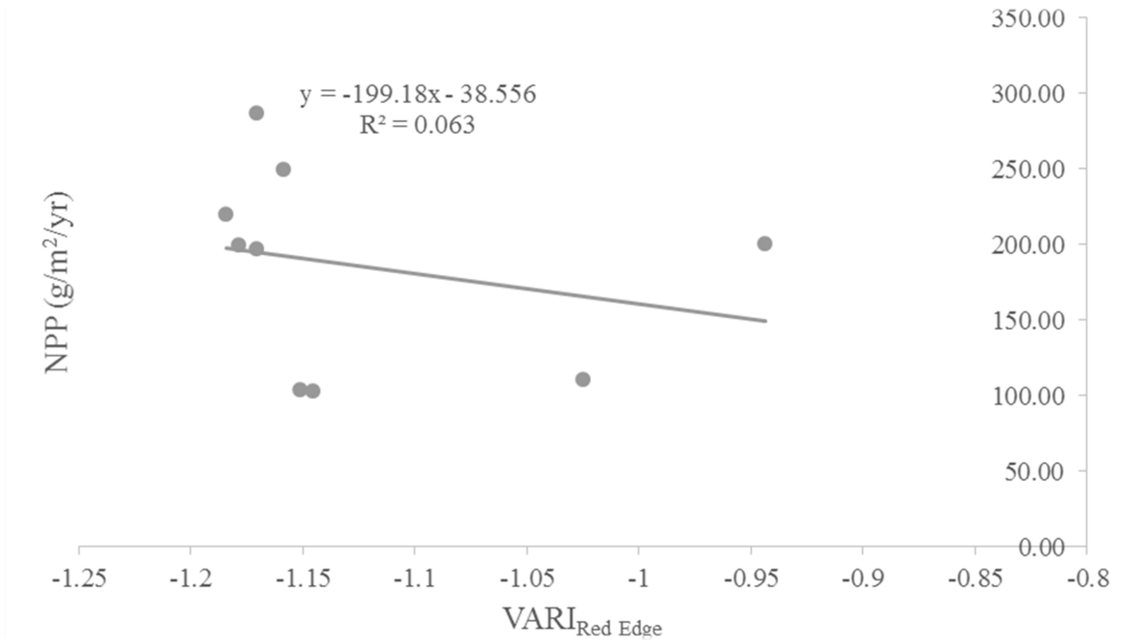

Figure 4.4 Linear regression between NPP and $VARI_{Red\ Edge}$ without the outlier.

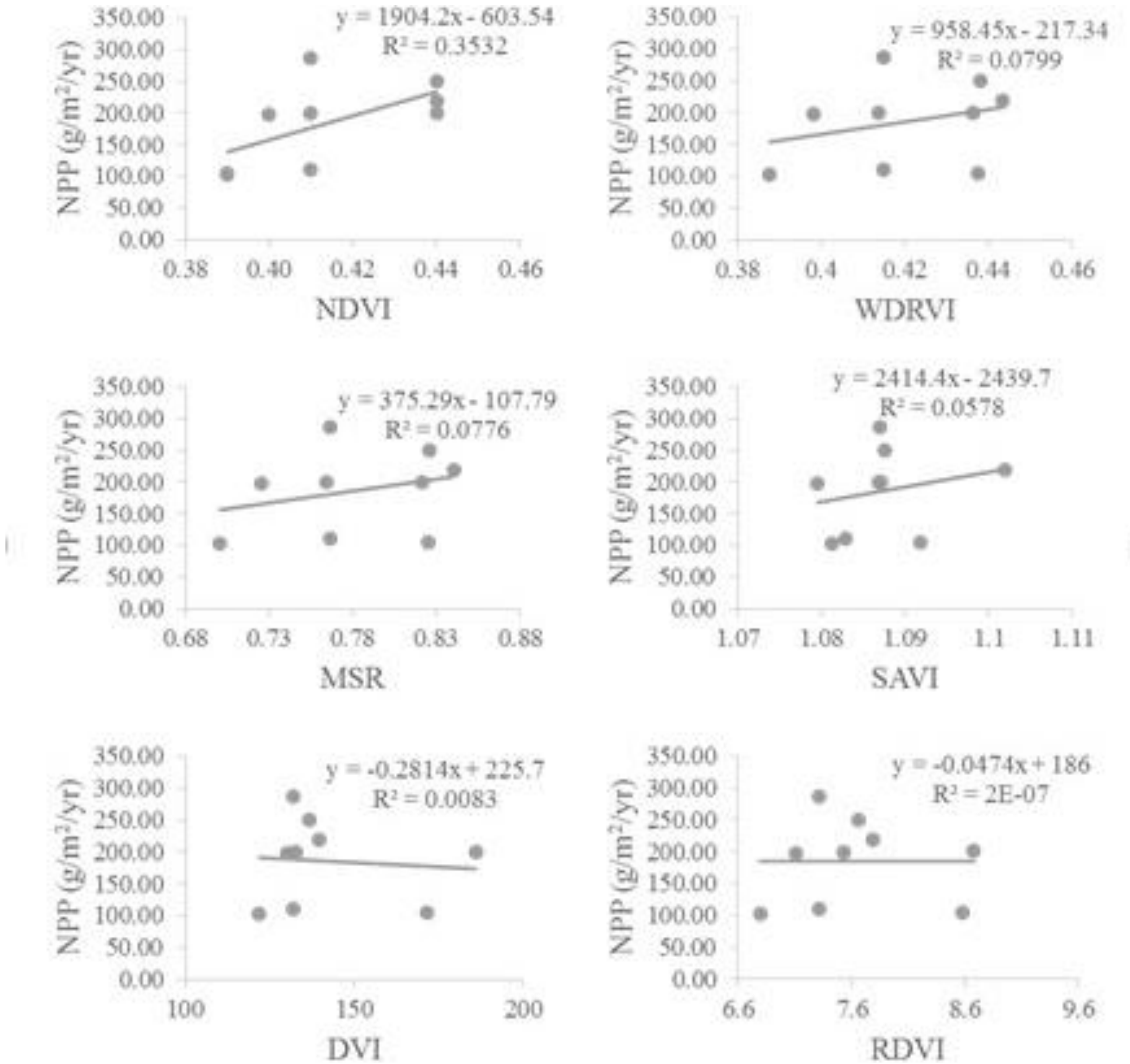

Figure 4.5 Linear regressions between NPP and the vegetation indices calculated from NAIP.

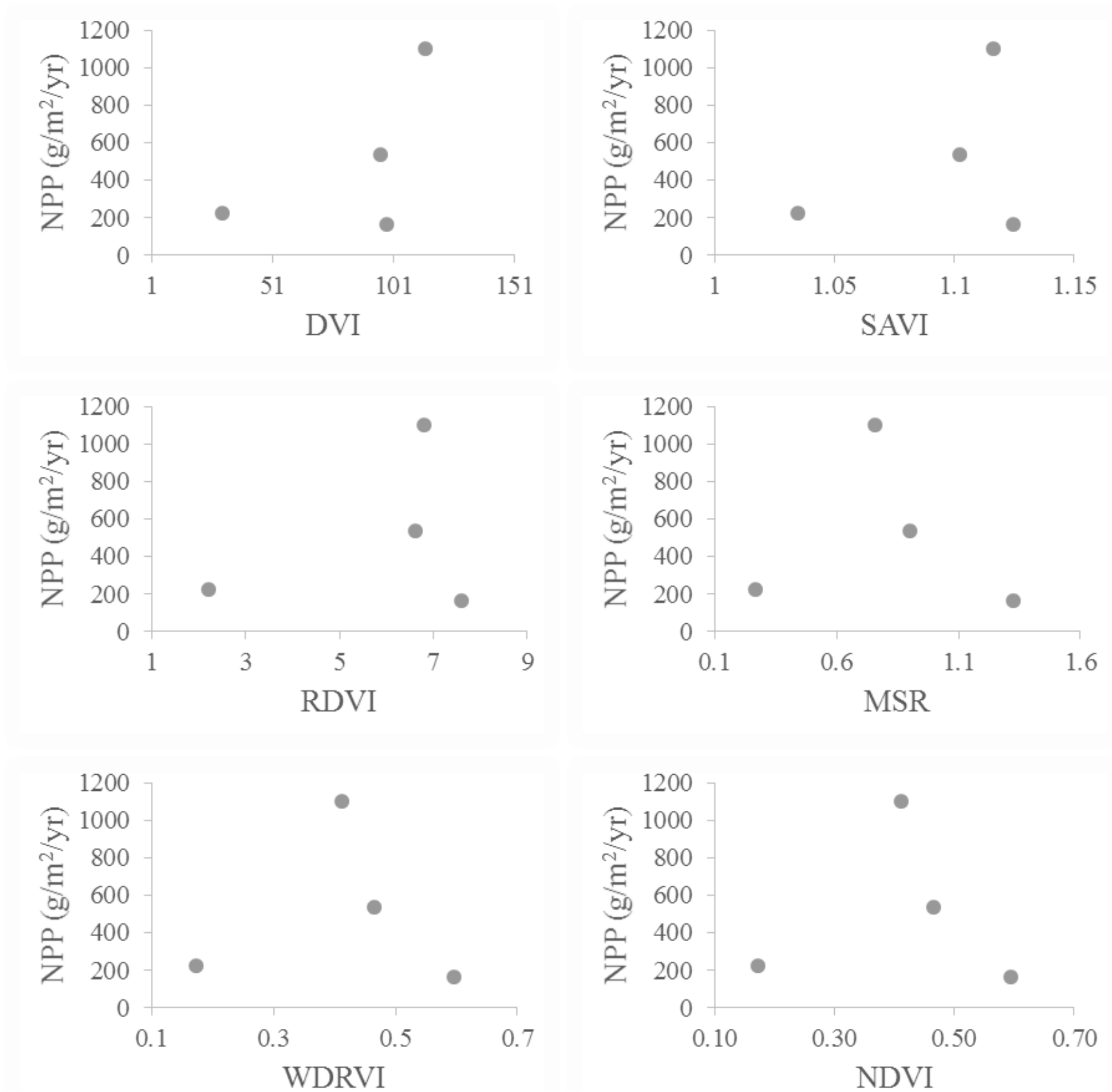

Figure 4.6 Linear regressions between NPP and the vegetation indices calculated from Landsat 8 OLI.

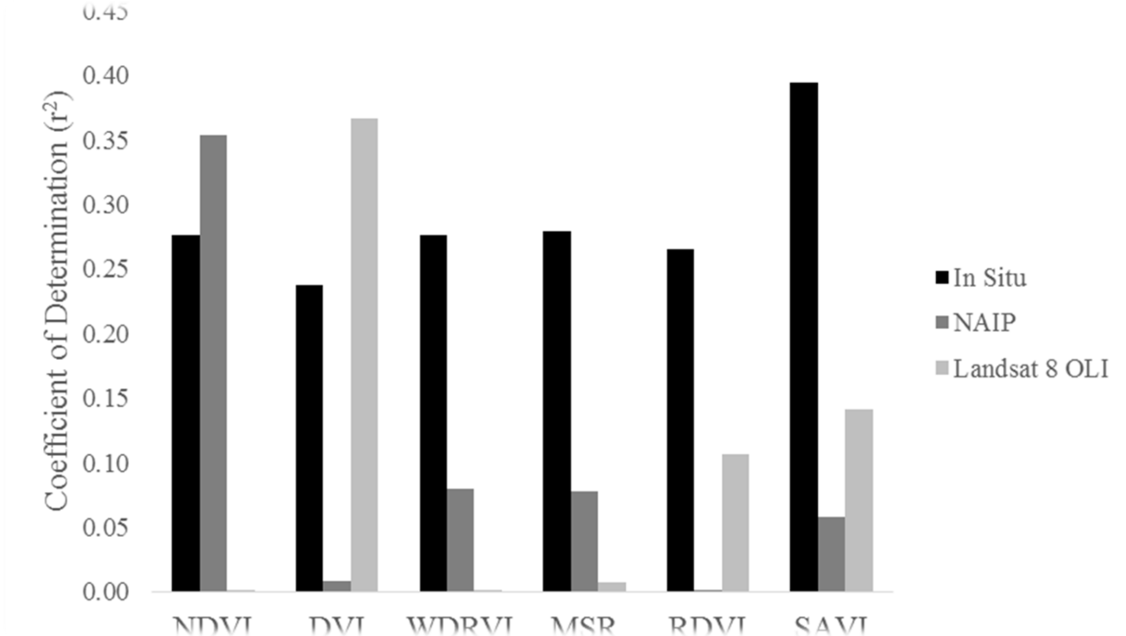

Figure 4.7 Ability of vegetation indices to explain NPP variance at the three platform levels.

CHAPTER V

CONCLUSIONS

This dissertation serves as the basis for understanding NPP in southern Appalachian wetlands. The work conducted has built a foundation of knowledge on defining the environmental factors that drive NPP in southern Appalachian wetlands (Chapter 2). This work also delved further into the environmental factors that drive NPP in southern Appalachian wetlands by examining the water chemistry of surface water and the relationship of those factors to underlying bedrock (Chapter 3). Finally, with the knowledge of what drives NPP in southern Appalachian wetlands, the dissertation shifted focus to monitoring NPP through proximally and remotely sensed data through vegetation indices (Chapter 4).

NPP in southern Appalachian wetlands is most highly correlated to discharge and precipitation, which are major parts of the hydrologic setting at each location. Hydrologic characteristics have been determined to be significantly related to NPP in montane wetlands in western North America (e.g. Dwire et al., 2004). Thus, perhaps it is a characteristic of all montane wetlands that hydrologic characteristics are important for NPP. Discharge is a factor that has been mostly absent from montane wetlands NPP literature, if not wetlands NPP literature in general. Studying discharge provides a new hydrologic factor for future wetlands work to focus on as an important NPP factor and this work provides a new theory that NPP in southern Appalachian wetlands is driven by discharge or an environmental factor closely associated with discharge. This chapter also helped to determine what needs to be done to properly manage southern Appalachian wetlands. In a more global context, this study put southern Appalachian wetlands in context as far as C storage.

By continuing work on stream characteristics, specifically the chemistry of the surface water, it was determined that pH was the water chemistry factor most highly correlated to NPP. Further analysis by removing stream discharge and examining the relationship between pH and the residual NPP that stream discharge could not predict verified the relationship between NPP and pH. Ca^{2+} and Mg did not have strong relationships with NPP. Herbaceous wetland plants are adapted to acidic conditions, thus more acidic conditions, provided by acid rain (Sullivan et al., 2004) which keeps stream levels high and acidic as well, might relieve or reduce the amount of stress that the plant undergoes so that the plant might be more productive and store more C. This research provided a further examination into an area in the southern Appalachians where little research has been done on NPP. Further examination continued to add knowledge for local management of wetlands in the southern Appalachians and for knowledge on impacts of nutrients on NPP in wetlands. This research also provided an analysis of how the aforementioned nutrients varied with changes in underlying bedrock, which is research that has only been conducted in montane wetlands in one other study.

Vegetation indices from remotely sensed data were examined because simply understanding what environmental factors have relationships with NPP is not sufficient to monitor the wetlands. Better understanding how the wetland is functioning can be tied to remote sensing, which also allows for monitoring without disturbance. The $VARI_{Red\ Edge}$

was the best vegetation index for in situ data, however the cost of the hyperspectral radiometers needed and time needed to conduct studies makes them an unrealistic choice for managers of southern Appalachian wetlands. At the airborne level, NDVI was the most sensitive vegetation index to NPP. At the satellite level, the DVI was the most sensitive vegetation index. The use of different platforms allows for managers to make more informed decisions. If the budget is large enough, in situ vegetation indices aided in calculating the most sensitive vegetation indices in terms of NPP. If the budget of the manager is smaller and monitoring can take place once every two years, NAIP data and the NDVI should be employed. If time and money are both factors, then the DVI calculated from Landsat 8 OLI data would serve best. Examining vegetation indices in montane wetlands is an uncommon practice, but testing vegetation indices at three levels is rare, making this research novel.

Future work could continue on the research conducted in Chapters 2, 3, and 4. Future work could build off of the work conducted in Chapter 2 and examine water table levels to determine if the intermediate step between precipitation and discharge (groundwater) has an impact on NPP. Research that could build off the work conducted in Chapter 3 could widen the focus on nutrient availability to N and phosphorus (P). Also, more research could be done to focus on the acidity of precipitation and groundwater. Finally, more research could be conducted to test the viability of the vegetation indices for sensitivity to NPP over several growing seasons and at higher temporal resolution.

The research conducted adds significantly to the scientific knowledge of southern Appalachian wetlands by examining environmental factors that can influence NPP. The findings of this research suggest that hydrologic characteristics, specifically discharge and precipitation to a lesser extent, were the factors that most highly influenced NPP in southern Appalachian wetlands. These findings are similar to research conducted on montane wetlands in the western United States. Further examination of the stream water yielded another novel finding that the pH of the water was most likely what was determining the contribution of the stream water to the wetlands. Finally, the examination of southern Appalachian wetlands by remote sensing yielded methodologies for managers of these unique wetlands to follow to monitor the ecological function without having to introduce new disturbance in the form of field work.

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