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Evaluating the Efficacy of Normalized Difference Vegetation Index for Monitoring Restoration Goals in the Shark River Slough, Everglades National Park

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EVAULATING THE EFFICACY OF NORMALIZED DIFFERENCE
VEGETATION INDEX FOR MONITORING RESTORATION GOALS
IN THE SHARK RIVER SLOUGH, EVERGLADES NATIONAL PARK

By

Juan Pedreno II

A THESIS

Submitted to the Faculty

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Juan Pedreno II

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<u>Evaluating the Efficacy of</u>
<u>Normalized Difference Vegetation Index</u>
<u>For Monitoring Restoration Goals in the</u>
<u>Shark River Slough in Everglades National Park</u>

Abstract of a thesis at the University of Miami.

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In 2000, the United States Congress passed the Comprehensive Everglades
Restoration Plan (CERP). Its focus is aimed at realigning the current hydrologic
patterns of the greater Everglades watershed to historical hydro-cycles. Particularly,
various restoration efforts being considered all concentrate on improving water flow
towards the southern portion of the ecosystem. One component was the construction of
a one-mile bridge in 2013 (the Limited Revaluation Report ("LRR") Bridge) as part of
the Tamiami Trail Modification Project (TTMP). The LRR Bridge is the first phase of
a planned 6.5-miles of bridging of the Tamiami Trail, which acts as a barrier to the
historic north to south sheet flow of the Everglades. If successful, the LRR Bridge
should result in increased photosynthetic activity, particularly during the dry season, as
a result of the increased penetration of water through the Shark River Slough.

This thesis seeks to assess whether MODIS-derived Normalized Difference
Vegetation Index (NDVI) serves as an effective tool to monitor long-term impacts of
the Tamiami Trail Modification Project on the ecosystem of the Shark River Slough.
Analysis of the relationship between ΣNDVI and water level yielded mixed results.

Strong correlations, with low r^2 values, were observed for all sites combined and when analyzed on or off slough. However, a site-specific analysis generated mostly weak correlations and yielded few clear patterns. MODIS-derived NDVI generated from 2002-2015 was then used to quantitatively examine trends in water level and photosynthesis. An examination of pre- and post-construction of the bridge yielded spatially comprehensible patterns. Pre-construction patterns show that negative slope was pervasive throughout the slough, but there is evidence that year-on-year increases in ΣNDVI are discernible post-construction. Positive trends in the Northeast Shark River Slough suggest that MODIS-derived NDVI has the potential to spatially evaluate ecosystem changes in order to quantify progress. Finally, this thesis concludes that these results can help guide new adaptive management strategies, specifically as they pertain to the next 2.6 mile bridge under consideration.

DEDICATION

This thesis is dedicated to all whose passion and fierce commitment to Everglades'
restoration efforts inspired me to explore and conduct this research. For those who have
supported me through this endeavor, I hope that this thesis serves as a testament to my
lifelong commitment of preserving the incredible treasure that is the river of grass.

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ABBREVIATIONS AND ACRONYMS

ANPP	Annual Net Primary Productivity
CERP	Comprehensive Everglades Restoration Plan
DEM	Digital Elevation Model
EAA	Everglades Agricultural Area
EDEN	Everglades Depth Estimation Network
EFA	Everglades Forever Act (1994)
ENP	Everglades National Park
LRR	Limited Reevaluation Report
MODIS	Moderate Resolution Imaging Spectroradiometer
MWD	Modified Water Deliveries
NESRS	Northeast Shark River Slough
NDVI	Normalized Difference Vegetation Index
P	Phosphorous (as in P-loading)
TS	Theil-Sen
TTMP	Tamiami Trail Modifications Project
USGS	United States Geological Survey
WCA	Water Conservation Area
WL	Water Level

CHAPTER I
INTRODUCTION

Problem Definition

Until the 20ᵗʰ century, the Everglades watershed had experienced insignificant anthropogenic alteration, owing to its vast extent (covering the lower third of the state) and inaccessibility (Lodge 2010; Gunderson and Light 2006, Grunwald 2006; Milon and Scrogin 2006; Chimney and Goforth 2001; McCally 1999). Records indicate a limited presence of indigenous populations, such as the Calusa and Tequesta, occupying the region's coastal highlands and rivers. Yet, the vast expanse of *Cladium jamaicense* (Sawgrass) prairies, freshwater sloughs and other diverse ecosystems that comprise the core of the Everglades ecosystem remained hydrologically intact until the early twentieth century (Lodge 2010; Grunwald 2006; McCally 1999; Hann 1991).

Subsequently, the literature amply documents the effects large-scale dredging and detrimental water management practices have had on the present day ecosystem. Strategies prior to World War II were based on management regimes focused on water drainage and land use transformation to increase access to dry land. Yet, the literature suggests a shift in practices after 1945 (Lodge 2010; Moorhead et al. 2010; Rutchey et al. 2008; Grunwald 2006; Waitley 2005; Chimney and Goforth 2001; Kiker et al. 2001; McCally 1999; Davis and Ogden 1994). Post war urbanization schemes sought to switch previous, highly transformative dredge-and-fill practices, to diverting water in large volumes, opening up newly dry land for agricultural and urban development (Lodge 2010; Grunwald 2006; Waitley 2005; McCally 1999; Davis and Ogden 1994).

Map 1.1 reveals the spatial extent of these interventions, with major extensification of water control features from Lake Okeechobee to Florida Bay. This paradigm shift restricted large-scale development across the Everglades but had severe impacts on the water cycles within the ecosystem. Despite local opposition from activists such as Marjorie Stoneman Douglas, increasing human population pressure and water management schemes throughout the subsequent decades culminated in a series of striking ecological disturbances (Douglas 1947). These included desiccation of marshes, loss of tree islands, disappearance of species, and invasions by non-native plants and animals, which motivated a renewed approach to Everglades' ecosystem management (Harvey et al. 2010; Lodge 2010; Grunwald 2006; Sklar et al. 2005; Kiker et al. 2001; Davis and Ogden 1994).

According to several authors, this current phase emphasizes management strategies that prioritize restoration efforts aimed at increasing resilience (Gerlak and Heikkila 2011; Lodge 2010; Gunderson and Light 2006; Grunwald 2006; Sklar et al. 2005; Ross et al. 2003; Kiker et al. 2001). Central to this reprioritization is the rehabilitation of water sheet flow to mimic the historical patterns of the Everglades watershed. Given the present extent of urbanization in South Florida and the intensive anthropogenic influence exerted over the ecosystem's functionality, restoration is likely to achieve only an approximation of the historic flow (Grunwald 2006; McCally 1999; Davis and Ogden 1994). Thus, contemporary restoration efforts are aimed at reducing flood risk while maximizing the magnitude of water flow south towards Florida Bay.

Lake Okeechobee

WEST PALM BEACH CANAL

S-3 S-2

S-5

L-1

L-25

Everglades Agriculture Area

HILLSBORO CANAL

L-7

West Palm Beach

L-2

MIAMI CANAL

NORTH NEW RIVER CANAL

WCA1

L-40

L-3

L-6

S-6
S-10E
L-39
S-10D S-10C S-10A

I-4 S-8 L-5

S-7

WCA2A

S-39

L-28

WCA3A North

L-38W L-38E

L-36

L-28I L-28

S-339

S-11C
S-11B
S-11A

S-144 S-145 S-146
L-35B
WCA2B

S-38

L-35A

Alligator Alley

S-140 C-60

L-123

S-141

L-3 5

L-68A

L-37

S-340

SOUTH NEW RIVER CANAL

Big Cypress Preserve

WCA3A South

S-9
L-33

C-304

Ft. Lauderdale

Atlantic Ocean

L-28

S-344

L-67A

S-337

S-31

L-67C

L-30

Tamiami Trail

L-28

WCA3B

S-343A
S-343B

S-333

S-335

S-12A S-12B S-12B S-12D
S-346
S-347

L-29

S-334

L-31

Miami

Everglades National Park

L-67 EXT.

G-211

"L" = Levee
"S" = Structure
■ Pump Station
Urban Area

S-331
S-173
L-31

South Dade Conveyance System

S-174 S-176

S-332
S-175

S-177

L-31W

S-178
C-111E

S-18C

C-111

S-197

N
W E
S

10 5 0 10
Kilometers

Map 1.1: Water management features built across South Florida, 1900-1970. Source: Sklar et al. 2001.

Viable restoration of the Everglades requires an understanding of its scope and an assessment of the projects aimed at increasing flows to historical levels. This presents difficulties, as research into this area is limited, despite an undertaking the size and complexity of CERP. Remote sensing offers a cost-effective alternative to biomass and other forms of ecological sampling, which is often highly labor intensive and expensive (Rutchey et al. 2008; Kiker et al. 2001). The analysis in this study can thus add tools for measuring the success of restoration projects, by documenting vegetation changes. If successful, it would also provide a consistent source of future and historical data, revealing temporal and spatial trends.

One component is the Tamiami Trail Modifications Project (TTMP). Approved by Congress in 2009, the project included the construction of a 1-mile bridge ("2008 LRR Bridge") and road improvements (shown fully completed in Figure 1.1). Central to its goal, the LRR Bridge will allow for 1,848 cfs peak flows into the park, representing a 47% increase over current conditions (National Park Service). As demonstrated by Map 1.2, the preferred implementation of TTMP plans for another 5.5 miles of roadway to be bridged, in addition to elevation of the existing roadbed. Therefore, data obtained by assessing the performance of the LRR Bridge may be critical to bolstering support for the plan (Gerlak and Heikkila 2011; Kiker et al. 2001; Turner et. al 2000). However, there is no guarantee that remote sensing methods provide a viable option to assess the bridge's impacts. Recent studies make use of techniques such as NDVI to investigate spatial and temporal changes in photosynthetic activity of wetlands (Adjei et al. 2015; Dong et al. 2014; Clerici et al. 2012).

Figure 1.1: The LRR Bridge on Tamiami Trail (construction: 2010-2013); enhancing water flow south into the ENP by allowing flow under the east-west barrier of Tamiami Trail.

Analysis of NDVI used in other works provides one way to gauge how remote sensing for the monitoring of restoration goals may perform. Using satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra, this thesis evaluates whether NDVI metrics can be use d to assess vegetative trends at varying temporal and spatial scales. Lastly, a comparative analysis of their value will also reveal the extent to which they provide a feasible and cost effective strategy in monitoring the stated restoration goals of the TTMP.
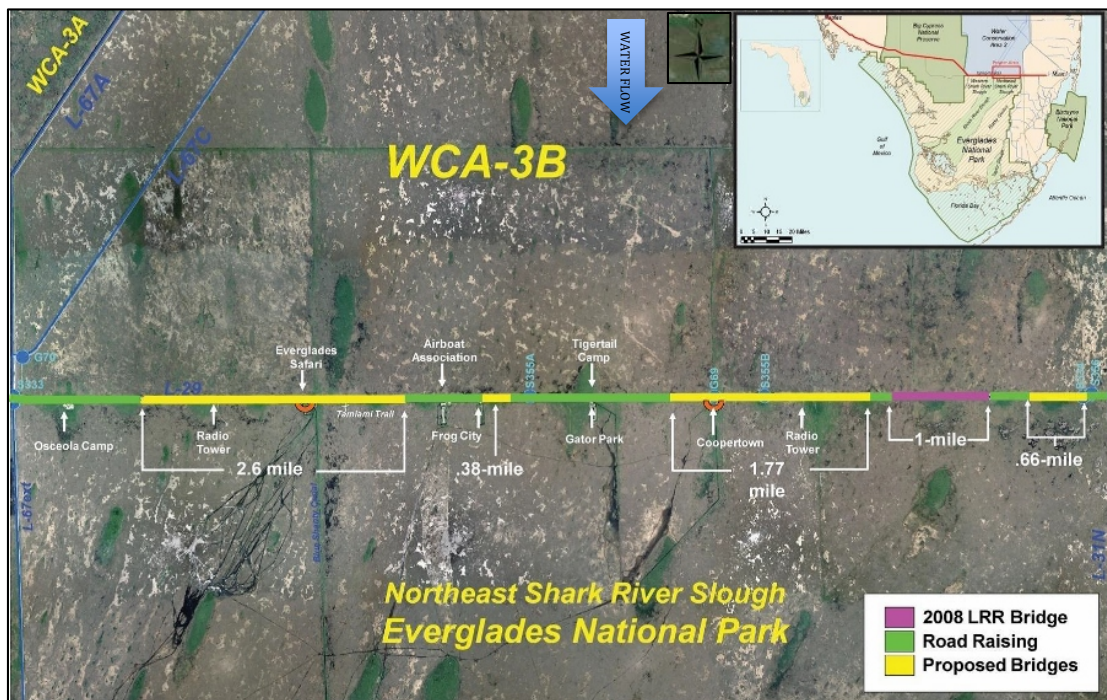
Map 1.2: TTMP Map outlining the preferred improvement plan (known as 6e) for the 10.7 mile stretch of Tamiami Trail, as of February 2015. The existing bridge is the 2008 LRR Bridge. The next proposed bridging is a 2.6 mile portion on the western side of the modification area.

Source: National Park Service.

Comprehensive Everglades Restoration Plan

The interconnected nature of the ecosystem and loss of resilience caused by human intervention had negative consequences. As excessive fires raged, fueled by dried *C. jamaicense*, wells began pumping up saltwater and wading birds abandoned (a 90% decline) or cannibalized their young (Grunwald 2006; Sklar et al. 2005; Kiker et al. 2001; Ogden 1994). Incidentally, other portions of the Everglades suffered from a reciprocal effect. Levee and canal construction redirected increased water flow to areas unsuited to sustaining such conditions. According to some authors, this affects ground-surface water interactions and increases upward mixing and discharge of saltwater, harming freshwater plant and animal communities (Fuller and Wang 2014; Harvey et al. 2010; Lodge 2010; Sklar et al. 2005).

Since its inception, the literature depicts human intervention in the Everglades as focused on controlling its critical resource: water (Lodge 2010; Grunwald 2006; Gunderson and Light 2006; Sklar et al. 2005; Chimney and Goforth 2001; Davis et al. 1994). Studies estimate that this intervention reduced the spatial extent of the Everglades over 50% (Grunwald 2006; Milon and Scrogin 2006; Chimney and Goforth 2001; Kiker et al. 2001; Sklar et al. 2001). Maps 1.3 A and B contrast a recreation of how the sheet flow in the ecosystem operated prior to the late 19th century to its current disjointed form. Map 1.3A shows the vast extent of the *C. jamaicense* prairies and slough as the spillover of water from Lake Okeechobee navigates towards Florida Bay. In comparison, Map 1.3B shows how compromised the current landscape has become after more than a century of intervention. The spillover plains south of the lake have been eradicated in favor of agricultural interests. Moreover, the growth of the coastal

plain occurred at the expense of draining the eastern wall of the slough. This resulted in the previously continuous *C. jamaicense* slough being compartmentalized via canals and levees. Central to this thesis' analysis was the construction of the L-29 (Tamiami Trail) canal and levee from 1915-1928, which given its size and orientation directly impeded the North-South water flow of the ecosystem (Lodge 2010, Sklar et al. 2005; Rizzardi 2001; McCally 1999; Davis and Ogden 1994).
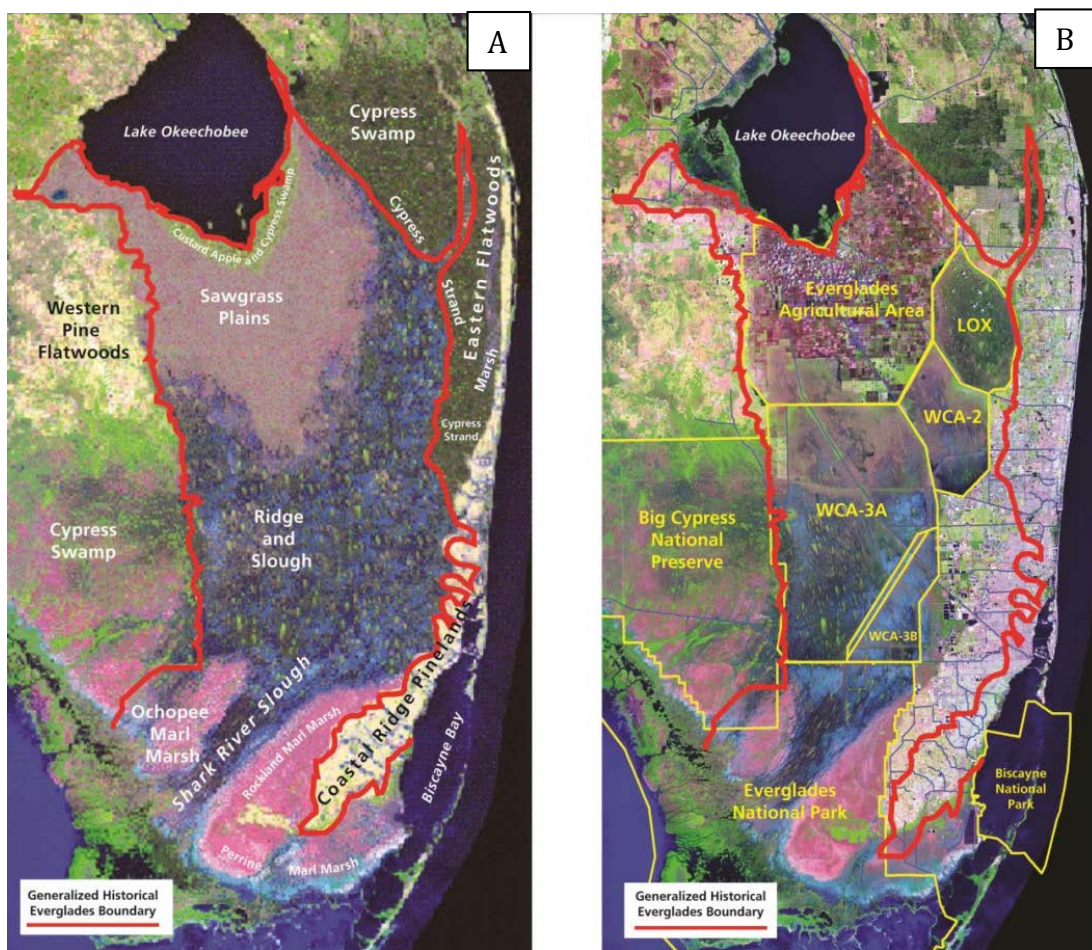
Map 1.3: A: Rendition of the pre-drainage water flow across South Florida. **B**: Present day composition of the alterations to the landscape, showing the compartmentalized water flow via canals, levees and roadways. Courtesy of the National Park Service: (Mitchell and Johnson 2015).

Modern considerations for what would become the Comprehensive Everglades Restoration Plan (CERP) emerged by 1989, after 107,600 acres of land in the Northeast Shark River Slough (NESRS) were added (Lodge 2010). Driving the acquisition were concerns over the deterioration of the Shark River Slough, owing to the uneven delivery of water from the Water Conservation Areas (WCA) 3A and 3B. Map 1.1 illustrates the problem, as the L-67 A levee bisects WCA 3A and 3B, leaving the latter water limited. This affects the ENP below, where the NESRS, defined as the area south of Tamiami Trail and east of the L-67 EXT levee, suffers from constricted flow. By 1992, the Modified Water Deliveries (MWD) project has been enacted to begin restoration of the NESRS. However, litigation regarding the scope and funding of the project quickly mired its prospects (National Park Service (MWD) 2016; Lodge 2010). Meanwhile, support for CERP emerged from a federal lawsuit citing negligence on behalf of the state in managing the restoration effort, whereupon the Florida Legislature passed the landmark 1994 Everglades Forever Act (EFA) (Lodge 2010; Grunwald 2006; Chimney and Goforth 2001).

Enacted in 2000, the authors describe CERP as an unprecedented culmination of cooperation between federal, state, regional, local and tribal actors (National Research Council 2013; Lodge 2010; Grunwald 2006; Chimney and Goforth 2001; Kiker et al. 2001). Encompassing 68 separate component projects, over three decades and costing 8-10 billion dollars, the aim of the plan is to realign water management across the watershed to reestablish a more natural sheet flow (Gerlak and Heikkila 2011; Lodge 2010; Rutchey et al. 2008; Sklar et al. 2005; Kiker et al, 2001). In addition, the cost of the construction, maintenance and operation of the projects is uniquely split

evenly between the federal and state government (Doyle 2001). As a holistic enterprise, CERP seeks to undo decades of compartmentalization, identifying engineering projects with shared goals seeking to improve water flow and maintain public safety (Gerlak and Heikkila 2011; Sklar et al. 2005). Thus, the following key components are necessary to achieve this safety-restoration dichotomy (National Research Council 2013; Lodge 2010; Sklar et al. 2001):

- Emulating pre-drainage, hydrologic patterns without compromising required flood protection and ensuring the right "quantity, timing and distribution of water." Achieve by removing barriers to sheet flow through canal backfilling, de-compartmentalization, upgraded pumping stations and elevated roadways and bridges (such as the LRR Bridge).

- Using the WCAs, storage reservoirs and controls at Lake Okeechobee to increase storage capacity of water reservoirs while redirecting overflow towards Florida Bay.

- Reduction of water loss from the system via improved seepage management, particularly near flood prone sites. Recharging the Biscayne aquifer to prevent saltwater intrusion.

- Improvement of water quality, particularly in reduction of P levels and discharges from industrial and agricultural actors in the Everglades Agricultural Area (EAA).

Despite the promise of such a through restoration initiative, implementation of CERP has struggled since its congressional authorization in 2000. The literature (Gerlak and Heikkila 2011; Lodge 2010; Layzer 2008; Grunwald 2006) details the

project delays, poor funding, lack of compliance by agricultural industries and lobbying at the state level that have stymied progress. Additionally, some authors (Gerlak and Heikkila 2011; Lodge 2010; Doyle 2001) note the difficulty of advancing such ambitious proposals where stakeholders at the local, state and federal level clash over project priorities and legal enforcement. While progress has been slow, CERP's survival more than fifteen years after approval yields promise that some of its goals will be realized.

Adaptive Management and NDVI Assessment

As local officials and the scientific community coordinated efforts to engineer restoration projects, a paradigm shift in water management strategy occurred. An adaptive assessment process, or adaptive management, was implemented to oversee application of CERP. As a strategy, it seeks to improve the function of a system by integrating performance measures. Data collected from these assessments is subsequently integrated into a management scheme, allowing for quick corrections and reducing uncertainty. (Milon and Scrogin 2006; Sklar et al. 2005; Doyle 2001; Kiker et al. 2001). By monitoring the ecosystem and how it responds to fluctuations (natural or engineered), adaptive management enables scientists and officials to assess the progress of restoration projects, such as the LRR Bridge.

This flexibility has been a defining feature in the execution of CERP. Research has demonstrated that adaptive management has also reduced ecological uncertainties and trade-offs in ways that prevented the impediment of critical projects (Sklar et al. 2005; Kiker et al. 2001). Its application has extended beyond the Everglades to state agencies

in a variation named adaptive governance. Explored by Gunderson and Light (2006), this method increases government responsiveness and reorganizes communication between agencies to better prepare for crises. Measures such as these allow for optimization of resources and are vital for bolstering the ecosystem's resilience.

Kiker et al. (2001) notes the LRR Bridge's role as an initial step in a larger bridging operation, making assessment of its performance critical to the project's integrity. Rutchey et al. (2008) reinforces this concept, arguing "cost effective mapping efforts will play a critical role" in the allocation of funds moving forward. Adaptive management of the TTMP would benefit from temporal and spatial data collection of the bridge's initial impacts on the NESRS. Spatial representation of those results, particularly in the form of maps and other figures, can distill complex scientific results into a more accessible format. NDVI monitoring thus serves as a potential tool to guide future management decisions.

A precedent for utilizing NDVI in wetland assessments can be found in various studies (Adjei et al. 2015; Dong et al. 2014; Steyer et al. 2013; Wang et al. 2013; Clerici et al. 2012; Rani et al. 2011; Ordoyne and Friedl 2008; Guo and Chen 2007; Santos-González 2002; Narumalani et al. 1999). It is often applied to classification of wetland plant biodiversity, owing to its cost effectiveness and high temporal availability of satellite imagery (Clerici et al. 2012; Rani et al. 2011). More recently, it has become a valuable tool for ecosystem monitoring and management (White et al. 2016; Steyer et al. 2013; Guo and Chen 2007). When corroborated with field assessments and data verifications, these studies find Landsat and MODIS NDVI to be accurate and effective (Adjei et al. 2015; Dong et al. 2014; Steyer et al. 2013).

However, research and field verification of biomass and land cover is sparse for the NESRS site and northern Shark River Slough. Gaiser and Childers (2011) conducted studies of above ground *C. jamaicense* biomass for the Florida Coastal Everglades Long Term Ecological Research Center from 2001 until 2010. However, four of the sites examined were immediately south of Tamiami Trail, resulting in just one site (SRS-2) within the slough area examined in this study. Furthermore, the time periods of the data collection varied significantly, some sites contain data for only one year while others for eight years. Biomass data was not obtained after 2010, limiting the ability to assess the impacts from the bridge.

Large scale mapping efforts as detailed by Rutchey et al. (2008) and Welch et al. (1999) in the 1990s provide some insight into vegetative species distributions, but NDVI performance for the Shark River Slough has yet to be evaluated. Moreover, studies have indicated that NDVI is not without limitations. The availability of reliable, annual cloud free imagery, particularly for Landsat, can be a challenge in tropical climates and atmospheric factors can affect NDVI by introducing significant noise in NDVI image series (Santos-González 2002).

Further, Adeji et al. (2015) and Wang et al. (2013) found that hydrological changes may not correlate well with NDVI values. This is partially explained by the sensitivity of NDVI to mixed pixels, where elevated water levels limit reflectance from vegetation. Conditions such as these can also be heightened by the coarse resolution of MODIS imagery (250m). Ultimately, NDVI and other spectral indices derived from satellite observations, if effective, may add an additional layer of insight into implementation of the TTMP.

CHAPTER II

PROFILE OF SHARK RIVER SLOUGH VEGETATION

The greater Everglades ecosystem historically consisted of a network of marshes, *C. jamaicense* prairies, hardwood hammocks, cypress strands and coastal mangrove forests spread out over 10,000 km^2 (Lodge 2010; Rutchey et al. 2008; Grunwald 2006; Chimney and Goforth 2001; Sklar et al. 2001; McCally 1999; Davis and Ogden 1994). Figures 2.1-2.4 demonstrate the present day vegetation cover (natural communities defined by plant associations) of the Everglades. Historically, the Shark River Slough developed a distinctive "ridge and slough" topography owing to the slow velocity of the sheet flow (Lodge 2010; Armentano et al. 2002). Vegetation that was less flood tolerant grew on the ridges, and the slough portions remained perennially hydrated. Vegetation distribution is also dependent on fire, soil depth and hydroperiod (defined as the amount of time vegetation is submerged annually). Minor changes in these variables affect species diversity and vegetation cover, with ±10cm soil depth and ±90-day hydroperiods serving as a catalyst for differentiation (Lodge 2010; Grunwald 2006; Chimney and Goforth 2001; Sklar et al. 2001).

Vegetation in the Everglades can be divided into forested and non-forested communities. Non-forested vegetation are concentrated in prairies, marshes and sloughs, with *C. jamaicense* (Figure 2.1) representing 70% of the vegetation cover in the Everglades. Well adapted to tolerate hydroperiods from <6 to 10 months, *C. jamaicense* forms dense clusters >2 meters in height on deeper peat soils while sparser, shorter clusters (<2 m) grow in limited water and soil (Lodge 2010 Ross et al. 2003).

Figure 2.1: *C. jamaicense* prairie with bayheads visible in the background. Note the matted periphyton in the foreground due to low water levels. This photo was taken in early February of 2013, on the western edge of the Shark River Slough.

Figure 1.2: Bald cypress strand at low water levels. With their buttressed trunks, these grow in dome-like clusters in areas deeply submerged for more than six to nine months (Casey and Ewell 1998).

Figure 2.3: Higher elevations are associated with communities that are flood intolerant, such as Pine Rocklands. Fires are necessary to prune back ground cover vegetation and prevent succession by hardwood species (Ruiz et al. 2013).

Figure 2.4: Tree islands in the Shark River Slough. Species diversity, typically high, is a function of their size and successional history. They are susceptible to fire during extreme droughts as well as prolonged flooding (Ruiz et al. 2013).

Alterations to the flow in the ENP have impacted species' productivity and resilience (Toth 1987). High water levels (between >60-90cm depending on plant height) result in diminished productivity or mortality (Richardson 2008, Roth et al. 2003). This is often a result of oxygen deficiency for soils and submerged root systems, as high inundation prevents *C. jamaicense* from transporting oxygen to its roots (Sklar et al. 2000). Conversely, rapidly fluctuating or diminished water levels can increase fire potential and plant stress (Sklar 2000; Toth 1987). Prolonged drought allows flood tolerant shrubs and invasive plant species to spread into *C. jamaicense* marshes, while quickly rising water levels submerge recently burned prairies, converting them to open sloughs (Sklar et al. 2000; Ross et al. 2003; Hofstetter and Sonenshein 1990). Stable, slightly shallow (30-50 cm) water regimes are thus ideal for quick regeneration and high cumulative leaf biomass (Richardson 2008; Sklar et al. 2000). They also promote root depth up to 50cm, an increase from 20cm in higher water conditions (Toth 1987).

Along the ridges and adjacent bedrock depressions, tree islands form (Figure 2.4). Tree islands with upland sections are hardwood hammocks, found in deep peat soils on elevations high enough to be the only perennially unflooded areas along the slough (Armentano et al. 2002). Characterized by their biodiversity, larger hardwood trees proliferate alongside extensive underbrush shrubs. Tree Islands are also an indicator of desired hydrologic conditions in the Everglades, as they are sensitive to dynamic water levels (Porter 2001; Sklar et al. 2000). Prolonged submergence can drown woodier species and increase penetration of herbaceous vegetation, while severe drought can fuel intense fires that exterminate all shrubs and trees (Richardson 2008; Sklar et al. 2005; Ross et al. 2003; Porter 2001). Bayheads, in contrast, form in slightly

lower elevations and experience a moderate hydroperiod (< 6 months). They are dominated by shrubs such as *Ilex Cassine* (Dahoon Holly) and *Chrysobalanus icaco* (Cocoplum) able to withstand seasonal flooding (Armentano et al. 2002). Wetter bayhead swamps that develop in bedrock depressions exhibit open canopies, while smaller trees typically form as a tail emerging from an upland hammock.

Alterations to the sheet flow of the Shark River Slough through decades of human intervention created a disproportionate hydration scheme, mostly affecting the over drained NESRS. This has resulted in an artificial compartmentalization of the slough, fragmenting once continuous wetlands and altering flow velocity, leading to a degradation of the ridge and slough pattern (Harvey et al. 2010). Figure 2.5 provides examples of barriers such as levees, canals and roads that cause fragmentation. Canals and levees, such as the L-67 EXT which bisects the northern Shark River Slough, create pools of water too deep to support diverse plant communities (Harvey et al. 2010).

Levees allow the spread of invasive species along the northern Shark River slough by providing artificially connected ridges (Harvey et al. 2010; Zellmer and Gunderson 2008). In particular, *C. jamaicense* prairies and marshes adjacent to these structures and the Tamiami Trail roadway have been colonized by *T. Latifolia*, as evidenced by the Welch et al. (1999) map. Tolerant of high submergence, their expansion is encouraged by P-loaded water from the EAA (Gucker 2008; Richardson 2008; Ross et al. 2003). Combined with stress from low water levels, *T. Latifolia* can succeed native vegetation and maintain a competitive advantage during flooding (Richardson 2008; Sklar et al. 2000). Even with low oxygen stress, *T. Latifolia* net photosynthesis and biomass tend to be greater than *C. jamaicense* (Porter 2001).
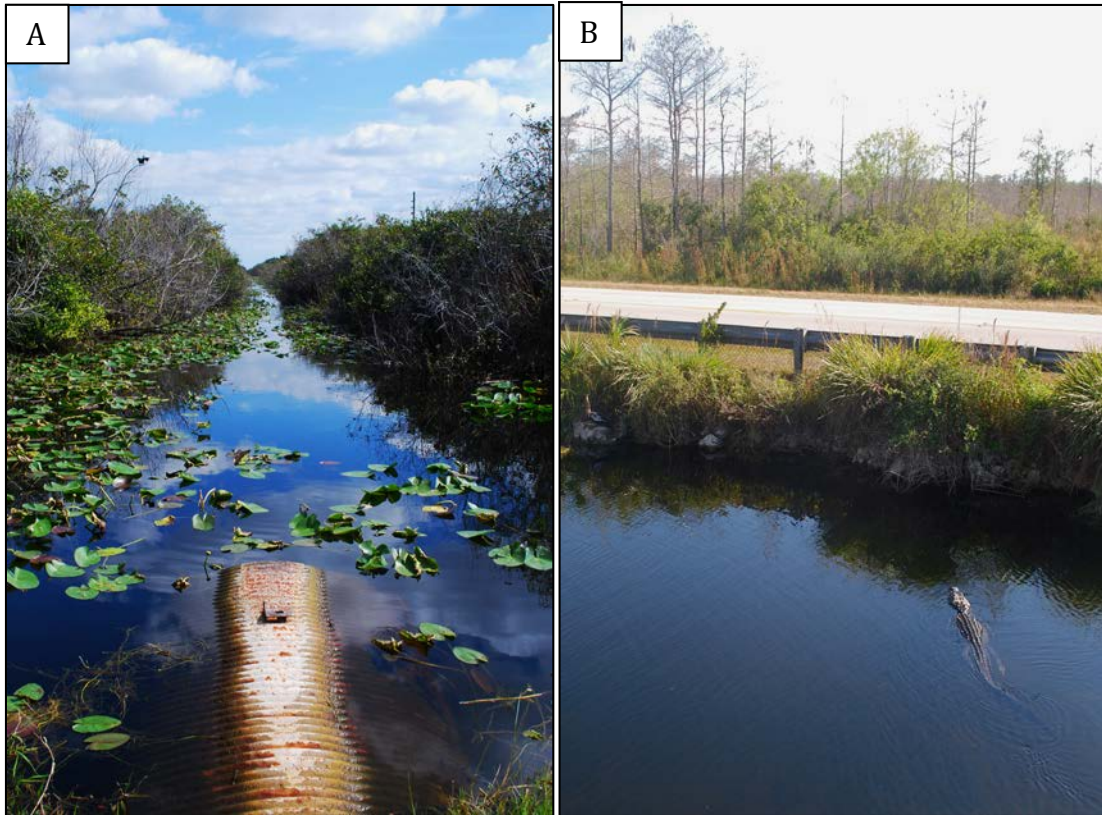
Figure 2.5: A.) Water flow is redirected via the complex system of canals and gates. This photograph shows the exit of a culvert, used to allow water to flow under the Tamiami Trail road. **B.)** View of US-41 (Tamiami Trail) from across the C-4 canal. The canal produces hydrological discrepancies, causing prolonged flooding north of the road while depriving the ENP south of needed water.

Deep water depressions along the slough act as buffers to wildfires, concentrating them in communities where they act as an abiotic control (Gucker 2008; Newman et al. 1998). However, areas south and east of the TTMP experience reduced water flow, making them over reliant on rainfall in the dry season to keep slightly hydric conditions. *C. jamaicense* and other marsh vegetation can withstand fire as survival of the root structure is the main component necessary for regeneration (Wu et. al 2008). However, frequently low water levels expose *C. jamaicense* and the underlying soils to more frequent and intensified fires (Kiker et al. 2001; Newman et.

al 1998). Furthermore, shortened hydroperiods and hydrologic stress in the southern and eastern portions of the NESRS have allowed succession of *C. jamaicense* by monotypic strands of *Salix caroliniana* (Coastal Willow) and the invasive *Melaleuca quinquenervia* (Armentano et al. 2002; Hofstetter and Sonenshein 1990). Both species tolerate hydroperiods of ~3 months (past seedling establishment) and mature trees can withstand drought owing to extensive root systems (Hofstetter and Sonenshein 1990).

Alterations to the hydrologic regime have produced changes in the volume, distribution and timing of water flows within the Shark River Slough (Mitchell and Johnson 2015; Miller et al. 2004; Lodge 2010). Pre-intervention, the Shark River Slough east of the L-67 EXT levee (Map 1.1) transmitted 2/3 of the sheet flow south into the ENP. Now, it accounts for less than 1/3 of the water inputs into the slough (Lodge 2010; USACE Jacksonville). Instead, unnaturally heavy volumes of water are arbitrarily diverted towards the western half of the slough through S-12 gages (Map 1.1) (Miller et al. 2004). Figure 2.6 shows the trends in total discharge amounts under the Tamiami Trail leading up to CERP in 2000. The light blue represents discharge rates into the ENP west of the L-67 EXT levee and the fuchsia corresponds to areas east, in the NESRS. Prior to the 1990s, plans to leave the gates open and allow water to flow into the ENP based on a hydraulic gradient largely backfired, as declining rates worsened dry conditions in the park (Miller et al. 2004). Since then, efforts to increase discharge volume have led to fluctuating amounts, stressing vegetation up-slough. Also notable is the low ratio of water flowing through the NESRS (L-30 to L-67) compared to the western slough. Though the early 1990s experienced increases, levels have since been depressed, prompting the TTMP efforts to restore more flow (Miller et al. 2004).
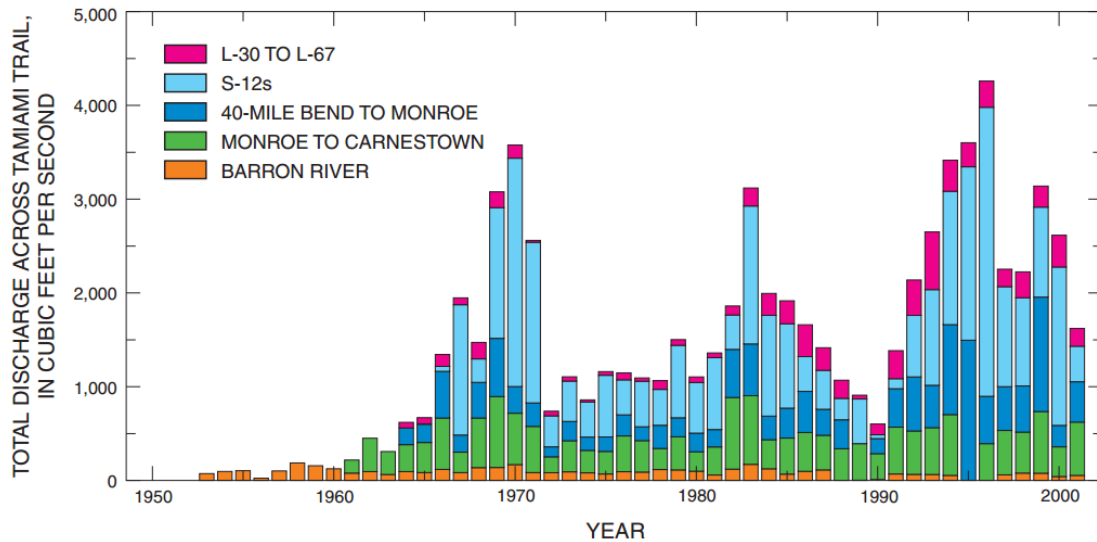
Figure 2.6: Total discharge under Tamiami Trail until 2001 (Miller et al. 2004)

Disproportionate water flow along the Shark River Slough has resulted in wetland loss, decreasing the water storage capacity of the ecosystem and increasing susceptibility to flooding and drought (Sklar et al. 2000). Pre-drainage hydrologic patterns favored limited dry periods, where soils remained moist, supporting germination and establishment of native species able to survive when water levels rose (Richardson 2008). However, decades of mismanagement have decreased wetland elevation, "flattening" the ridge and slough topography. Sklar et al. 2000 explain peat accumulations that previously averaged 0-2 feet above the bedrock in *C. jamaicense* prairies are now often less than a foot deep. Additionally, water levels in these prairies used to range between 1-3 feet above these peat surfaces, but now typically range from <0 to 2 feet above the peat (Sklar et al. 2000). Similar trends of declining water depths and reduced hydroperiods are found throughout the Everglades, particularly in marl prairies off of the slough (Sklar et al. 2000).

Figure 2.7 compares dry season water level trends across four sites. NESRS2 and G-3272 are both located in the NESRS, where reports indicate more than 3 feet of peat soils were lost since 1946 to oxidation and fire (CEPP EIS 2014). To prevent peat loss to oxidation, water levels should not drop by a foot or more below ground for > 30 days and the total range should not fluctuate much year-on-year (Porter 2001; Sklar 2000). Currently, dry season water levels for the NESRS range from 1 foot above to 3 feet below ground level, less than the 3 to -1 foot range pre-drainage (Sklar et al. 2000). This is evident in Figure 2.7, where G-3272 in particular rarely has water present above ground (1.67 meters) and suffers during extreme droughts, most notably in 2009 and 2011.

NESRS2, situated on the northeastern extent of the Shark River Slough, also suffered from declining water levels since 2002, though its proximity to the Tamiami Trail and lower elevation (1.27 meters) prevented the severe water deficit visible at G-3272. Low levels at both sites and fluctuations in yearly ranges corroborate findings of peat loss in the area. In contrast, there is evidence southern portions on the Shark River Slough may have been less affected by the structural alterations up north (Ross et al. 2003). Data from NP202 and P36, located south of the NESRS (along the slough), uphold those findings, exhibiting a more stable and reliably hydrated water regime. Water levels do not often drop below ground in either site, though lower water levels and elevation appear to make P36 more susceptible. In addition, the range for both is relatively constant, a stark contrast from sites in the NESRS.
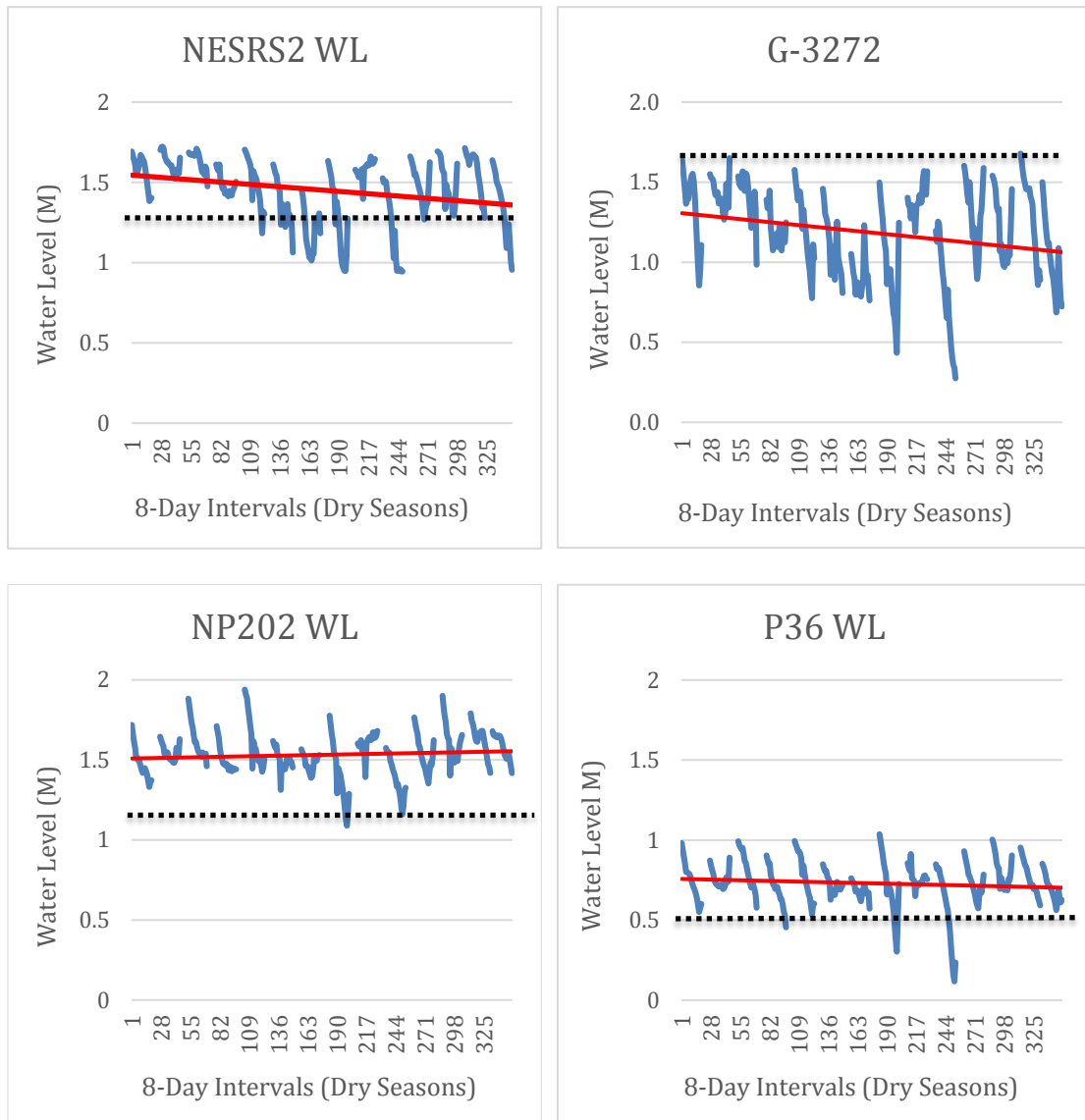
Figure 2.7: Graphs of four EDEN gages depicting water levels in the dry seasons (January-May) from 2002-2015. The red line represents trends during the 13 years observed; black dotted lines indicate the ground elevation in NGVD at each site.

Historically, vegetation in the Everglades was well adapted to respond to dynamic hydrologic conditions since annual precipitation totals across the region have always fluctuated (Lodge 2010). However, this resilience was bolstered by a topography which has been altered substantially. Extended periods of low precipitation,

such as from 2007 to 2011, stress the ecosystem by leaving flooded conditions only in the deepest portions of the slough (Lodge 2010). Water levels for 2014 were consistent with recent positive trends, except for declines in G-3272. Comparatively, 2015 showed large declines in water levels for sites in the NESRS. Precipitation totals for 2013 and 2014 in Figure 2.8 explains some of this variation. Both were optimal years for rainfall totals, each falling within the desired "normal range" of roughly 58 inches for South Florida. Maintaining proper hydroperiods requires these inputs to be unevenly distributed, with an average of ~23% occurring during the dry season and the remaining ~77% during the wet season (Brandt et al. 2014). For 2014, dry/wet season inputs were roughly 26% and 74%, indicating consistency with the average. Additionally, neither 2013 nor 2014 were influenced by El Niño or La Niña conditions (Brandt et al. 2014). Evaluation of precipitation totals in the ENP from the SFWMD demonstrated consistency with results in Figure 2.8, with the park district receiving 14.5 inches, or 94% of its historical average (SFWMD Rainfall Historical, January-May 2014).
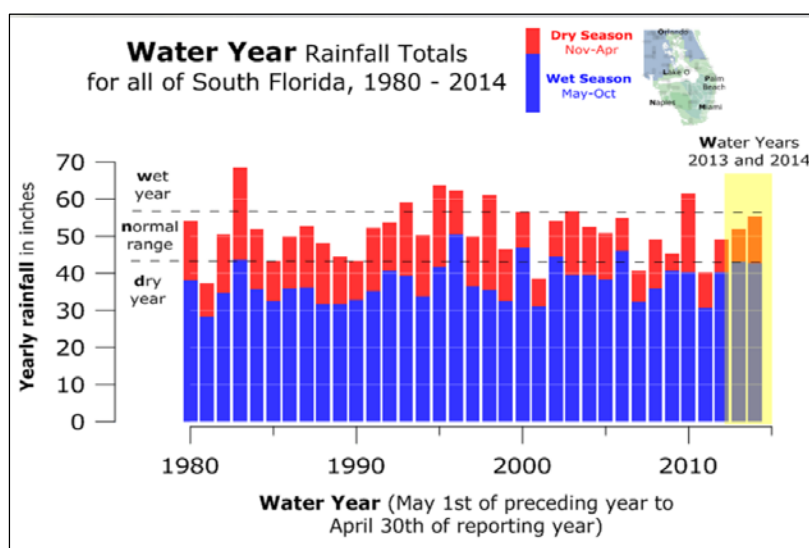

Figure 2.8: Precipitation totals from 1980 to 2014 (Brandt et al. 2014).

Methods:

Study Site and Variables

This study focuses on the Shark River Slough section of the historic Everglades watershed, covering area roughly 1,166.74 Km^2 in size. The broad study area is bounded by the northern extent of the Everglades National park (just south of US-41/Tamiami Trail), and Florida State Road 997 (Krome Avenue) to the east. The western extent focuses on the Shark River Slough from Bottle Creek east and the southern border is analyzed up until the northern extent of the main Everglades National Park (ENP) entrance. Rather than delineate exact borders, this study focuses on 30 water estimation sites (gages) operated by the Everglades Depth Estimation Network (EDEN). EDEN is a collaborate effort between the United States Geological Survey (USGS), Department of the Interior, Army Corps of Engineers and the South Florida Water Management District. Daily median water level, precipitation, and evapotranspiration measurements recorded by the gages, from 01/01/02 through 12/30/14 were obtained from the EDEN website:

http://sofia.usgs.gov/eden/eve/index.php?rainfall=rainfall.

The study area exhibits a wide variety of species diversity and differentiating impacts of the bridge on multiple vegetative communities is key. The 30 gages examined are listed in Table 2.1, with site specific vegetation classification and elevation data obtained from EDEN.

Table 2.1 – Detail of Gage Site Vegetative Communities and Elevation

GAGE	Vegetation (UGA)	Vegetation (EDEN)	Elevation (feet):
A13	*C. jamaicense*	Ridge or Sawgrass/ emergent marsh	3.24
ANGEL	*C. jamaicense* (disturbed site)	N/A	4.73
Bottle Creek	*C. jamaicense* (Near Mixed Shrub)	N/A	N/A
CR2	Mixed Prairie/Marsh	Wetland shrub and forested	4.12
CR3	*C. jamaicense*	Wet prairie	4.03
E112	*C. jamaicense*	Wet prairie/ Ridge or Sawgrass/ emergent marsh	2.43
G-3272	Invasive Species	N/A	5.44
G-3273	Invasive Species	N/A	5.21
G-3574	Tall *C. jamaicense* (Krome Canal)	N/A	4.65
G-3576	*C. jamaicense,* neat tall variety.	N/A	5.05
G-3577	Sawgrass (Near strand of PGct)	N/A	5.05
G-3578	*C. jamaicense*	N/A	5.05
G-3626	Exurban Miami-Dade	N/A	5.75
G-3628	*C. jamaicense* (with Scrub/Shrub)-disturbed	N/A	5.55
G-620	Hardwood Forest and Shrub/Scrub Mixed (Shark Valley Observatory)	N/A	5.29
MO-215	*C. jamaicense* (tall and sparse)	Sawgrass and emergent marsh	-0.32
NESRS1	Hammock/Bayhead	Ridge or Sawgrass and emergent marsh/ Slough or open water	4.33
NESRS2	*C. jamaicense*	Ridge or Sawgrass and emergent marsh/ Wet Prairie	4.29
NESRS3	*C. jamaicense*	Ridge or Sawgrass and emergent marsh	4.4
NESRS4	PGc - Sawgrass (near Cattails)	Ridge or Sawgrass and emergent marsh/ Wet Prairie	4.14
NP202	Bayhead - with wetland shrub mixed and upland hardwood forest	Wet prairie	3.8
NP203	Bayhead with tall *C. jamaicense*	Wet prairie	3.13
NP206	*C. jamaicense*	Ridge or Sawgrass and emergent marsh/ wetland shrub forest	4.01
NP62	Tall *C. jamaicense* /Hammock mixture, next to Cypress/Pine Savanna	Wetland shrub forested/ Ridge or Sawgrass and emergent marsh	0.99
P33	Tall *C. jamaicense*	Sawgrass and emergent marsh	3.92
P36	Hammock and *Tall C. jamaicense*	Ridge or Sawgrass and emergent marsh/ Slough or open water	1.74
R3110	*C. jamaicense* prairie with pockets of shrub growth.	Wet prairie	3.65
RG1	*C. jamaicense* prairie with pockets of shrub growth.	Wet prairie	3.76
RG2	Mixed Prairie/Marsh	Wet prairie	4.61
RG3	*C. jamaicense* – disturbed	N/A	5.09

Only gages deemed "active" by EDEN were included, to preserve the temporal integrity of the study. Georeferenced gages were then projected (using NAD83 / UTM zone 17N) onto a (1:15,000) large-scale vegetation map generated by Welch et al. (1999). Maximizing the extent of gage locations across the slough necessitated the inclusion of sites from the more hydrated portion west of the L-67 EXT levee and east in areas adjacent to the ENP perimeter. This enabled the evaluation of trends at the scale of the Shark River Slough as well as insight into the consequences of the NESRS over drainage. Examining this dichotomy also provides a comparison of the bridge's effects on vegetative patterns in environments where species are subjected to varying hydroperiods.

Data was then aggregated from raw daily values into 8-day steps to temporally match the NDVI results for MODIS. Regressing Water Level (WL) against NDVI for the Shark River Slough required that the WL variable not be compromised by precipitation and evaporation inputs. These factors are mitigated during the dry season but remain present. Calculating a net WL using precipitation and evapotranspiration data from EDEN allowed us to determine if these variables skewed WL. Samples were included of on and off slough sites to account for contrasting hydroperiods. Figure 2.9 demonstrates the results of the generated net WL against raw WL values, indicating consistency between their measurements.

Dataset integrity for the MODIS NDVI analysis was complete except for sites Bottle Creek (until NDVI #7), L31NN (until NDVI #91) and G3574 (all NDVIs), where instrument failure resulted in missing or corrupted values. Additionally, an unknown error was observed in the EDEN data corresponding to the 18th NDVI index for both

2004 and 2008 across all gages, and their values were eliminated from the analysis. All data points were subsequently arranged into an excel spreadsheet and numbered 1 to 598, representing each 8-day window from 2002 to 2014.

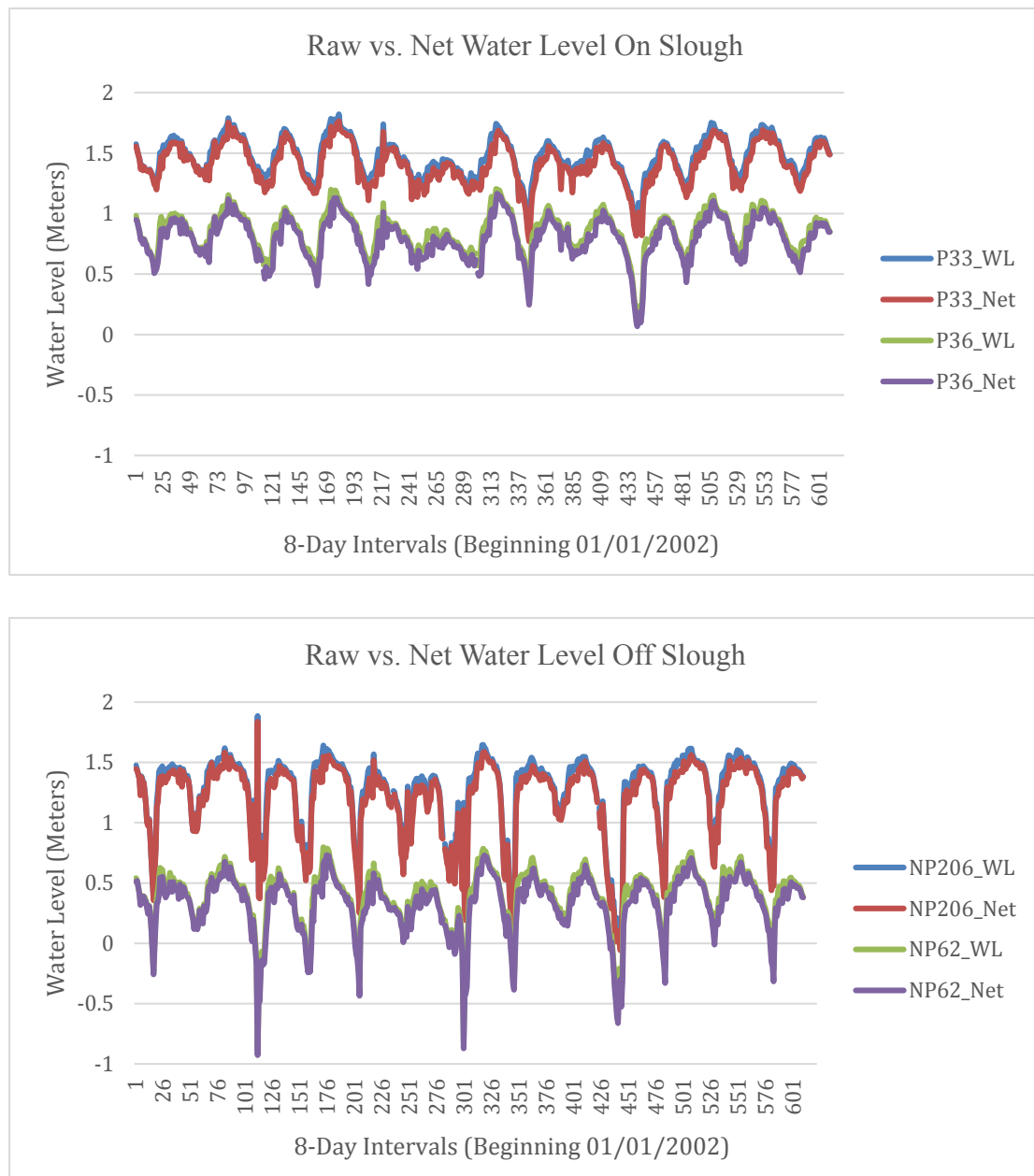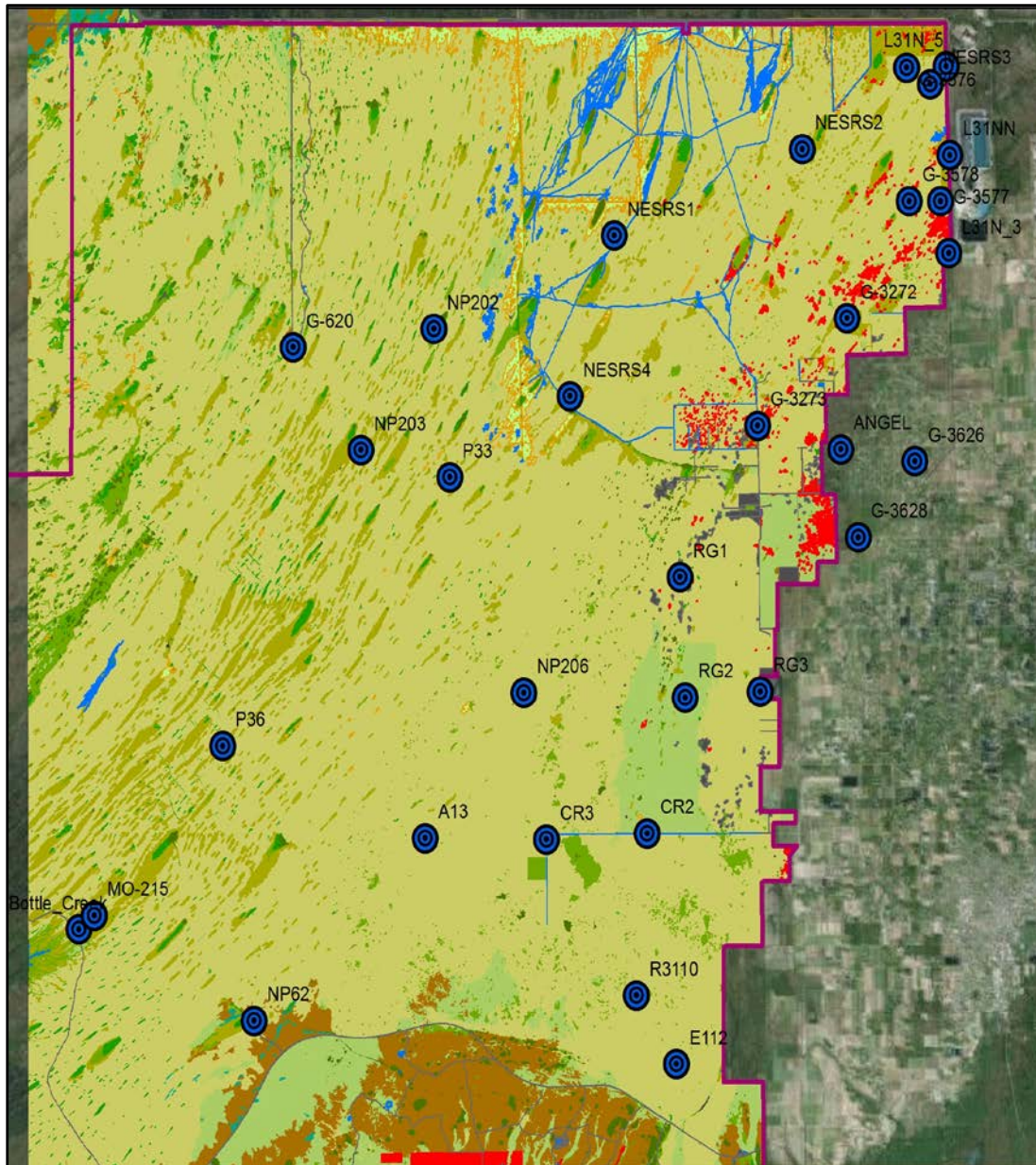**Figure 2.9:** Plots of WL (Raw and Net) vs. Time on and off slough demonstrating consistency between raw WL and Net WL (which factored in precipitation inputs).

Results:

Map 2.1: Vegetation map of the Shark River Slough study area generated from Welch et al. (1999). Most dominant vegetative communities in the study area are represented. Additionally, 33 gages are shown along with the ENP boundary.
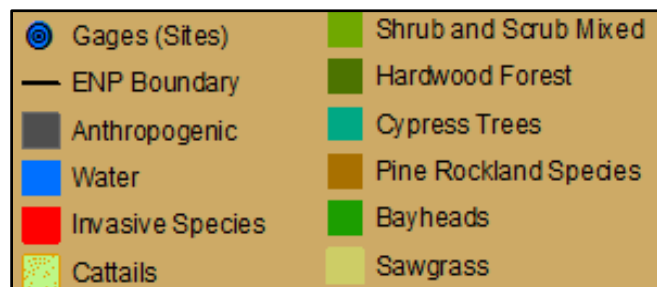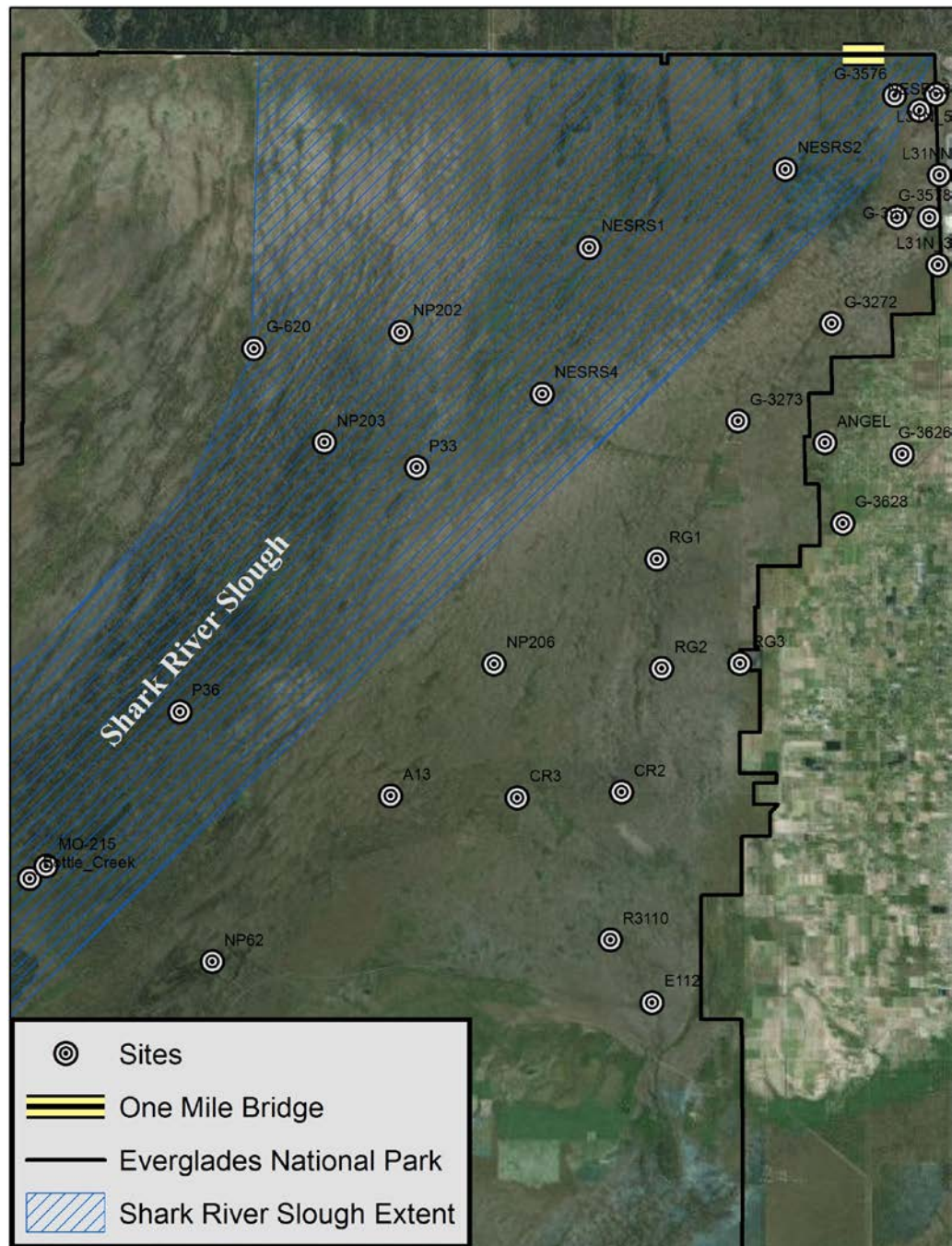
Map 2.2: Map of the Shark River Slough within the study area, showing gages located on and off slough. Areas of the eastern Everglades, off slough, consist mainly of marl prairies, with thin, calcitic soil layers above jagged limestone (Miller et al. 2004). Additionally, the area between RG1-CR2 encompasses a wet prairie, a lower marsh with a mixture of various less dense, emergent vegetation (Lodge 2010).

CHAPTER III

QUANTITATIVE ASSESSMENT OF MODIS-NDVI

NDVI metrics are often used to measure the extent of forest cover, but can also be utilized for less dense vegetation, including tropical wetland ecosystems such as the Everglades (Sader and Jin 2006). However, space-based reflectance of emergent plants, such as *C. jamaicense*, may be confounded due to water absorption in the infrared portion of the spectrum (Adjei et al. 2015). A concern for this study is the presence of mixed pixels (containing both water and vegetation) among the results. The northwestern and central Shark River Slough portions typically remain wet throughout the year and often experience increased hydroperiods owing to water diversion away from the NESRS (Sklar et al. 2001). However, water levels during drought years can drop to <0.3 m in the core of the slough, with decreased hydroperiods occurring along a gradient towards the southeast (Clark and Reddy 2011). Limiting the temporal scale from January through May attempts to limit infrared absorbance. However, vegetation along the deeper slough elevations is emergent and thus sparse or partially submerged. The NESRS section in contrast should exhibit less uncertainty. Well below average and irregular flows degraded the slough's structure here, limiting the hydroperiod of *C. jamaicense* (Sklar et al. 2001). Evaluating NDVI trends on and off the slough is thus useful to determine how differences may be attributable to elevation. Viable long term monitoring requires MODIS-NDVI to be robust against issues such as mixed pixels. If present, subsequent bridging attempts outlined in the TTMP will only increase water flow and depth, further highlighting this phenomenon.

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Methods:

IDRISI Terra was used to extract site specific NDVI values for all gages to align them with their corresponding 8-day averages for water level. Of these, the first 19 NDVIs of each year were selected for the analysis. Following evidence that temporal variations of NDVI are observed with hydrologic variables, this study incorporated a temporal lag in its analysis (Ji et al. 2005, Wang et al. 2003). Wang et al. (2003) further notes that temporal variations depend heavily on location. For the Shark River Slough, the distinction between a wet and dry season is pronounced as water levels drop precipitously January through May. Thus, a lag of 19 time steps (each step consisting of 8 days) was evaluated to establish if a relationship existed.

Lastly, relationships between NDVI and WL may be influenced by plant response to varying elevations and hydroperiods on and off slough. The data was therefore aggregated and graphed according to the three spatial scales (all sites, off slough and on slough) while a linear regression analysis was used to determine significance. Table 3.1 outlines the on/off sites selected. Two sites emerged as noticeably removed clusters: MO-215 for the on slough and NP-62 for off slough. Located far south, the sites contain a greater presence of shrubs and hardwood species than found in the northern slough. Higher NDVI values of dense, woodier vegetation in these areas may have influenced the graphical representation of the quantitative analysis. Accordingly, an additional analysis was performed excluding these outliers to assess if trends emerged.

On Slough	MO 215	NESRS 1	NESRS 2	NESRS 4	NP 203	P33	P36
Off Slough	A13	CR2	CR3	G-3272	G-3578	NP 206	NP 62

Table 3.1: List of selected sites on and off slough.

Individual gages exhibited varying water level averages both on and off slough. These differences were heightened as water levels receded during the dry season, with levels at certain sites dropping faster than others. To analyze site level behavior, time analysis of NDVI v. WL was performed for sites selected on and off slough sites. Un-aggregated NDVI values were regressed against water level to visualize trends across the following time periods: 2002-2014, 2002-2009, 2010-2013 and 2014. The sites examined were G-3576, G-3272, NESRS 2, NESRS 4, P36, A13, NP 62 and NP 206.

G-3576, containing sparse and tall varieties of *C. jamaicense*, was selected owing to its proximity to the LRR Bridge (immediately south). G-3272 is located further south in the NESRS, and represents a heavily disturbed site. Both sites contain large clusters of *M. quinquenervia*, which has taken advantage of deterioration and disturbance of the landscape to invade *C. jamaicense* communities. Able to survive in wet and dry environments, *M. quinquenervia* can take advantage of increased fire potential (fire prompts heavy seed dispersal) during prolonged dry spells (Lodge 2010; Laroche 1999; Hofstetter and Sonenshein 1990).

NESRS 2 and NESRS4 are located on what was once a continuously inundated, deeper portion of the slough that has since lost soil depth and seen hydroperiods fluctuate (Porter 2001). NESRS 2 is on the tail of a bayhead, surrounded by tall *C. jamaicense* and facing increased successive pressure. Trends assessed may reveal the implications of more consistent and elevated water levels from the bridge. NESRS 4 is located on the slough in artificially deep-water. As evidenced in Map 2.1, such disturbance, and its proximity to the L-67 EXT levee and canal, has allowed heavy infestation of *T. Latifolia* into a predominantly *C. jamaicense* prairie (Florida Department of Environmental Protection 2000).

The farthest site analyzed on the slough is P36. Records suggests water levels in the area pre-drainage rarely dropped below the existing ground elevation (bottom of the slough) but now do so more frequently (Lodge 2010). As such, the area has experienced greater fluctuation in water levels and vegetation has been subjected to decreased hydroperiods. East of P36 are sites A13 and NP206, both located off slough, in open marl marshes that contain a variety of graminoid species in a low hydroperiod environment that is increasingly water deprived (Lodge 2010; Miller et al. 2004).

Vegetation in deeper slough portions consists of *Nuphar advena* (Spatterdock), *Utricularia spp.* (Bladderwort) and mixed, sparse graminoids, such as *Eleocharis cellulose* (Spikerush)*, which lack sufficient cover. Following suggestions outlined in Adjei et al. (2015), an adjusted analysis excluded irregular points to evaluate the effects of increased water flow following the bridge's construction. Values with signatures of < 0.2 were excluded and the site-specific analysis used 2014 water levels to measure the effects of an average precipitation year on the ΣNDVI v. WL relationship.

One of the assumptions of the liner regression model is that there is no autocorrelation within the data. To detect autocorrelation, the Durbin-Watson statistic was calculated from the residuals for each linear regression analysis (Durbin and Watson 1950). The following equation was used to calculate the t-statistic, where T is the number of data points and e_t = yt − yˆt, the observed and predicted values:

$$d = \frac{\sum_{t=2}^{T}(e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t{}^2}$$

As part of the Durbin-Watson statistics the following hypotheses were used, (1) H_0: the residuals of a regression are not autocorrelated and (2) H_1: the residuals of the regression are autocorrelated. Values that were found to exhibit autocorrelation were identified and included in the tables of results, but not considered in evaluating the performance of MODIS-NDVI. In an effort to check the validity of the Durbin-Watson test, a Wald-Wolfowitz Test (Runs Test) was performed, which checks for non-randomness within the data. The results of the Runs Test confirmed the results of the Durbin-Watson Test, that the data is not random enough and is autocorrelated. These results were used to reject the H_0, and accept the H_1.

Results:

Table 3.2 presents regression results between the ΣNDVI of gages during the dry season and water level at various temporal and spatial scales. Additionally, the correlation and coefficient of determination results of adjustments calculated by eliminating NDVI values less than 0.2 are also displayed. Values in bold are statistically significant at $p < 0.05$. Values italicized were found to be auto-correlated. Their results are presented, but not included in the analysis. Valid correlation coefficient values across all time periods in ΣNDVI v. WL were mainly moderate to strong (except for 2002-2009) and statistically significant (except 2011). In addition to all temporal periods exhibiting a negative relationship between ΣNDVI and WL, the strongest correlations were from 2010 and 2012.

Figure 3.1 shows the graphical representation of the regression line for 2002-2014. The data are loosely spread around the mean, consistent with the weak r^2 calculated (0.113). This trend was consistent across all time periods. The highest value was from 2010, with 30% of the variance explained. Figure 3.1 also reveals that areas with a mean WL below 0.3 m exhibited higher NDVI sums. Adjusting the data by eliminating water levels <0.3 m and signatures less than 0.2 failed to improve results. When adjusted, valid correlations were lower in all time periods compared to the un-adjusted results except for 2002-2009. The 2002-2009 period had the highest r value (and a reversal of relationship sign) as well as being statistically significant. This, however, is likely attributable to the size of the data set, rather than the relationship's strength.

ΣNDVI v. WL	r	r^2	r (Adj.)	r^2 (Adj.)
2002-2014	**-0.336**	0.113	**0.122**	0.015
2002-2009	-0.231	0.053	**0.208**	0.043
2010	**-0.508**	0.260	0.062	0.004
2011	-0.343	0.120	0.084	0.007
2012	**-0.544**	0.260	0.125	0.016
2013	**-0.478**	0.300	0.180	0.032
2010-2013	**-0.491**	0.241	0.046	0.002
2014	*-0.493*	*0.243*	*-0.145*	*0.021*
ΣNDVI v. WL on Slough				
2002-2014	*-0.539*	*0.290*	*-0.440*	*0.194*
2002-2014 MO215 (R)	*-0.09*	*0.008*	*0.107*	*0.011*
2002-2009	**-0.425**	0.181	**-0.333**	0.111
2002-2009 MO215 (R)	0.14	0.020	0.277	0.077
2010-2013	**-0.734**	0.539	**-0.546**	0.298
2010-2013 MO215 (R)	-0.437	0.191	0.003	0.000
2014	**-0.878**	0.771	**-0.861**	0.741
2014 MO215 (R)	-0.445	0.198	-0.369	0.136
ΣNDVI v. WL off Slough				
2002-2014	**-0.609**	0.371	**-0.482**	0.232
2002-2014 NP62 (R)	-0.1	0.000	0.216	0.047
2002-2009	**-0.532**	0.284	**-0.393**	0.155
2002-2009 NP62 (R)	*0.216*	*0.046*	*0.388*	*0.151*
2010-2013	**-0.698**	0.488	**-0.591**	0.345
2010-2013 NP62 (R)	-0.320	0.102	-0.046	0.002
2014	**-0.825**	0.681	**-0.849**	0.721
2014 NP62 (R)	-0.363	0.132	-0.488	0.238

Table 3.2: Sum of NDVI v. Water Levels 2002-2014 at various spatial and temporal scales. (R) denotes when that gage is removed from the analysis.
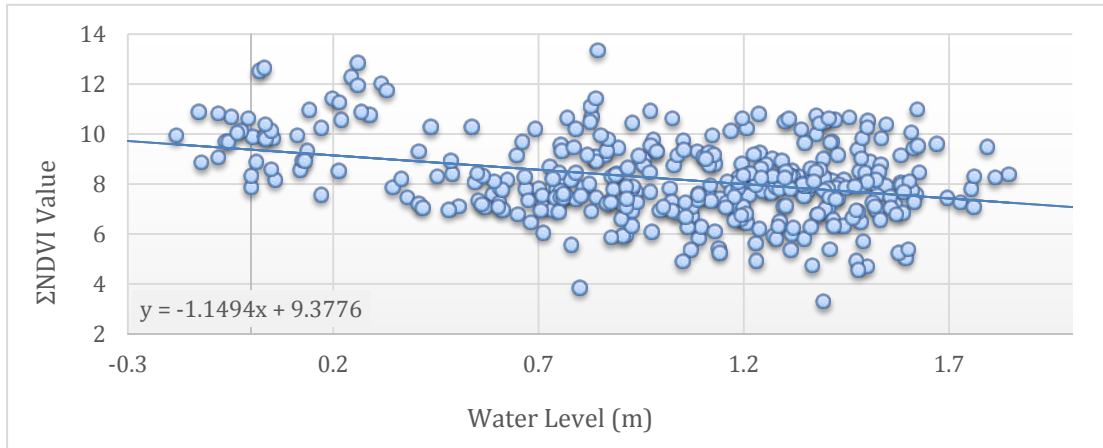
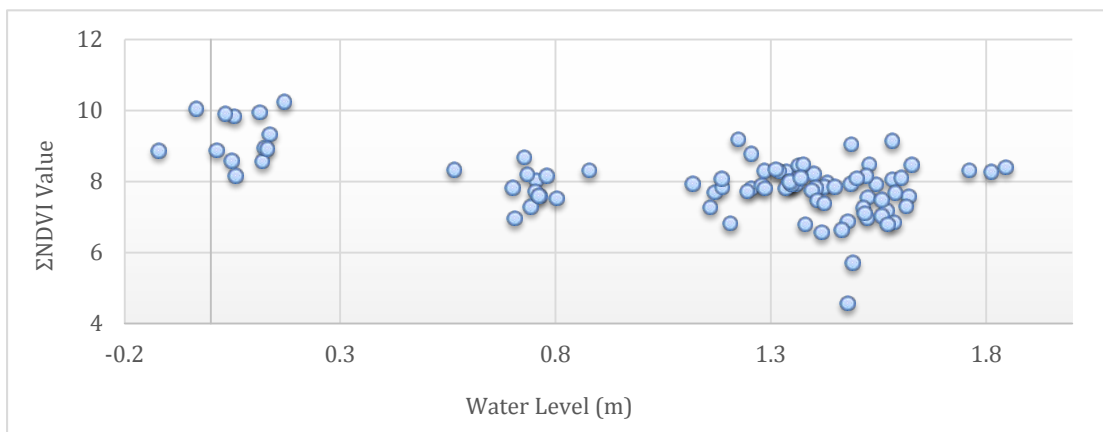**Figure 3.1:** Sum of NDVI v. WL for all sites from 2002-2014.

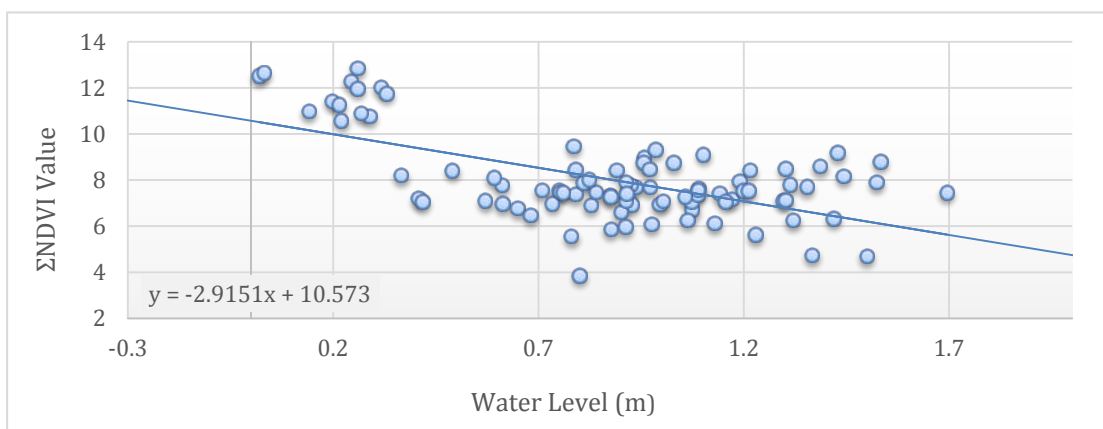**Figure 3.2:** Sum of NDVI v. WL 2002-2014 for sites located on slough

Figure 3.3: Sum of NDVI v. WL 2002-2014 for sites located off slough.

Analysis of sites on slough initially resulted in improved correlations of NDVI against WL across all time periods, except for 2002-2014 which exhibited autocorrelation. All r values were statistically significant at $p < 0.05$ and except for 2002-2009 (which grew from a weak -0.231 across all gages to a moderate -0.425 on slough), all time periods exhibited strong correlation. 2010-2013 and 2014 indicated the strongest relationships, and 54% and 77% of the variance was explained by WL (highest among all spatial scales). Moreover, all time periods recorded inverse relationship between WL and NDVI sums, consistent with other spatial extent examined.

Despite exhibiting autocorrelation, graphing on slough sums from 2002-2014 in Figure 3.2 reveals that data points were clustered into three groups. One cluster, corresponding to the southernmost site MO-215, is far removed from the rest, exhibiting high ΣNDVI (values >10 units) with <0.3 m of water depth. After removing these values from the analysis, autocorrelation remained present in 2002-2014. Additionally, reduced results among all correlations that did not exhibit autocorrelation rendered them statistically insignificant. Furthermore, omitting MO-215 had an effect on the fit of the data, with the range of valid r^2 values occurring from < 0.2 to 0. Adjusting the NDVI values revealed results consistent with the unadjusted figures, though slightly lessened. All temporal periods remained significant at $p < 0.05$, though as before, removal of values from MO-215 (ΣNDVI > 10) reduced correlations and eliminated significance. This affected correlations for 2010-2013, but mostly 2014, weakening results more than 50%.

Off slough, the analysis yielded similar or improved results compared to the on slough sites. All time periods indicated statistically significant, strong negative correlations between NDVI sums and WL. Compared to the two previous spatial scales, performance improved for 2002-2014 (excluding on slough) and 2009 most. However, the highest r values occurred in 2010-2013 and 2014 (-0.698 and -0.825), as with observations from on slough sites. Evaluating the r^2 values revealed improved figures across all temporal periods compared to the non-autocorrelated results from analyses of all gages and on slough sites. Except for 2002-2009, all time periods exhibited a moderate to strong fit among the data, with 49% and 68% of the variation accounted for in 2010-2013 and 2014, respectively. The strength of these results suggest focusing on off slough sites appears to be a more effective spatial level for assessing the relationship between NDVI productivity and WL.

Figure 3.3 graphs the data from the off slough analysis. As occurred in Figure 3.2, a separated cluster with high NDVI sums at low water levels (<0.3m) emerged. This cluster is comprised of values from site NP62, located amongst dense, woodier vegetation. Omitting NP-62 from the analysis significantly reduced correlations across all time periods and resulted in autocorrelation for 2002-2009. As had occurred with the removal of site MO-215, the remaining r and r^2 values were rendered statistically insignificant. Furthermore, adjusting the analysis to remove possible mixed pixels (NDVI < 0.2) reduced correlations across most time periods. However, performance increased slightly for 2014 with NP-62 removed. Adjusted r^2 values were only moderate and strong in 2010-2013 and 2014, respectively.

Table 3.3 shows the results of the site specific analysis for sites on slough. Autocorrelation was present in G-3576, NESRS 2 and NESRS 4, with 2002-2014 being most impacted. Sites closer to the bridge exhibited autocorrelation for the same temporal periods (2002-2014 and 2010-2013), while NESRS 4, located further from the bridge, was autocorrelated in 2002-2014 and 2002-2009. Site P36, farthest along the slough, exhibited no autocorrelation when tested, as with the 2014 time period across all sites. Valid results indicate sites located in the NESRS (G-3576, NESRS 2 and NESRS 4) had weaker relationships than P36, located farther along the core of the slough. NESRS 2 and NESRS 4 resulted in a low to non-existent correlation (except for 2014 in NESRS 4). G-3576 r values were moderate and statistically significant for 2002-2009, though the correlation for 2014 was the weakest out of any site. Furthermore, sites in Table 3.3 occur sequentially along the slough. Interpreting correlations along that line suggests an inverse relationship between distance along the slough and strength of the correlation for the 2014 time period.

Apart from a single indication of strong correlation for site P36 in 2014, the on slough site analysis lacked sufficient evidence of a strong relationship between NDVI values and WL. Data adjustments for all on slough sites excluded NDVI values <0.2. For NESRS 2, adjustments also excluded WL <1.2 meters, with little change in correlation strength. Both analyses and the presence of autocorrelation for data from 2010-2013 and 2002-2014, suggest NESRS 2 is inconclusive in monitoring trends on slough. Similarly, NESRS 4 failed to generate evidence of a strong relationship and exhibited autocorrelation across two time periods. Adjusting the data as with NESRS 2 improved performance for 2014, but only 27% of the variance could be explained.

	r	r^2	r (Adj.)	r^2 (Adj.)
G-3576 NDVI V. WL				
2002-2014	*0.119*	*0.014*	***0.184***	*0.034*
2002-2009	**0.368**	0.135	**0.486**	0.237
2010-2013	***-0.251***	*0.063*	***-0.184***	*0.338*
2014	-0.032	0.001	0.044	0.002
NESRS 2 NDVI V. WL				
2002-2014	*0.028*	*0.001*	*0.095*	*0.009*
2002-2009	0.083	0.007	0.128	0.016
2010-2013	*-0.071*	*0.005*	*0.036*	*0.001*
2014	0.240	0.000	0.227	0.184
NESRS 4 NDVI V. WL				
2002-2014	*0.215*	*0.046*	***0.287***	*0.083*
2002-2009	*0.213*	*0.045*	***0.334***	*0.112*
2010-2013	0.188	0.035	0.091	0.008
2014	0.365	0.134	**0.522**	0.272
P36 NDVI V. WL				
2002-2014	**0.264**	0.070	**0.338**	0.114
2002-2009	**0.401**	0.161	**0.361**	0.131
2010-2013	0.027	0.001	**0.300**	0.090
2014	**0.761**	0.580	**0.718**	0.515

Table 3.3: NDVI v. Water Levels 2002-2014 on slough Gages.

Site G-3576 is located immediately south of the bridge. Assessing the site's performance provides insight into the efficacy of MODIS-NDVI in an area immediately affected by the bridge's construction. Autocorrelation in 2002-2014 and 2010-13 and low r and r^2 values for 2014 left moderate correlation only in the 2002-2009 period (r = 0.368). Figure 3.4 graphs 2002-2009 and demonstrates that the highest NDVI values generally occurred when water level exceeded 1.4 m. Despite the initial suggestion of a relationship between higher NDVI and higher WL, inconsistent data points of low NDVI values with higher water levels are present. This reveals why correlations were low in 2014, where a greater presence of NDVI data points below 0.3

occurred at WLs > 1.4m. This suggests site G-3576 may lack reliability in establishing trends between photosynthetic activity and water level. Precipitation totals for 2009 were abnormally low (Brandt et al. 2014); excluding that year, water levels for G-3576 in the 2002-2009 time period were consistently above 0.8m. Adjusting the data to remove NDVI values <0.2 and WL < 0.8m slightly improved results. Correlation increased to 0.486 and almost 24% of the variance was explained, still relatively low, but double the previous value ($r^2 = 0.135$).
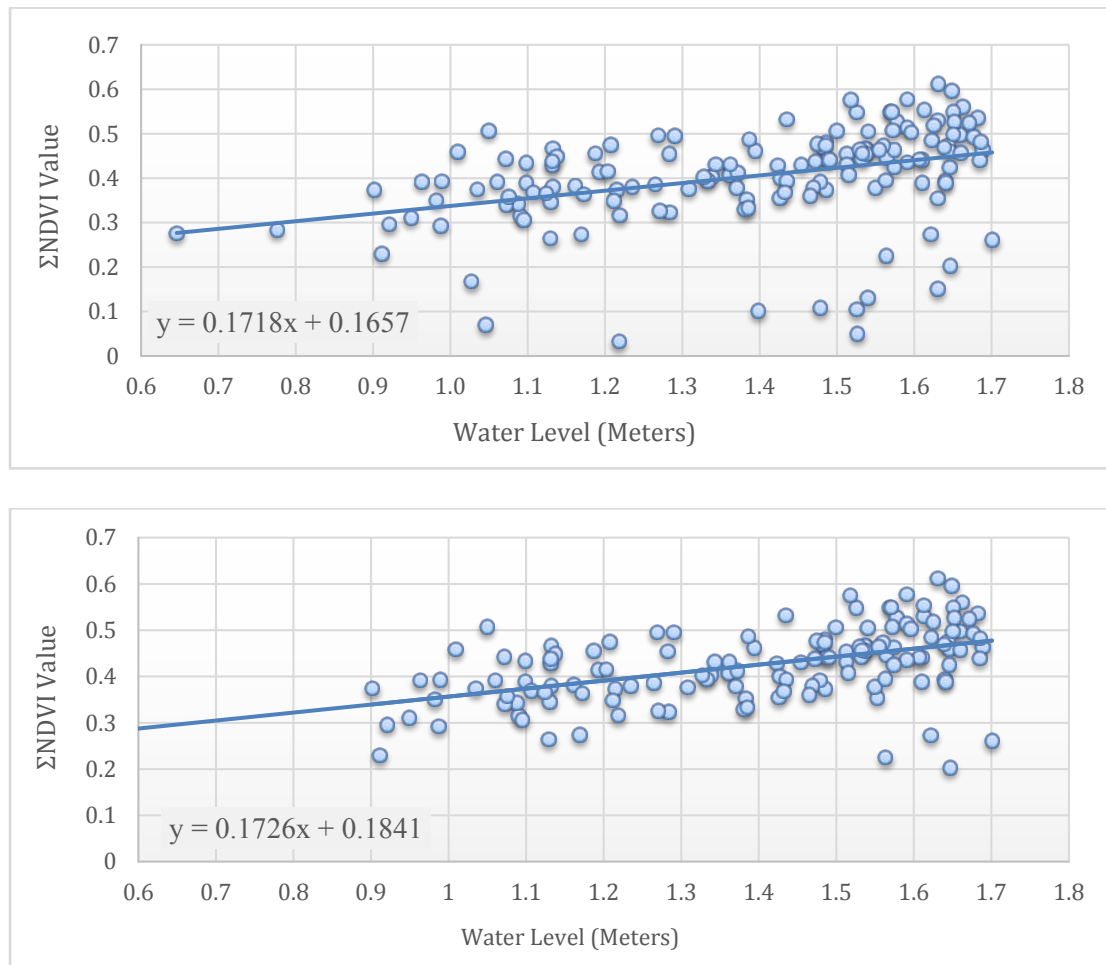

Figure 3.4: G-3576 NDVI v. WL for 2002-2009 (above) and adjusted (below).

Despite adjustments, Figure 3.4 reveals four points (NDVI values < 0.3 with WL > 1.5 m) far from the regression line. Re-calculating the linear regression analysis without these points increased correlation to a stronger, statistically significant 0.625 at $p < 0.05$. Additionally, the r^2 value improved such that 40% of the variance was explained by the independent variable. This result remains the highest r^2 value across all non-autocorrelated time periods, except in 2014 for P36. This underlines the sensitivity of outliers in the quantitative analysis of MODIS-NDVI. It also supports the viability of graphing the regression analysis and implementing adjustments to generate a stronger relationship than originally observed.

Performance for on slough sites was highest in P36, though only 2002-2009 and 2014, had significant correlations. Of those, 2014 demonstrated the strongest relationship and best fit of all time periods in the on slough site analysis. Figure 3.5 demonstrates this result, showing the strength of the positive relationship ($r = 0.761$) and a slope of 0.43 with 58% of the variance in NDVI accounted for. Despite the presence of an outlier (WL > 0.9 m with NDVI value < 0.4), there is a consistent relationship between higher NDVI values and elevated WL. Adjustments for site P36, removing low NDVI values and WLs < 0.6m, produced negligible results in changing the strength of correlations. 2010-2013 and 2002-2014 r values improved to significant, moderate strengths (0.300 and 0.338) but r^2 values for both were < 15%. As seen in Figure 3.6, the removal of data points for 2002-2009 adversely affected the strength of the relationship, as slope declined from 0.334 to 0.193. 2014 still exhibited the best fit and strongest correlation after adjustments, with mostly unchanged values. These results suggest adjustments had a negligible effect on the analysis for site P36.
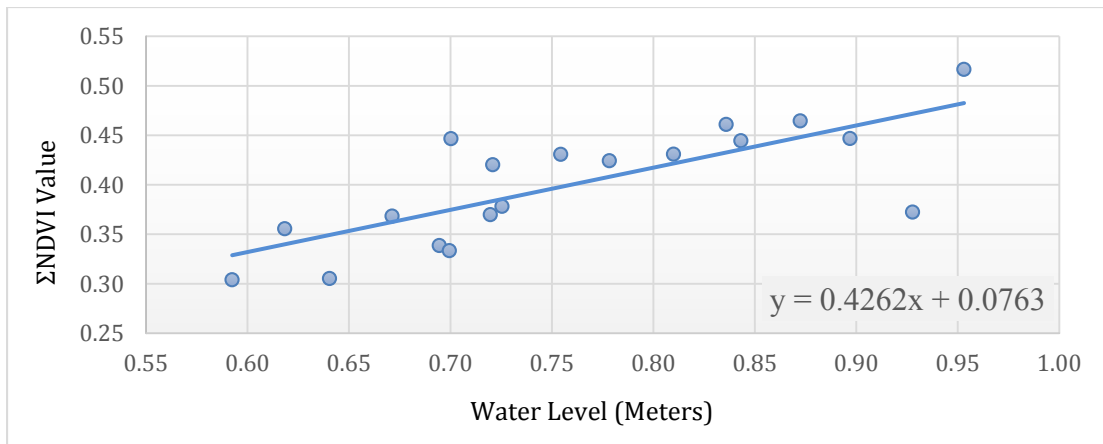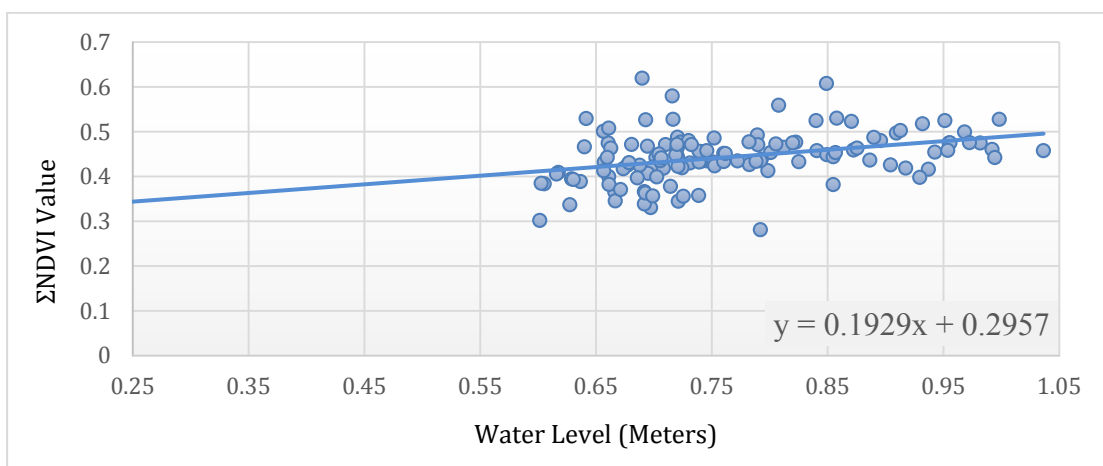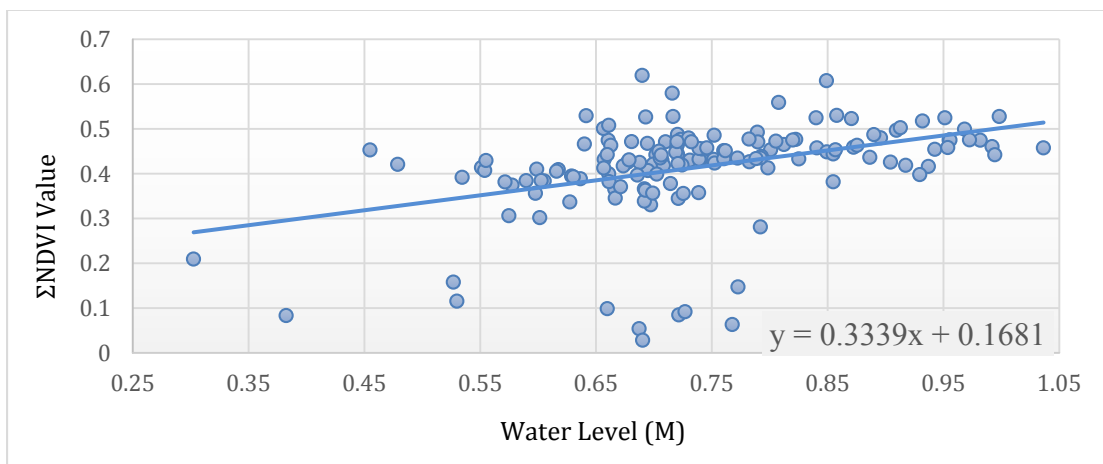
Figure 3.5: P36 NDVI v. WL for 2014.

Figure 3.6: P36 NDVI v. WL for 2002-2009 Original (Top) and Adjusted (Bottom).

	R	R^2	R (Adj.)	R^2 (Adj.)
A13 NDVI V. WL				
2002-2014	0.118	0.014	**0.256**	0.065
2002-2009	0.13	0.017	0.173	0.030
2010-2013	*0.006*	*0.000*	***0.351***	*0.123*
2014	**0.660**	<u>0.436</u>	**0.744**	<u>0.553</u>
G-3272 NDVI V. WL				
2002-2014	-0.022	0.000	0.162	0.026
2002-2009	*0.019*	*0.000*	***0.221***	*0.049*
2010-2013	-0.046	0.002	0.101	0.010
2014	-0.079	0.006	0.205	0.042
NP206 NDVI V. WL				
2002-2014	*0.248*	*0.062*	***0.297***	*0.088*
2002-2009	*0.342*	*0.117*	***0.403***	*0.162*
2010-2013	0.033	0.001	0.084	0.007
2014	**0.725**	<u>0.525</u>	**0.725**	<u>0.525</u>
NP62 NDVI V. WL				
2002-2014	0.069	0.005	-0.046	0.002
2002-2009	0.1	0.010	-0.043	0.002
2010-2013	-0.08	0.006	-0.103	0.011
2014	0.241	0.058	-0.042	0.002

Table 3.4: NDVI v. Water Levels 2002-2014 off slough Gages

Table 3.4 compiles the results of the site-specific analysis for sites off slough. Autocorrelation was present in A13, G-3272 and NP 206. 2002-2009 was the most autocorrelated time period with two instances, followed by 2002-2014 and 2010-2013 with one each. As with the on slough site analysis, 2014 exhibited no autocorrelation. Valid results indicate performance was lower than on slough sites. Two sites, A13 and NP206, each generated a single statistically significant, non-autocorrelated result, in the 2014 time period. Notably, the sites were in close proximity and contained relatively similar vegetation cover and elevation. G-3272, located in a heavily disturbed tract on the southern extent of the NESRS and NP 62, near the southern extent of the study area, exhibited the lowest performances. Despite no autocorrelation in NP62 and

a single instance for G-3272 (2002-2009), the sites exhibited virtually no correlation for any time period (except 2014 for NP62). Unlike in on slough sites, trends relative to distance from the bridge were not discernable. This initially suggests the effectiveness of relating NDVI to WL off slough is much less than sites on slough.

For sites A13 and NP206, only results from the 2014 time period exhibited strong correlations (r = 0.66 and 0.725, respectively). When adjustments were made, values for A13 IN 2002-2014 and 2014, as well as 2014 for NP 206, were the only significant results after testing for autocorrelation. 2014 remained the time period demonstrating the strongest relationship and best fit. Values for NP 206 remained unchanged, but A13 exhibited increased correlation from 0.660 to a statistically significant 0.744. Both explained >50% of the variance in NDVI, better than the results generated on slough.

Figure 3.7 displays both adjusted data graphs for 2014. Note that although NDVI values only range from 0.3-0.5, there is a significant, positive relationship present. The similarity between both plots also suggests a level of consistency between the sites' NDVI v. WL relationship, perhaps explained by the decreasing hydroperiod and homogeneity of vegetation cover in the area. Overall, recognizing the lack of strong results from sites NP62 and G-3272, it appears that the off slough analysis was not successful. A common limitation were the low r^2 values observed across all time periods and sites. This reveals that despite the strength of the correlation, the data are often not closely fitted to the regression line. Figure 3.8 graphs the adjusted A13 data for 2002-2014, demonstrating the difficulty of discerning trends with such a poor fit. Areas off slough have experienced a greater loss of reliable water flow, and water levels

can fluctuate depending on precipitation trends (Sklar et al. 2000). Thus, much of the variability in NDVI v. WL for these sites could stem from the decline in hydrologic stability.
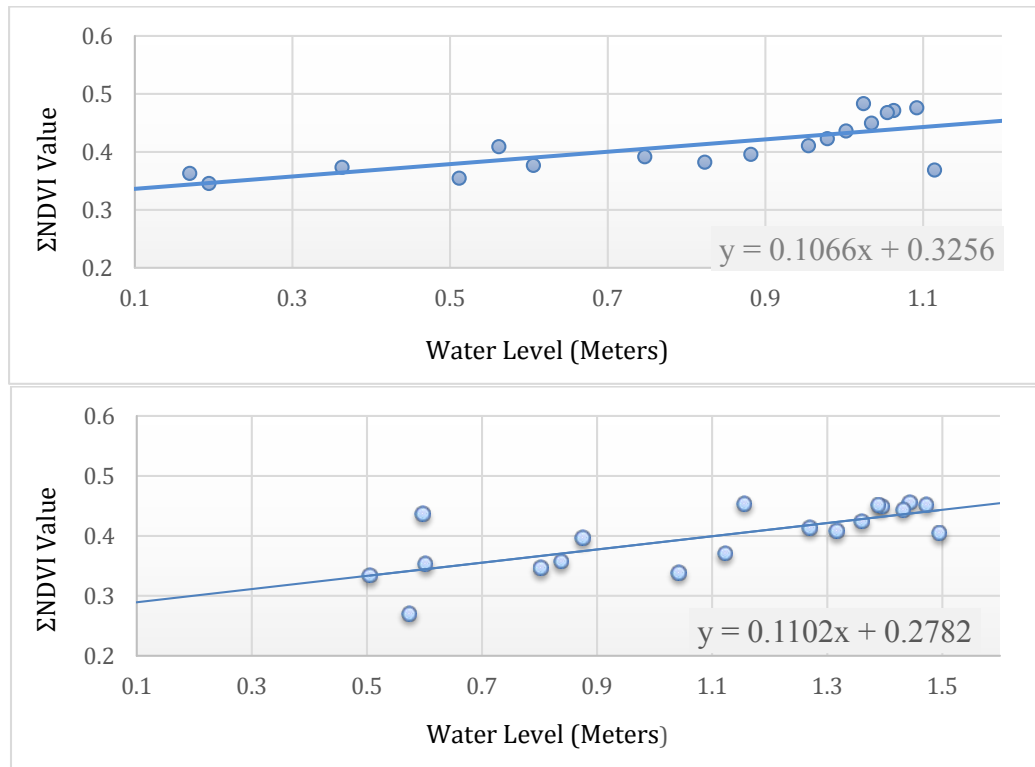

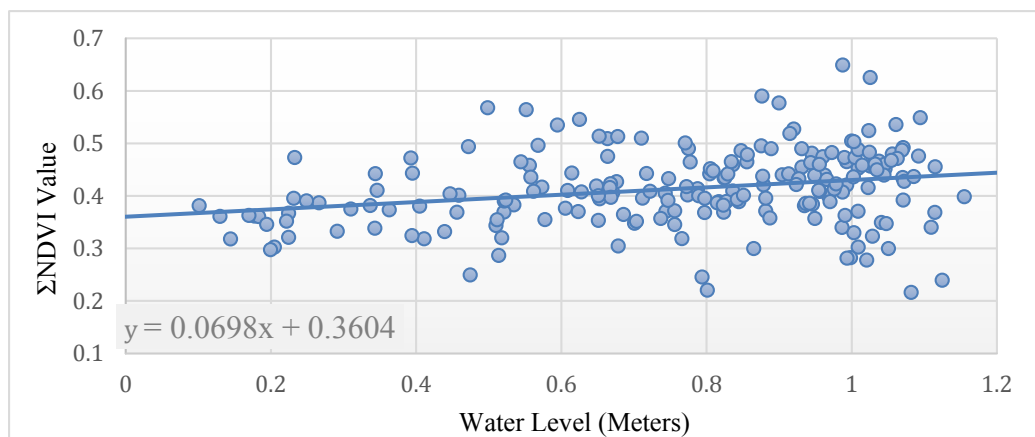**Figure 3.7:** Adjusted A13 (above) and NP206 (below) NDVI v. WL for 2014.

Figure 3.8: Adjusted A13 NDVI v. WL for 2002-2014.

CHAPTER IV

SPATIOTEMPORAL ASSESSMENT

OF MODIS-NDVI

This study exploits 13 years of MODIS 250m imagery across South Florida to generate sums of NDVI indices. NDVI is a useful metric for assessing trends in vegetation cover as it is generated from spectral band ratios of the red and near infrared portions of the spectrum. The combination enables NDVI to provide a "direct measurement of the fraction of absorbed photosynthetic activity" (Fuller and Wang 2015). However, the predominance of emergent vegetation in the Everglades implies potential challenges to the applicability of NDVI techniques. The Landsat thematic mapper (TM) and ETM+ are often used for studies involving land cover classification or NDVI, owing to their archival extent and fine spatial resolution (3m) (Adjei et al. 2015; Dong et al. 2014; Islam et al. 2008).

Yet, the temporal resolution of Landsat (16-days) is less than that of MODIS (8-day), and viable monitoring requires a consistent source of cloud-free imagery to assess trends over time. Obtaining reliable cloud-free imagery for South Florida is a challenge, even when limiting the study to the dry season. Table 3.1 provides a list of the only available cloud-free Landsat 5 and 8 imagery. Water levels can drop significantly over the course of the dry season, owing to lessened precipitation inputs, necessitating imagery from the beginning and end of the dry season. Only four years had at least two viable images, and 2011 did not produce any useful images. Data would be unavailable for 2011-2013, almost the entire period of the bridge's construction.

	January	February	March	April	May	Landsat TM/ ETM+
2002	01	02				
2003	20					
2004	23		11			
2005	25			15		
2006	01				04	5
2007	31					
2008				23		
2009		05				
2010		08				
2011						
2012						
2013	N/A					
2014				24		8
2015		06				

Table 4.1: Landsat images from 2002-2015 without cloud cover are shown in green. The numbers under the months correspond to the date of the image.

Over the 13 years examined by this study, almost 25% of the imagery would be unobtainable. This renders Landsat unfeasible for trend analysis of restoration projects in the ENP. Despite its coarse resolution, authors note that MODIS provides sufficient spatial resolution for assessing wetland vegetation trends (Adjei et al. 2015; Dong et al. 2014; Islam et al. 2008). Advantages of MODIS include high temporal frequency, low data volume for large spatial extents and easy accessibility of free imagery (Sader and Jin 2006).

Methods:

Spatial Analysis

I obtained 2000-2015 version 5 MOD09Q1 250m 8-day reflectance imagery for MODIS bands 1 (620-670 nm) and 2 (841-876 nm) for South Florida from the website http://reverb.echo.nasa.gov/reverb/. Windowing the images in IDRISI Terra narrowed the spatial extent, using 7891142.2056663 for the maximum X coordinate, -8186735.7135830 for the minimum X coordinate, 3034698.2985833 for the maximum Y coordinate and 2712464.3099375 for the minimum Y coordinate. This data was used to create a temporal sequence of 8-day NDVI images such that each time series contained 46 composite images, corresponding to each year studied. The equation used to create the NDVI image was:

$$(Band\ 2 - Band\ 1)/(Band\ 1 + Band\ 2)$$

Subsequently, images were re-projected into UTM 17 and grouped to create yearly time series. Though the National Park Service classifies the Everglades' wet season as May through November, this study adjusts that timeframe to January through May instead. Increased water inputs occurring throughout the wet season remain heightened during the first two months of the dry season (November/December). Conversely, water levels are depressed at the start of the wet season (May). Thus, NDVI from January through May were grouped in the time series to assess trends in the dry season.

Sums of the first 19 NDVI observations were calculated from 2002-2015 to serve as a proxy for above-ground net primary productivity (Fuller and Wang 2014) in the dry season. The time series were aggregated at two temporal stages in relation to the bridge: pre-construction (2002-2013) and post construction (2014-2015). A Theil-Sen slope was calculated for each NDVI time series' pixels along with significance in IDRISI Terra. TS Slope is the median of slopes calculated between observations X_j and X_i at pairwise time steps t_j and t_i (Fuller and Wang 2014):

$$TS\ Slope = Median\left(\frac{X_j - X_i}{t_j - t_i}\right)$$

The TS slope is non-parametric and robust against outliers, thereby reducing the necessity of smoothing the time series to reduce high frequency noise (Fuller and Wang 2014). Mann-Kendall calculations for p confidence were generated, highlighting areas of significance. Additionally, IDRISI Terra was used to establish mean values for each pixel over the corresponding time series. These products were subsequently imported into GIS software (ArcMap 10.3.1) to generate time series maps for TS Slope, p value, areas of slope for pixels with $p < 0.05$ (significance) and mean pixel value. Additionally, year on year differences in sums of NDVI values for 2013-2015 were analyzed.

To assess significant spatial trends, a Hot Spot Analysis using the Getis-Ord Gi* statistic was performed in ArcMap. The results indicated where features with either high or low values clustered spatially by examining each pixel in the context of neighboring pixels. This determined which clusters of high or low values were statistically significant (Esri Resources). The Gi* statistic calculated is a z-score; larger, significant positive z-scores indicate a more intense clustering of higher values labelled

"Hot Spots". Smaller, significant negative z-scores indicate an intense clustering of lower values labelled "Cold Spots" (ESRI Resources). The Getis-Ord local statistic is given as (Esri resources):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}}$$

Where x_j is the attribute value for feature j, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and:

$$\bar{X} = \sum_{j=1}^{n} x_j$$

$$S \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2}$$

To gain further insight into trends in vegetation cover, significant hot and cold pixels at p < 0.05 from the standard Hot Spot Analysis were isolated as polygons for 2014-2013 and 2015-2014. Areas where these polygons overlapped were extracted and subsequently overlaid on a digital elevation model (DEM) of the study area. The Welch et al. (1999) map was then used to evaluate spatiotemporal vegetative patterns from these significant clusters. Layers for invasive species, cattails, mixed marsh graminoids, shrub and scrub mixture, hardwood hammocks, bayheads, *C. Jamaicense* (sparse and tall varieties separate) were isolated. These were intersected with the polygons of hot and cold clusters for 2014-2013 and 2015-2014. Calculating geometries for spatially significant clusters of NDVI sum differences thus provided data on the change in area (Km^2) across vegetative communities.

Results:

Map 4.1 shows TS Slope values across the Shark River Slough pre-bridge completion (from 2002-2013) while Map 4.2 shows the p-values generated for areas of significant slope (where $p < 0.05$). These maps reveal spatially discernable patterns on and off slough, particularly in the NESRS and areas south of it. An immediate dichotomy is visible in the northern slough, where the L-67 EXT canal and levee (seen in Map 1.1) appears to bisect the trend in slope values. East of the L-67 EXT, trends indicate a dominance of lower slope values, growing more negative in proximity to the bridge and the northeastern ENP border. The literature details negative hydrologic trends in the NESRS since 2002, highlighting the instability of water level trends as a contributor to plant stress. These findings are corroborated by the lower NDVI values in the NESRS.

Site NESRS 2 is identified in Figure 2.7 as having a negative water level trend since 2002. Figure 2.7 revealed that from 2007-2009 and in 2011, water levels dropped approximately 30 cm below ground elevation. The literature reviewed suggests this is equal to the deepest extent of *C. jamaicense* roots, which is the dominant vegetation cover in the area (Table 2.1). Studies have also indicated that water levels <5 cm above ground impacted *C. jamaicense* ANPP most negatively (Sklar et al. 2000). Map 4.1 shows generally negative slope trends around NESRS 2, which is consistent with declining water levels resulting in increased plant stress, affecting NDVI measurements.
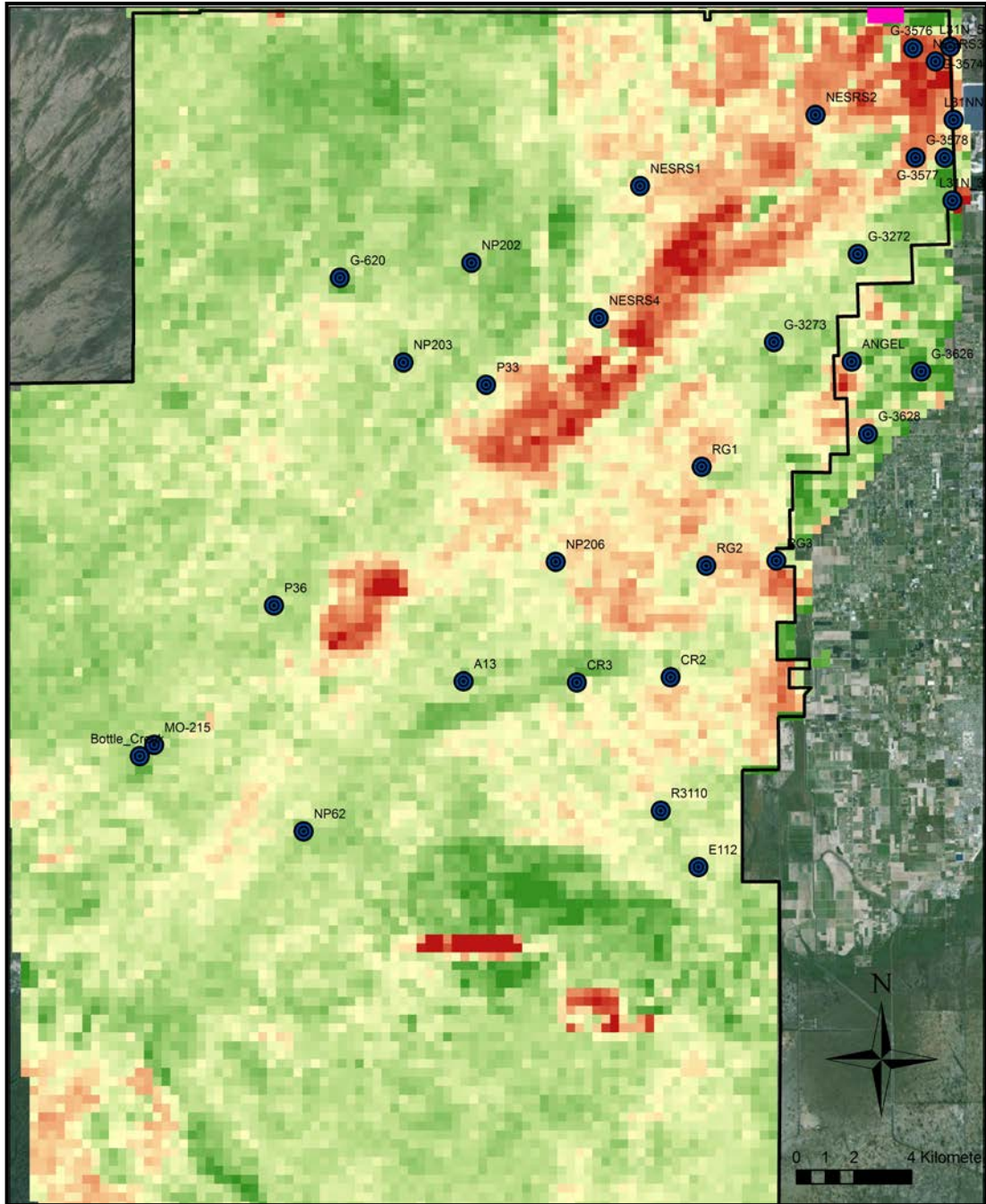
Map 4.1: TS Slope values for Dry Seasons from 2002-2013 across the Shark River Slough.

Pixels indicating higher slope values in the NESRS appear to form in linear segments, particularly close to (and often emerging from) Tamiami Trail. Map 2.1 suggests higher slope values along these segments coincide with anthropogenic disturbances to the landscape. Figure 2.5 details how deep water channels carved by airboat activity as well as the L-67 EXT canal and levee provide pathways for exotic species to penetrate the slough. The mapping effort by Welch et al. (1999) and various studies indicate that *T. latifolia* has spread along these features (Richardson 2008; Porter 2001). *T. latifolia* becomes highly competitive in flooded conditions, able to tolerate artificially deep water pooled along levees and canals (Sklar et al. 2000). Under low oxygen stress brought upon by deep water, *T. latifolia* has been shown to exhibit greater net photosynthesis and biomass than *C. jamaicense* (Porter 2001). Thus, if higher slope values along disturbed areas of the NESRS are representative of *T. latifolia*, this corroborates studies which have observed increased resilience of exotic species at the expense of *C. jamaicense* (Richardson 2008).

T. latifolia is not tolerant of drought conditions, and is thus restricted to areas where water depths have been altered. Furthermore, their expansion is fueled by P-loaded water, which enters the ENP through culverts under Tamiami Trail (Richardson 2008). This offers an explanation for the linear segments of higher slope that appear to originate from Tamiami trail. *T. latifolia* proves resistant to water stress trends exhibited in the NESRS, owing to better adaptation to abnormally deep water and low oxygen stress (Sklar et al. 2000). However, this limits its range to these disturbed sites. When juxtaposed against an area of negative slope possibly representative of stressed *C. jamaicense*, they appear distinguishable on MODIS-NDVI.

Figure 2.6 demonstrates the diminished volume discharge under Tamiami Trail in the NESRS portion since the ecosystem was modified decades ago. As a consequence, the L-67 EXT levee pools water along its eastern edge. Examining trends in water level for NESRS 1 reveals differences in the graph of NESRS 2 from Figure 2.7. Despite their proximity and similar elevation, NESRS 1 water level only dropped below ground level in years with severe drought (2009 and 2011). In contrast, NESRS 2 regularly experienced substantial declines in water level during the dry season, often dropping below ground level or close to it. These trends are corroborated by the slope analysis in Map 4.1. Pixel values trend lower moving farther east from the L-67 EXT levee, despite being on slough. This supports the assessment of the NESRS as affected by unreliable (and deficient) water flow. Areas of the NESRS that are more regularly hydrated during the dry season, such as those closer to artificial barriers, exhibit higher slope values. Conversely, water deprived eastern portions of the NESRS experience decreasing slope trends.

However, an exception is evident when observing the off slough portion of the NESRS, particularly near the ENP border. Our hydrologic assessment, in agreement with the literature, identified this area as most affected by irregular water flow in the NESRS (Lodge 2010; Armentano et al. 2002; Kiker et al. 2001; Sklar et al. 2000). Figure 2.7 shows the hydrologic profile of water level for site G-3272, located in this cluster of higher slope values. It reveals that water levels at the site seldom extend above ground level and during severe drought, can plummet to depths of 100 cm below ground elevation.

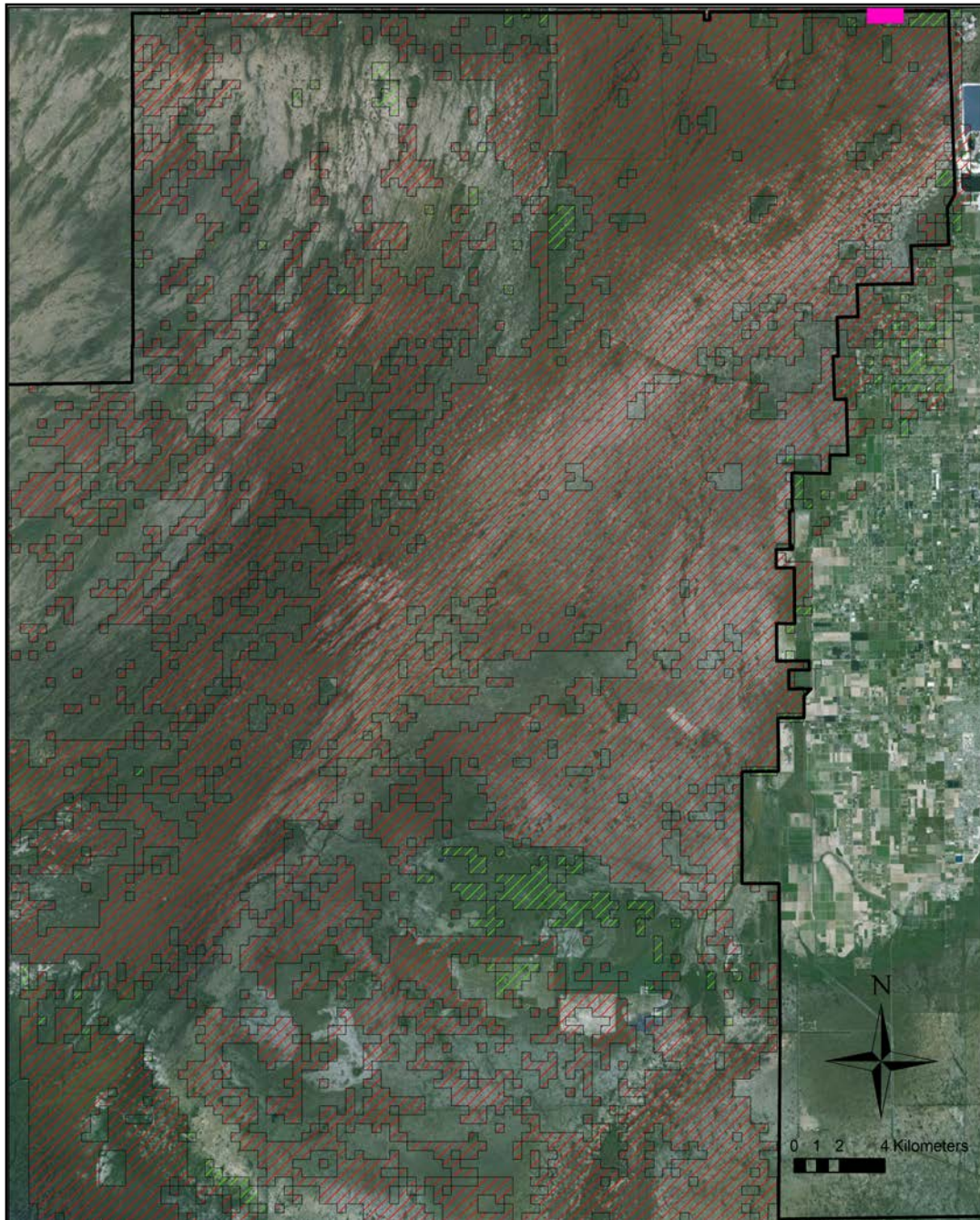High pixel values recorded there are inconsistent with the literature regarding *C. jamaicense* roots remaining adequately hydrated, as they reportedly reach maximum depths of 50 cm under ideal growing conditions (Richardson 2008). However, as can be observed in Map 2.1 and studies from the area, there has been an enduring proliferation of *M. quinquenervia* for decades (Armentano et al. 2002; Hofstetter and Sonenshein 1990). The loss of ~3 feet of peat soils since the 1940s and declines in water level have shortened the hydroperiods in the area (CEPP EIS 2014; Porter 2001; Sklar 2000). This increased fire frequency over the past decades, which enabled succession by strands of *M. quinquenervia* and *S. caroliniana,* now mature with deeper roots and tolerant of wet season flooding (Armentano et al. 2002; Hofstetter and Sonenshein 1990). Their recorded presence in the area and ability to better withstand water deprivation than *C. jamaicense*, provide an explanation for the clustering of higher slope values.

Map 4.2A shows the p-values for areas of significant slope (where p <0.05). Slope across the NESRS is largely significant, supporting research characterizing the area's vegetation as suffering from water stress. Significance was most present among areas of negative slope, as seen in Map 4.2B. Despite being spatially comprehensible, higher slope values observed around sites G-3272, G-3273, and the L-67 EXT levee were found to be insignificant. Only three, small clusters exhibited positive significance: along the L-67 EXT canal, near the ENP border and along Tamiami Trail, just east of the bridge. Thus, pixels with higher slope in the NESRS are still potentially affected by declining hydrologic conditions, but less so than significant negative pixels.
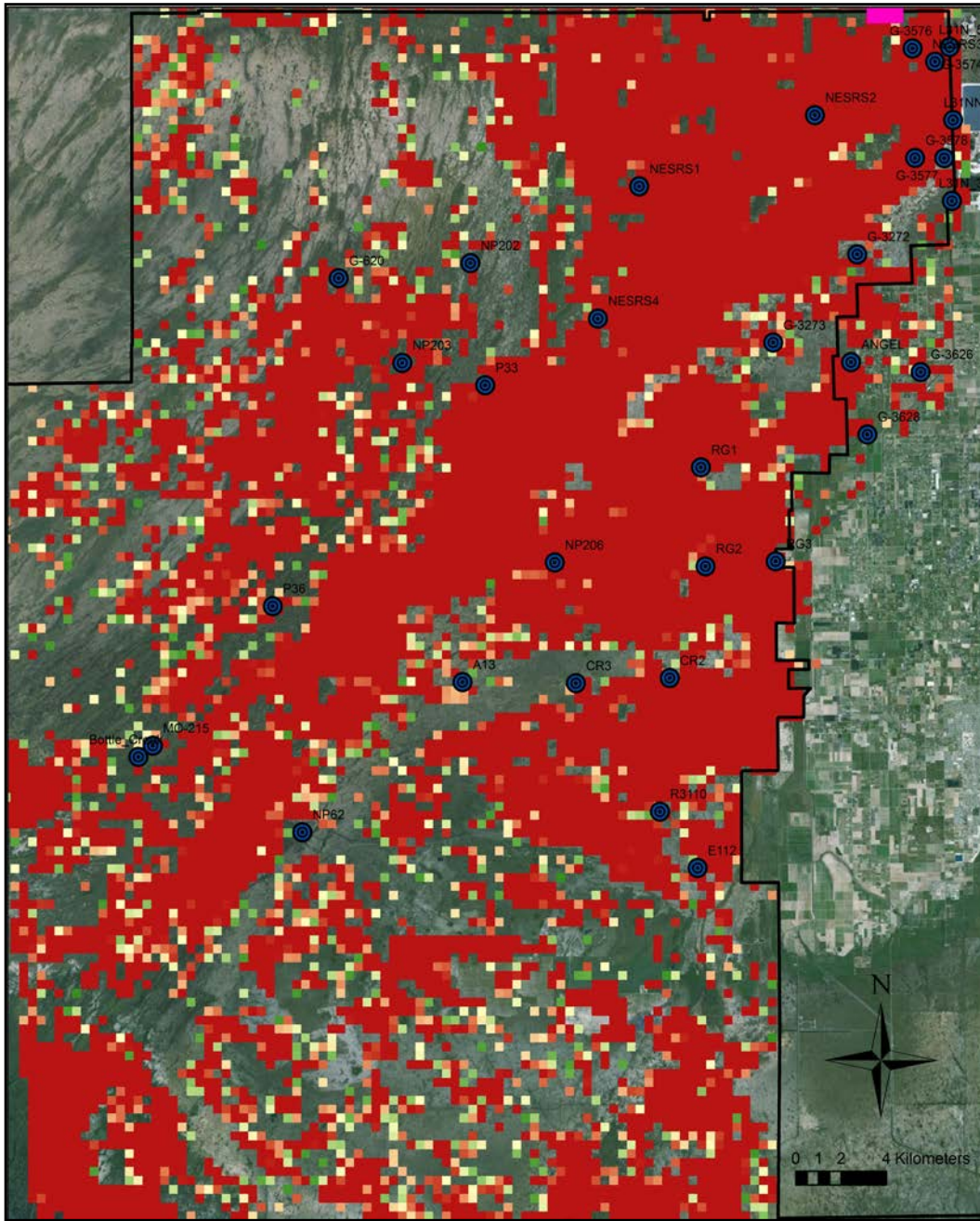
Map 4.2 A: p-values for areas of significant slope (where $p < 0.05$) in Dry Seasons from 2002-2013.

Dry Season 2002-2013

- ⦿ Gages (Sites)
- ▮ Tamiami Trail Bridge
- ── ENP Boundary

P Value

High : 0.05

Low : 0
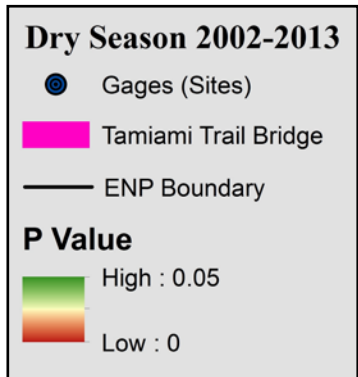
Map 4.2 B: Areas with significant positive and negative trends for dry seasons from 2002-2013 over Google Earth satellite imagery.

Dry Seasons 2002-2013

Tamiami Trail Bridge

ENP Boundary

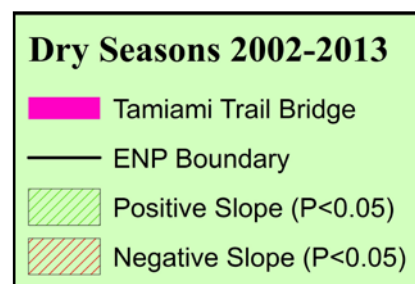Positive Slope (P<0.05)

Negative Slope (P<0.05)

Figure 2.6 showed diminished water flow under Tamiami Trail into the NESRS, but conversely, an increase in volume of water discharged into the slough west of the L-67 EXT levee. Despite declining average precipitation trends since 2002, Map 4.1 demonstrates that slope values are among the highest on slough. This is a visibly stark contrast to trends in the NESRS, despite both areas being historically dominated by the same vegetation cover, *C. jamaicense*. Low water flow discharge into the NESRS appears to lower pixel values, while increased flow west of the L-67 EXT levee increases them. Productivity from *C. jamaicense* is greatest when submerged in 30-50 cm of water (Sklar et al. 2000). Therefore, increased hydration of the area during the dry season may have influenced higher slope trends. This reaffirms efforts to elevate Tamiami Trail and increase water flow into the NESRS, lessening the reliance on fluctuating precipitation inputs. However, as evident in the NESRS, Maps 4.2 A and B show that the p-values for areas of significant slope were predominantly negative. Most of the higher slope values recorded in the area appear insignificant, though pockets of significant positive slope do appear among clusters of the highest slope values. Hydration may be adequate to avoid significant declines as observed in the NESRS, but it does not appear to translate to increases in NDVI measurements.

Furthermore, factors influencing the higher slope values closer to the Tamiami Trail appear to diminish further south along the slough. Map 4.1 identifies low negative slope trends between sites G-620 and P36. These findings are consistent with research that suggests decreased oxidation from diminishing hydroperiod has resulted in thinner peat elevations along the south, and affected plants during drought (Lodge 2010; Sklar et al. 2000). Figure 2.7 demonstrates this effect, indicating site P36 has a ground

elevation of 0.5 meters, less than half of NESRS 2 and more than a meter less than G-3272. However, sites P36 and NP202 do not suffer from as much water constriction as the aforementioned sites to their north. Water levels seldom dropped below ground in NP202, and flooded conditions generally persisted throughout the dry season (Figure 2.7). This stability may be reflected in Map 4.1, where NP202 is surrounded by a cluster of higher, though insignificant, slope. Site P36 itself appears to follow slope trends similar to NP202 and exhibits a stable water flow range that remains between 1- 0.5 meters, except during severe drought (Figure 2.7). Trends in between the sites do reveal a swath of significant slope, but negative pixel values are not as low as those found in the NESRS, owing possibly to a less compromised water regime.

A significant, negative pattern of slope is visible in Map 4.1 along the eastern periphery of the Shark River Slough. NP202 is located on the slough, while NESRS 4 is <4 km to the east, on the slough's periphery. Despite their proximity, ground level elevation is lower at NP 202, preventing the area from drying completely. In contrast, NESRS 4 experiences declines that regularly bring water level at or below ground level, leaving extended dry periods with no flooding. As Figure 4.1 demonstrates, these effects become pronounced when precipitation inputs are low and water flow remains restricted from the NESRS. This was evident in 2008, where Figure 2.8 showed abnormally low precipitation inputs. This lack of precipitation is believed to have been a significant factor fueling a severe wildfire (the 2008 "Mustang Fire") that burned ~16,000 acres of land around site NESRS 4 (Ruiz et al. 2008; Ruiz et al. 2013). This was the largest wildfire outbreak since 1989, when more than 180,000 acres burned across the ENP (Anderson 2012). Given the severity of this fire and the below ground

water levels in Figure 4.1, much of the *C. jamaicense* burned down to the root, hampering the plant's recovery (Ruiz et al. 2013).

We can see evidence to support this, noticing significant negative trends across the slough's periphery coincide spatially with areas affected by the Mustang fire. *C. jamaicense* plants with submerged roots can fully recover burned biomass in less than a year, but when the roots and soils ignite, that recovery can take substantially more time (Anderson 2012; Wu et. al 2008). Thus, increased water flow should provide a buffer against abnormally low hydroperiods that increases *C. jamaicense* susceptibility to fire. With more reliable water flow, areas of noticeably high negative slope should decrease, as the potential for greater biomass loss from more intense fires decreases.

Moreover, higher elevations on the slough's periphery (and areas off slough) suggest increased water penetration will not affect the landscape evenly. Figure 4.1 shows that while normal precipitation inputs from 2012-2014 helped maintain water levels from reaching ground level in NP202, NESRS 4 still experienced drawdowns that virtually eliminated standing water. This indicates that given the current condition of the slough's periphery, even normal precipitation patterns appear to generate diminished hydroperiods, implying larger volumes of water flow may be required to minimize negative NDVI trends on the slough's periphery.
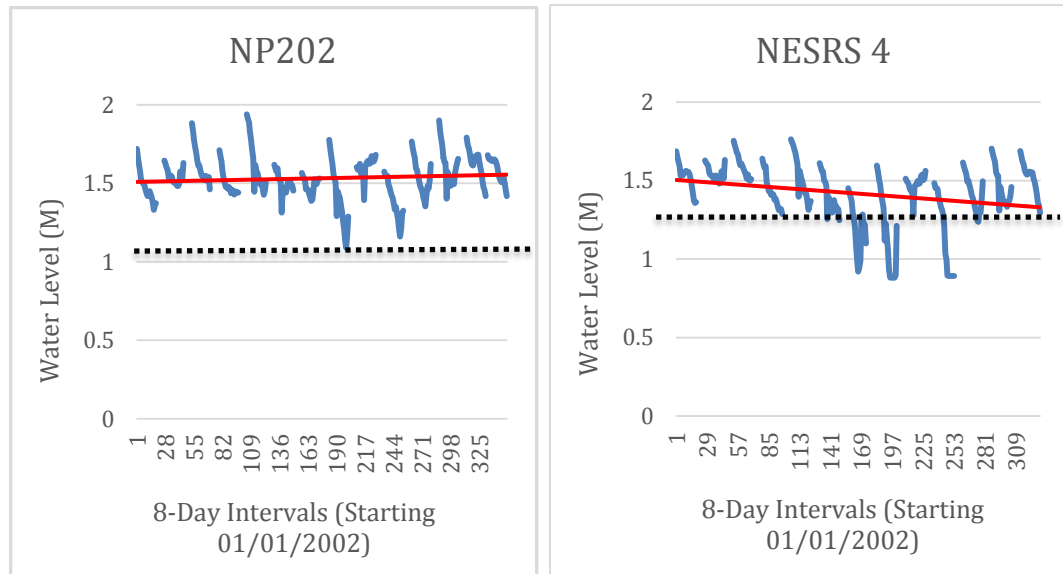
Figure 4.1: Graphs of two EDEN gages depicting water levels in the dry seasons (January-May) from 2002-2015. The red line represents trends during the 13 years observed; black dotted lines indicate the ground elevation in NGVD at each site.

The short time period since bridge construction limits the utility of trend analysis, thus I analyzed year-on-year change in dry season NDVI sums to assess trends. Maps 4.3 and 4.4 depict out changes in ΣNDVI for 2014 (from 2013) and 2015 (from 2014). ΣNDVI differences shown in Map 4.3 represent the initial effects after the LRR Bridge's construction and provide insight into the performance of MODIS-NDVI in monitoring those changes. Large increases in ΣNDVI are visible in the NESRS, from NESRS1 to the LRR Bridge. This area was identified in Map 4.1 as an area of broad decline in slope from 2002-2013. Furthermore, the periphery of the slough in the NESRS also appears to have increased in ΣNDVI. This was another area of significant, negative slope in 2002-2013, although increases in ΣNDVI are less prominent than areas on slough in the NESRS. The L-67 EXT levee appears

discernable as a linear segment of negative ΣNDVI difference. Near sites G-3272 and G-3273, decreases in ΣNDVI coincide with areas identified as increasingly water stressed in Figure 2.7.

On slough, differences in ΣNDVI for Map 4.3 are mixed. South of Tamiami Trail, a broad cluster of negative values is evident in an area that experienced higher slope values from 2002-2013. Comparatively, observations from the central slough show increases in ΣNDVI relative to negative slope trends in Map 4.1. Notably, an intense cluster of high ΣNDVI difference east of site P36 coincides with one of the most visible clusters of negative slope from 2002-2013. This suggests vegetation may be benefitting from conditions in 2014 as NDVI sums increase. Towards the southern extent of the slough, ΣNDVI broadly declined in 2014 from 2013. Peat soils in the area are thinner and water level tends to be lower than in the northern slough (Lodge 2010). Off slough, spatial patterns are difficult to discern in Map 4.3. Areas south of the NESRS, along the ENP border, experienced increases in ΣNDVI, though a cluster of negative differences in ΣNDVI are visible between A13 and RG2. Lastly, a broad area east of site NP62 showed increases in ΣNDVI.
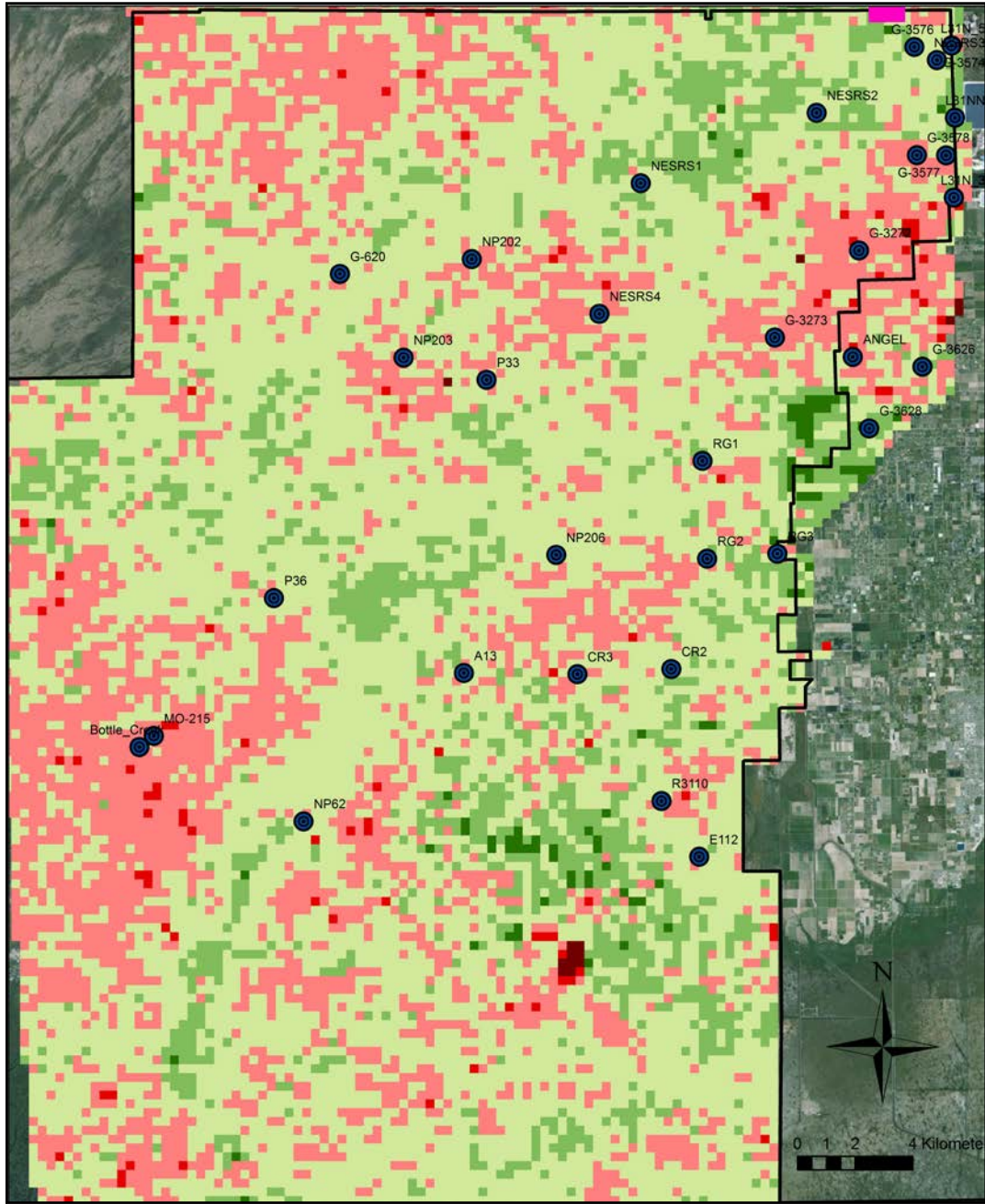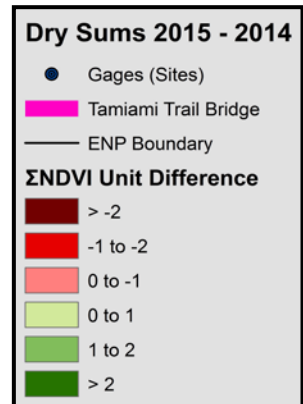
Map 4.3:

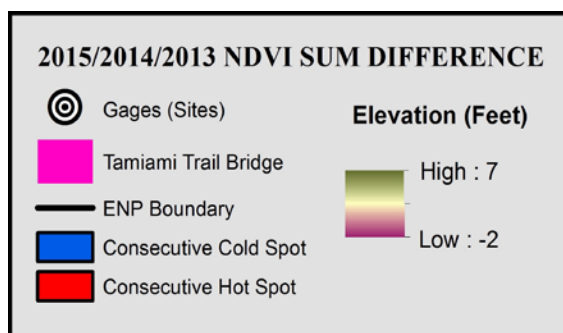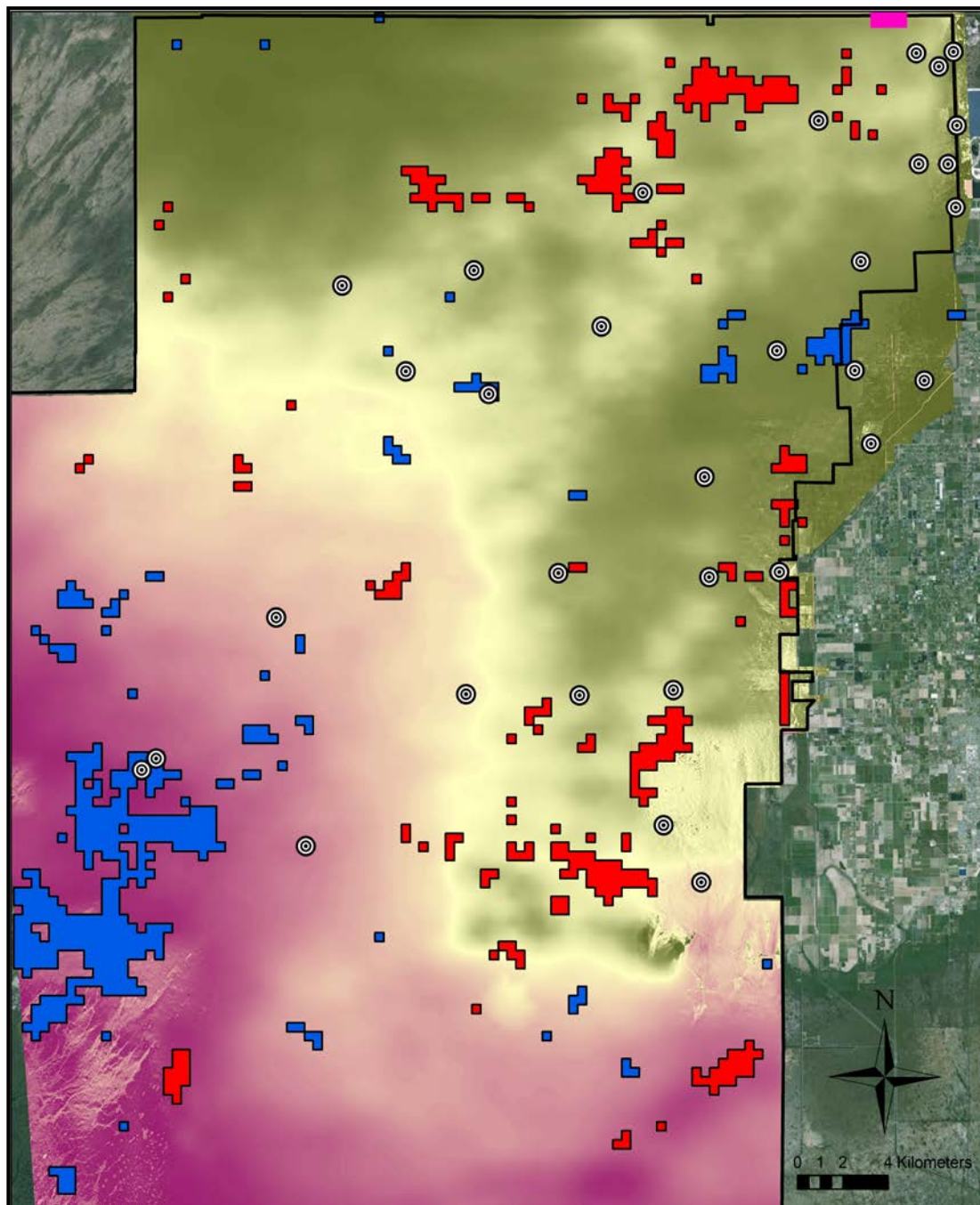Dry season ΣNDVI 2014 – dry season ΣNDVI 2013.
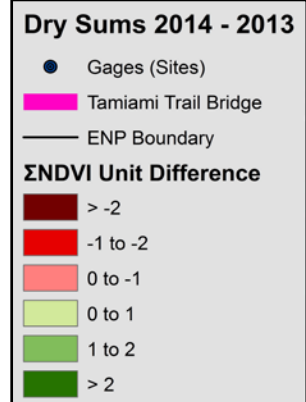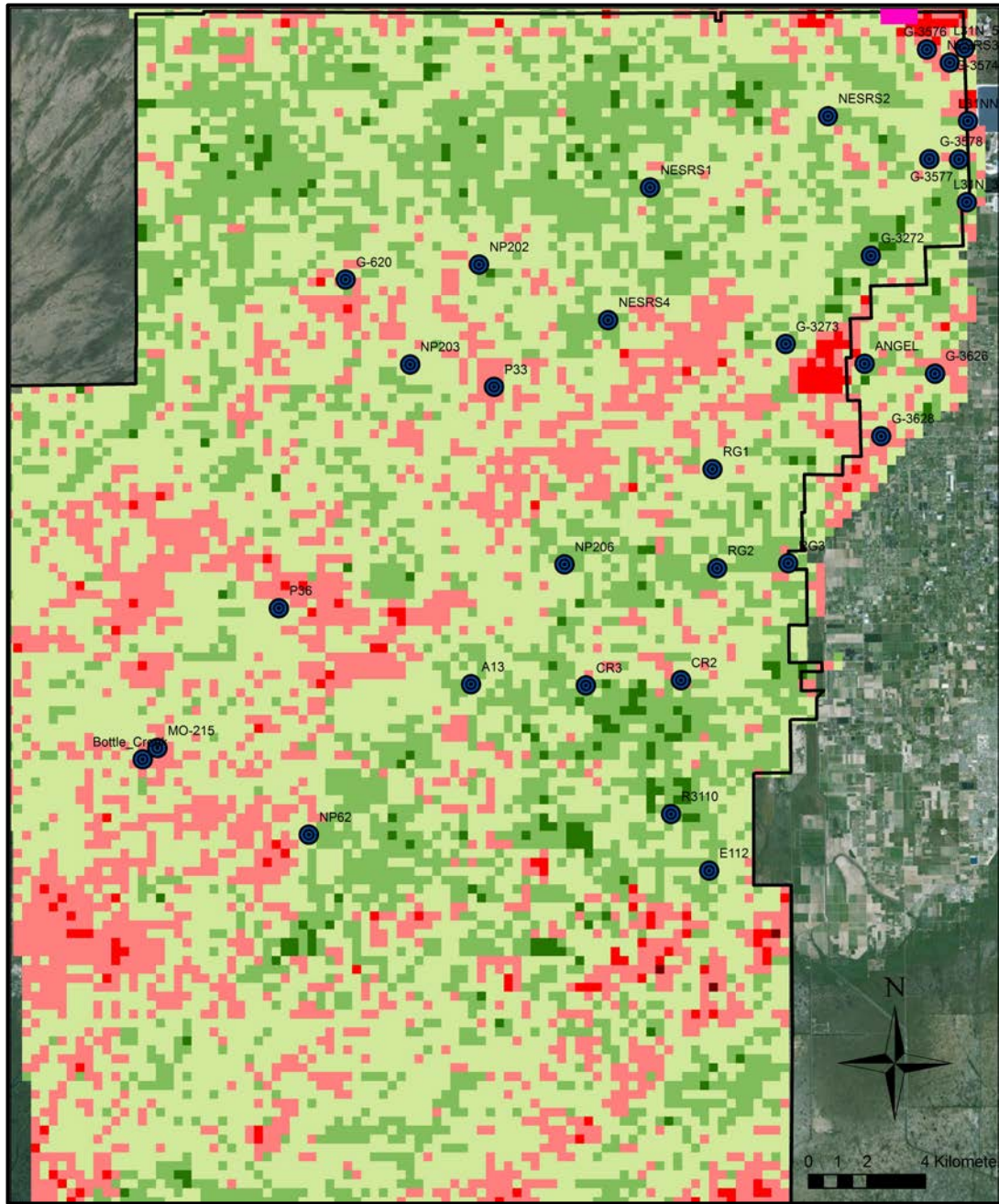
Map 4.4:

Dry season ΣNDVI 2015 – dry season ΣNDVI 2014.

Map 4.4 reveals the difference between ΣNDVI for 2015 and 2014 and allows us to compare results to spatial patterns in Map 4.3. 2015 was the bridge's second year post-construction and unlike 2014, occurred during a dry season with diminished precipitation inputs. ΣNDVI generally increased again in the NESRS, though it is no longer possible to discern differences west and east of the L-67 EXT. Increased ΣNDVI in Map 4.4 for clusters around sites G-3272 and G-3273 reversed declines exhibited in Map 4.3. Figure 2.7 revealed declining water levels at G-3272 abated somewhat due to increased precipitation inputs from 2012-2014, but declined again in 2015. Higher slope values from 2002-2013 and increased ΣNDVI in 2015 compared to 2014 suggest that NDVI trends appear to increase during water constriction.

Assessing patterns on slough, the norther portion appears to have increased ΣNDVI, whereas central and southern slough sections generally exhibited declines (with mixed pockets of increases). The periphery of the slough demonstrates visible declines in ΣNDVI values, particularly compared to gains observed in Map 4.3 and similar to negative slope trends observed from 2002-2013. The intense cluster of increased values east of site P36 appears to have lost much of the gains in ΣNDVI from 2014. Off Slough, widespread increases in ΣNDVI differences were observed in Map 4.4. These results contrast with generally declining trends on slough in 2015, suggesting that NDVI sums off slough appear to be less affected by limited precipitation.

Map 4.5 depicts the intersection of polygons generated from the Z scores of ΣNDVI 2015 – 2014 and ΣNDVI 2014 – ΣNDVI 2013, revealing significant areas (at p <0.05) of consecutive increasing and decreasing ΣNDVI difference. These were subsequently overlaid on a DEM. Spatially, the consecutive Hot Spots appear to cluster around two locations: in the NESRS, extending west of the L-67 EXT levee and far down the slough. Furthermore, a pattern emerges between Hot/Cold Spots and elevation. Significance appear predominantly in lower elevations (below 5 feet), evidenced by the general lack of significant polygons in the highest elevations: the northern slough and south of the NESRS. Examining the cluster extending west from the NESRS supports this, as the Hot Spot polygons only extend into a depression surrounded by higher elevation. Southeast, off the slough, a fragmented Hot Spot cluster is located between six gages. As with the NESRS, it appears that consecutive Hot Spots are occurring in lower elevations, which may remain more hydrated during the dry season. Significant Cold Spots cluster extensively far south along the slough, where it intersects with the low laying estuaries of Florida Bay. Limited decreases elsewhere appear to lack a spatially comprehensible pattern relating to elevation.

Map 4.5: Cumulative spatially significant clusters for dry seasons of ΣNDVI 2015 –ΣNDVI 2014 and ΣNDVI 2014 – ΣNDVI 2013 overlaid on a DEM of the study area. The red polygons in the NESRS spatially depict where interannual increases in ΣNDVI are occurring.

Figure 4.2: Area in Km^2 of major vegetation types that occurred in spatially significant ($p < 0.05$) hot or cold clusters for 2014-2013 and 2015-2014. Interannual increases among Hot Spots suggest increased ΣNDVI, while increases among Cold Spots suggest decreased ΣNDVI.

Figure 4.2 uses major vegetation types from Map 2.1 to examine trends in the Hot Spot analysis by calculating percent change of total area (in Km^2) for each vegetation type identified within a Hot or Cold Spot, between 2013-2014 and 2014-2015. Total area of invasive species within an identified Hot Spot decreased 41% between the time periods; while area identified as being in a Cold Spot increased 41%. Similarly, total area of hammocks located in Hot Spots declined 24% from 2013-2014 to 2014-2015, while area in Cold Spots increased 30% over the consecutive time periods. Total area of bayheads in a Hot Spot increased 63% between 2013-2014 and 2014-2015, while presence in a Cold Spot decreased 41%.

Patterns in mixed marshes/prairies followed that of bayheads, though the vegetative group was more extensive (particularly in Hot Spots). Total area within a Hot Spot grew by 24%, while total area within a Cold Spot declined 42%. Shrub/Scrub total area experienced the greatest percent gain within a Hot Spot, with a 116%. Despite that, Cold Spot total area declined only 12%. Both vegetative communities exhibit similar trends and are largely located off Slough. As demonstrated in Map 4.6, this area had spatially significant clusters of higher ΣNDVI across both time periods. Significant total area for *T. Latifolia* was among the lowest for all vegetative classes and highest for tall *C. jamaicense*. Total area in a Hot Spot declined between 2013-2014 and 2014-2014, falling just 1% for *T. Latifolia* and a moderate 12% for tall *C. jamaicense*. In contrast, changes in total area within a Cold Spot from 2013-2014 and 2014-2015 were highly varied between them. Tall *C. jamaicense* experienced a slight 3% increase, but *T. Latifolia* declined by 49%, the largest drop of all major vegetation classes in spatially significant Cold Spots of ΣNDVI change. This decline results from significantly positive ΣNDVI change in 2015-2014 throughout the northern Shark River Slough.

Figure 4.3 displays results for sparse *C. jamaicense* prairies. Total area of sparse *C. jamaicense* ΣNDVI occurring in Hot Spots increased 15% in 2015-2014 when compared to 2014-2013. In contrast, change in total area occurring within a Cold Spot was only a 3% decline. Overall, significant Hot Spots were more prevalent in 2015-2014 when compared to Cold Spots in the same time period.
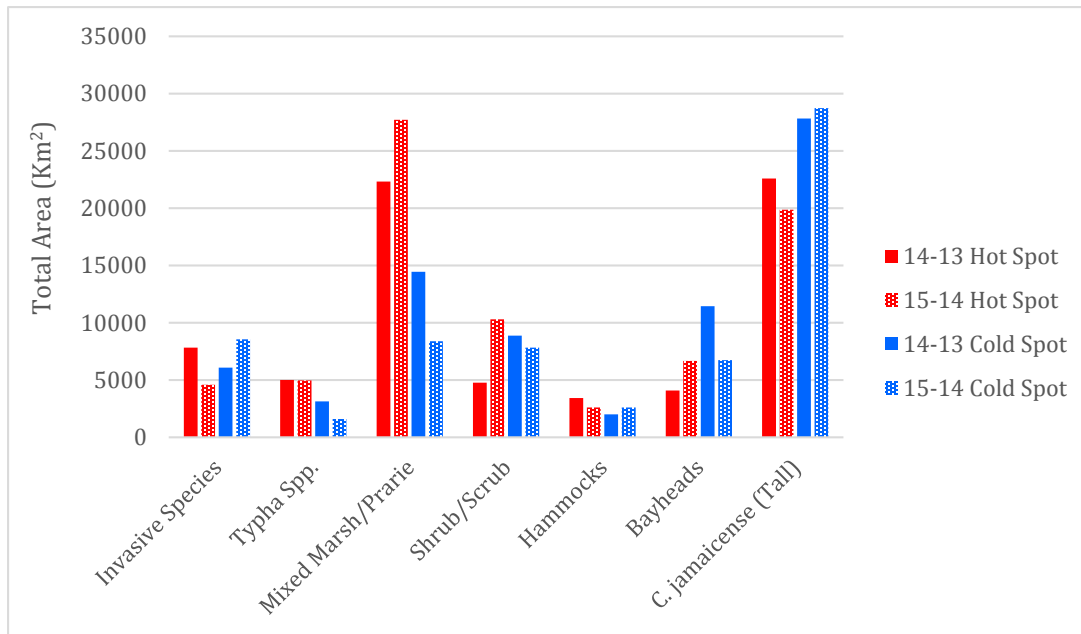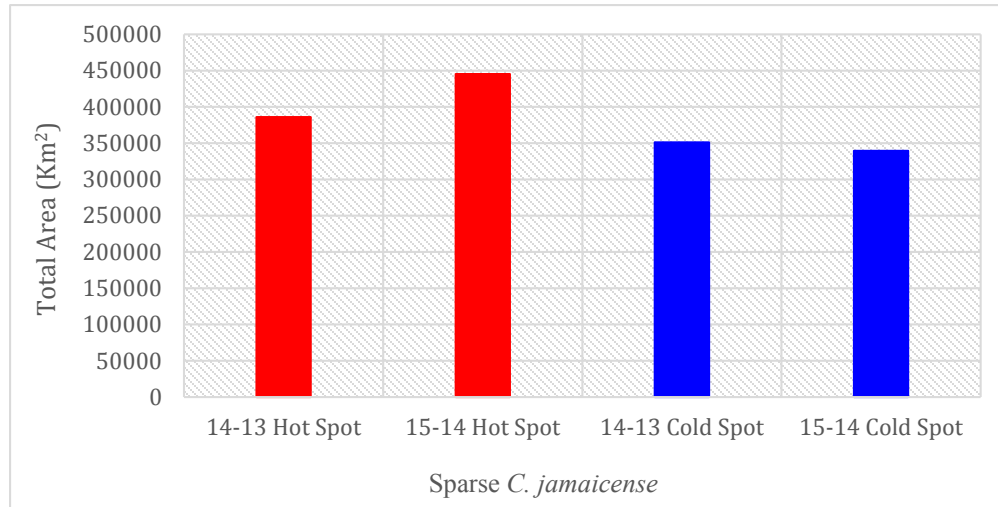
Figure 4.3: Area in Km^2 of *C. jamaicense* that occurred in spatially significant (p < 0.05) hot or cold clusters for 2014-2013 and 2015-2014.

CHAPTER V:

CONCLUSION

Figure 1.2 outlined the goals of the TTMP, which has called for an additional 5.5 miles of bridges along Tamiami Trail to increase freshwater flow. The plan remains under consideration, as efforts are underway to secure the $180 million dollars for its construction. The next target for bridging under a preliminary proposal is a 2.6 mile portion of Tamiami Trail, between Frog City and Camp Osceola (identified in Figure 1.2). Adaptive management strategies employed under CERP are a critical component of the TTMP (Kiker et al. 2001). As we assess pre and post-bridge construction patterns in the NESRS, data acquired can be used to maximize the benefits of future TTMP projects and help spatially guide adaptive management strategies.

Numerous studies have used Landsat imagery for NDVI wetland assessments, but heavy cloud cover rendered it unsuitable for this analysis (Adjei et al. 2015; Dong et al. 2014; Steyer et al. 2013; Wang et al. 2013; Clerici et al. 2012; Rani et al. 2011; Ordoyne and Friedl 2008; Guo and Chen 2007). MODIS imagery was therefore used, exhibiting sufficient spatial resolution and an extensive temporal range to generate 247 NDVI measurements, which served as a proxy for annual net primary productivity (ANPP) (Fuller and Wang 2014). These were examined in a spatiotemporal quantitative analysis designed to evaluate whether data derived could supplement existing monitoring techniques, such as above ground biomass sampling.

A linear regression analysis between ΣNDVI and water level was also performed at various temporal and spatial scales (Table 3.1). Autocorrelation can occur

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with time series data (Ragavan and Fernandez 2006). A Durbin-Watson test was performed on the regression analyses in Table 3.2 and found four of the time periods to be autocorrelated. Despite occurring in < 20% of cases, it nevertheless limited the utility of the regression analysis. For the on slough analysis, 2002-2014 was autocorrelated and thus not examined in depth. Overall, the regression analysis produced mixed results for the relationship between ΣNDVI and water level. Trends were almost exclusively negative at moderate to strong correlation. There is evidence rapid water level fluctuations and extended hydroperiods (in levels >50cm) have a negative effect on slough vegetation, particularly in *C. jamaicense* (Richardson 2008; Ross et al. 2003; Sklar et al. 2000). However, above ground water levels tend to not exceed those heights in the dry season, which is inconsistent with the negative trends observed.

The graphical representation in Figures 3.1-3.3 revealed ΣNDVI measurements to be clustered at times, which affected the regression analysis. Excluding those sites greatly affected results, eliminating any correlation between ΣNDVI and water level while indicating a large amount of variance between the data points. Adjei et al. (2015) highlighted mixed pixels as a potential source of error in NDVI assessments. Removal of data points further undermined results, reducing both r and r^2 values. One of the benefits of MODIS-NDVI is the ability to gather archival data, a limitation that was observed in previous biomass sampling along the Shark River Slough (Gaiser and Childers 2011). However, the lack of a consistent and strong relationship between ΣNDVI and water level failed to make it a suitable alternative, despite its large temporal resolution.

A site-specific analysis was subsequently conducted to see if a stronger relationship was discernible on a smaller scale (Tables 3.3 and 3.4). Autocorrelation occurred more than in the previous analysis, present in roughly a 33% of sites. Unlike in Table 3.2, a positive relationship was observed between water level and ΣNDVI, more consistent with previous assessments of the relationship (Brandt et al. 2014; Richardson 2008; Sklar et al. 2000). Examining the results from site G-3576 should reveal patterns in the relationship given its proximity to the bridge. However, results were inconsistent though, with negative trends during the bridge's construction, positive trends pre-construction and no correlation post-construction. Despite that, Figure 3.4 graphed data from G-3576 in 2002-2009 and reveals a slight, positive trend. Ideal precipitation in the 2014 dry season and increased water flow from the bridge could have impacted NDVI measurements by increasing absorption in the infrared portion of the spectrum (Adjei et al 2015; Brandt et al. 2014). This is supported by clearer results in P36. As demonstrated in Figure 2.7, P36 had relatively lower, stable water levels. Correlations were highest in 2002-2009 and 2014, suggesting that reliable water flow in low volumes could improve the analysis. However, the trend of low r^2 values persisted.

Overall, the regression analysis of NDVI v. WL yielded inconsistent and unreliable results. Even the adjusted analysis, which attempted to limit the influence of mixed pixels and abnormally low water levels, failed to improve results and often lessened them. It is unclear if emergent vegetation interfered with the pixels analysis or NDVI as a measurement could not relate to water levels consistently. In addition, autocorrelation eliminated time periods critical to establishing long term trends.

Adaptive management improves the function of a system by incorporating data on uncertainties and fluctuations in an effort to enhance performance (Milon and Scrogin 2006; Sklar et al. 2005; Doyle 2001). However, the regression analysis of MODIS-NDVI does not exhibit the necessary consistency in results to reduce uncertainty and successfully monitor change from the TTMP.

A spatiotemporal assessment of trends using TS Slope values yielded clearer results. An advantage of the slope analysis, utilizing continuous pixels instead of a sample of 30 gages, is the ability to visualize trends across the entire Shark River Slough. This supports the holistic nature of CERP restoration efforts, considering effects across the ecosystem are not independent of each other (Gerkak and Hekika 2011; Sklar et al. 2005). It also enables a method of spatially highlighting areas that have changed over time. The magnitude of CERP is unprecedented and the project has witnessed increased federal holdings as part of its implementation. Demonstrating the viability of remote sensing to identify and document changes between vegetation and hydrology thus serves as an additional tool in determining the progress of restoration efforts. Map 4.1 demonstrated that from 2002-2013, significant negative slope trends were most visible in the NESRS.

Various authors, and as demonstrated in Figures 2.6 and 2.7, report that since 2002, the hydrologic regime in the area has been characterized by irregular water flow, low precipitation inputs, declining soil elevation and below ground water levels during the dry season (CEPP EIS 2014; Porter 2001; Sklar et al. 2000). This has contributed to plant stress, particularly for *C. jamaicense*, which prefers slightly flooded conditions but is unable to access soil water if water levels drop 30 cm below ground *(*Richardson

2008). Utilizing slope measurements from MODIS-NDVI, we assessed whether trends match these findings. In the NESRS, they appear to support the findings, as declines were generally observed in areas where vegetation cover is identified as *C. jamaicense* by the Welch et al. (1999) map. Lower discharge of water flow under Tamiami trail, as seen in Figure 2.6, and declining precipitation inputs, appear to have lowered dry season *C. jamaicense* productivity in the NESRS, supported by the predominance of pixels indicating declines in TS slope.

Additionally, the TS slope analysis in the NESRS also detected spatially comprehensible features that if accurate, increase the utility of MODIS-NDVI for adaptive management goals. Linear segments of pixels with significant high values appear to coincide with anthropogenic disturbances to the landscape (such as deep water channels and levees) as detailed in Figure 2.5. These disturbances create abnormally deep pools of water not beneficial to native vegetation (Harvey et al. 2010). Richardson (2008) and Porter (2001) corroborate the findings of Welch et al. (1999) that show *T. latifolia* has exhibited a competitive advantage over *C. jamaicense* in disturbed areas and proliferated.

The slope analysis reveals higher pixel values along these linear segments, which appear to penetrate a broad area of pixels with significant negative trends. This could indicate expansion of *T. latifolia* over *C. jamaicense,* owing to its greater net photosynthesis and biomass under low oxygen stress (Porter 2001). This is a critical finding with regards to the restoration of native *C. jamaicense*, as increased hydroperiods are unlikely to be effective in combating *T. latifolia* in the NESRS. Additionally, the increased freshwater diverted south is likely to remain p-loaded until

CERP efforts in the EAA progress, aiding in *T. latifolia* expansion. Thus, tracking the changes in slope of these linear segments is a supplementary tool for monitoring of non-native species' through future MWD projects.

Additionally, a similar pattern is discernable in the southeastern NESRS. Clusters of pixels with significant high values initially appear inconsistent with general declining trends of the NESRS. Figure 2.7 shows strong negative trends water levels at site G-3272, with levels often dropping too low for *C. jamaicense* roots to access soil moisture (Richardson 2008). However, Armentano et al. (2002) and Hofstetter and Sonenshein (1990) have documented an enduring proliferation of *M. quinquenervia* in the area. Mature trees have deeper roots, able to withstand water level drawdowns, and are spread by fires fueled in dry conditions. These trends corroborate results of the TS slope analysis, where the area shows a cluster of significant, positive pixels. Given decades of modification to the water regime and vegetation cover in the NESRS, monitoring of restoration efforts cannot simply focus on assessing change in positive or negative slope trends post-construction. For example, increased hydroperiods during the dry season may be unintentionally beneficial to exotic and invasive species, given their heavy proliferation. Thus, knowledge of the vegetation cover and its relationship to observed slope trends is essential to understanding what changes are occurring in the Shark River Slough.

Assessing post-construction change using the difference in ΣNDVI from 2013-2014 revealed more patterns than in 2014-2015. Trends in the NESRS were distinguishable. Initial observations appears to suggest the bridge resulted in an increase in pixels of higher value in the NESRS, over areas that were identified as

having significant, negative slope from 2002-2013. Furthermore, increases in ΣNDVI along the ENP border in the NESRS appear opposite to trends discovered in the slope analysis. Examining the slough's periphery, identified by its noticeable, significant, negative slope in Map 4.1, appears to suggest the increased freshwater flow contributed an increase in ΣNDVI. However, it is unknown whether these gains were observed due primarily to precipitation, which was ideal in 2014 or increased freshwater flow (Brandt et al. 2014). This method allows for a spatial examination of patterns in the immediate years following the bridging of a portion of the Tamiami Trail. Moreover, it has the potential to inform management officials of areas with increasing or decreasing ΣNDVI trends. With this tool, we can identify which areas are of concern (such as the NESRS) and the effects of the various bridging projects on vegetation.

Continued increases in 2014-2015 for ΣNDVI in the NESRS appear to suggest the bridge may have succeeded in maintaining adequate water levels, despite low precipitation in 2015. However, these trends were inconsistent. The slough's periphery, having increased ΣNDVI in 2013-2014, sharply declined by 2014-2015. Furthermore, Miller et al. (2004) states that areas west of the L-67 EXT levee are more adequately hydrated, owing to a larger share of discharge under Tamiami Trail. This ought to generate consistency in water levels for the area, which was observed in our hydrologic assessment in Figure 2.7. Yet, analysis of trends in Maps 4.3 and 4.4 show mixed results. In 2013-2014, large swaths of the area recorded lower pixel values, which appeared to reverse itself in 2014-2015, despite less precipitation. Perhaps prolonged submergence was an issue, but authors note that levels high enough to induce plant stress in *C. jamaicense* (> 50 cm) seldom occur in the dry season (Sklar et al. 2000;

Toth 1987). Overall, this indicates that more year-on-year ΣNDVI analyses may be required to build a more accurate profile of the post-construction effects on vegetation in the Shark River Slough.

Analyzing change in ΣNDVI produced mixed results, making it difficult to discern patterns and information. However, a Hot Spot analysis (Figure 4.5) identified areas of significant clustering and enabled us to assess the significance of results from changes in ΣNDVI. Consecutive Hot Spots were observed in the NESRS and further south, off slough. This indicates that there were statistically significant increases in ΣNDVI for the area in both 2014 and 2015. Given the limited size of the project (so far only a mile has been bridged), the NESRS was most expected to demonstrate changes. As observed in Map 4.5, a discernable relationship was revealed between the Hot Spots and elevation. Pockets of lower elevation in the NESRS appear to coincide with the Hot Spot polygons. This suggests that the bridge may be responsible for channeling more water into lower elevations, sustaining longer hydroperiods and resulting in gains in ΣNDVI for *C. jamaicense*. If further analyses into changes for 2016 and beyond corroborate these findings, it would lend evidence to the ability of the bridge to restore the Shark River Slough ecosystem.

Moreover, while Hot Spots were concentrated in the NESRS and areas off to the east, Cold Spots were overwhelmingly present at the southern extent of the slough. This suggests that while increased freshwater penetration may have benefitted the NESRS, areas further along the slough remain deficient. These findings demonstrate the efficacy of remote sensing and year-on-year ΣNDVI monitoring through a Getis-Ord Gi analysis as a tool to inform the adaptive management process. Through these

Hot Spots, we have a criteria by which to measure and quantify the success of restoration efforts. Additionally, Figures 4.2 and 4.3 demonstrates ways to discern vegetative trends from the Hot Spot analysis. In them, we observed that consecutive Hot Spots of increased ΣNDVI in the NESRS appeared to benefit *C. jamaicense* while Hot Spots further south most impacted wet prairies. Regarding the goals of CERP and the bridge project, these findings once more corroborate the theory that increased freshwater penetration was a vital, missing component of a viable Everglades restoration plan.

Overall, the spatiotemporal analysis of MODIS-NDVI was most successful in the TS slope analysis. It provides a method to observe trends across the slough, and identifies areas most in need of intervention. Additionally, the ability to identify significant Hot Spots and Cold Spots in year-on-year ΣNDVI is useful when intersected with vegetation cover maps. Researchers and management officials can thus utilize the Hot Spot analysis results to conduct biomass sampling (and other corroborative field work) in targeted areas of observed change. The 2.6 mile bridge portion is expected to begin construction in 2018, and following the schedule of the LRR Bridge, completion is likely around 2022 (National Park Service). This would provide roughly nine years from which additional slope analyses could assess where and how the slough has changed since construction of the LRR Bridge. Additionally, the data collected and analyzed in this study can serve as a reference for pre-construction vegetation patterns. Building upon research into vegetation cover and utilizing mapping efforts and biomass sampling to corroborate findings, the TS slope analysis becomes a useful tool to refine adaptive management strategies.

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