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Amor Elder
University of South Florida, aelder2@mail.usf.edu

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Using Remote Sensing to Evaluate Wetland Recovery in the Northern Tampa Bay Area Following Reduction in Groundwater Withdrawals

by

Amor Elder

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Arts Geography
School of Geosciences
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Major Professor: Ruiliang Pu, Ph.D.
Mark Rains, Ph.D.
Steven Reader, Ph.D.

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ABSTRACT

In the past, the Northern Tampa Bay Area (NTBA) wetlands saw severe declines in hydrologic conditions due to excessive groundwater withdrawal rates. Eventually these rates were reduced to allow the wetlands to recover. To monitor this recovery, the Southwest Florida Water Management district (SWFWMD) set up a fieldwork based scoring methodology, called the Wetlands Assessment Procedure (WAP). WAP has been used in many studies of the area since groundwater withdrawal reductions; with many of those studies finding the recovery to be mixed at best. However, these studies were very limited in the number of wetlands they could assess due to the limitations of fieldwork. Therefore, it was proposed that remotely sensed variables associated with water consumption and stress be used to assess the recovery of the NTBA wetlands, as remote sensing allows for efficient assessments of targets over large area. Utilizing ASTER imagery scenes from 2005 and 2014, 211 wetlands' remotely sensed responses of NDVI, Land Surface Temperature (LST), and Evapotranspiration (ET) were mapped and statistically examined for trends indicating improvement or decline. Furthermore, a subset of WAP scores for the two years were examined and compared to the remotely sensed values. The results were contradictory, with remotely sensed responses showing an improvement over the time period, WAP scores indicating a decline in hydrologic conditions, and the two methods showing little to no fit when modeled against each other. As such, it is believed at this time that the remotely sensed method is not suitable for measuring the indicators of wetland recovery used in the WAP methodology.

INTRODUCTION

The State of Florida is home to a large number of wetlands, historically covering about 50% of the state (Haag & Lee, 2010). Human activities have reduced their numbers and areas, with wetlands only covering 29% of the state as of 1996 (Haag & Lee, 2010). Laws and regulations, acquisition programs and other efforts at various governmental levels have helped reduce and reverse negative impacts on wetland health and numbers (Haag & Lee, 2010).

In the mid-90's, groundwater was the main source of water to the Tampa Bay area, with withdrawals from the main wellfields in the hundreds of millions of gallons per day (MGD) (Haag & Lee, 2010; Metz, 2011; Haag & Pfeiffer, 2012). This ever increasing amount of pumping within the Tampa Bay area was found to be negatively impacting the surrounding isolated freshwater wetlands (Lewis et al., 2009; Haag & Lee., 2010; Haag & Pfeiffer, 2012). Isolated wetlands are not connected to surface water bodies such as rivers or coastlines, and therefore depend on precipitation and the underlying aquifer to remain inundated (Haag & Lee., 2010; Metz., 2011). Due to groundwater withdrawals lowering of the Upper Floridan Aquifer potentiometric surface, there was a reduction in the amount of flooded area, and an altering of the flora species makeup within the wetland boundaries (Lewis et al., 2009; Haag & Lee., 2010; Haag & Pfeiffer, 2012). These impacts led to the implementation of lower groundwater withdrawal total MGD from the wellfields within the area, as well as the increased utilization of alternative sources of water such as surface water (Lewis et al., 2009; Haag & Lee., 2010;

Haag & Pfeiffer, 2012). Reductions started around 2003, and have helped raise the potentiometric surface of the aquifer, and led to the recovery of some of the wetlands (Haag & Lee, 2010; Metz, 2011; Haag & Pfeiffer, 2012; Tampa Bay Water., 2012). However, not all wetlands have shown improvement, as some wetlands have recovered despite being in the wellfield cone of depression, while others that were adjacent did not, and even continued to decline in health (Metz. 2011; Haag & Pfeiffer, 2012; Nilsson et al., 2012).

It is clear that more research is needed as to the extent of the recovery of the wetlands within the Northern Tampa Bay Area (NTBA). At the time of this thesis, no research was found utilizing remote sensing to evaluate the recovery of the wetlands within the NTBA following reductions in groundwater withdrawals. Therefore, this thesis will focus on the use of multi-temporal satellite remote sensing technology to map and evaluate the recovery of wetlands within the NTBA.

LITERATURE REVIEW

Wetland Health and Recovery in the NTBA

Many studies have been conducted within NTBA's isolated wetlands measuring their response to groundwater withdrawals. For example, Craig et al. (2001) used ground surveyed stress level data to classify cypress wetlands within the area. Stress level data attributed with 184 cypress wetland shapefiles were loaded against Landsat5 TM imagery from 1992 and 1994, and classified against a larger cypress Land Use Land Cover (LULC) shapefile. Results showed distribution of stressed wetlands within the NTBA, the severity, and changes in numbers from 1992 to 1994, with severely stressed wetlands increasing in percentage from 1992 to 1994. Their study demonstrated both the presence of stressed wetlands during higher maximum MGD and the feasibility of remote sensing and GIS in monitoring the health of the wetlands within the NTBA (Craig et al., 2001).

After the reduction in maximum MGD, Haag & Pfeiffer (2012) examined 11 wetlands of various vegetation community types, for increase in Wetland Assessment Procedure (WAP) scores and flooding duration during the years 1997-2010. WAP scores are a wetland condition scoring system used by the Southwest Florida Water Management District (SWFWMD), the most recent version in use from the year 2005 to the present. WAP scores are based on vegetation species and their locations within the wetland, with higher WAP scores correlating to appropriate species in appropriate locations, thus indicating a better functioning wetland. Examination of the changes in flooded area and WAP scores revealed improvement in some wetlands, but none or slight degradation in others. Their in depth study of a small subset of wetlands indicated that more research is needed as to exactly how many wetlands are actually recovering within the NTBA (Haag & Pfeiffer, 2012).

Metz (2011) also examines wetlands within the NTBA for recovery after reductions in pumping. The study examined what conditions facilitate wetland recovery, by studying nine wetlands. Metz (2011) reported four primary factors that affected wetland recovery which are listed by importance: Potentiometric surface of the Upper Floridan Aquifer, karst sinkhole activity, permeability of underlying sediments, and topographic elevation . The importance of potentiometric surface of the Floridan Aquifer indicates that the overall factor affecting wetlands is the ability to stay inundated. Wetlands where the potentiometric surface is close to the bottom are able to stay wet, instead of losing precipitation and overland flow to percolation into the underlying aquifer, due to the maintained increase in water table levels (Metz, 2011).

Nilsson et al., (2013) examined 56 isolated wetlands within the NTBA from 2001 – 2007. Using well level data as well as WAP water level and wetland pool data, Nilsson et al. (2013) calculated an estimate of the level and duration of flooding within a wetland. Results showed that wetlands acted as recharge zones, with water percolating from them into the aquifer, over 50% of the time. Flooding trends did not vary significantly between wetland classes, indicating that wetlands in the area are similar in hydrology. Wetland flood duration varied between sites despite close proximity to each other and wellfields, indicating a much more complex confinement unit than previously thought (Nilsson et al., 2013).

Remote Sensing of Vegetation and Thermal Infrared

Remote sensing of land surface characteristics was used in Craig et al. (2001) to examine wetland health. While Craig et al. (2001) used general Digital Numbers (DNs) to classify wetland stress, there are many other variables that could be used to examine wetland health, specifically methods that target the physiological processes of transpiration (usually paired with evaporation, and will here in be referred to as evapotranspiration (ET)), temperature control, and photosynthesis.

Stomata, small openings on the undersides of plant leaves used for photosynthesis and ET, control most of the water loss within the leaves of a plant (Taiz & Zeiger, 2006). As water is a vital resource for plants, stomata are not left open at all times, especially when water is scarce (Taiz & Zeiger, 2006). However, when water is abundant, plants will leave their stomata open despite the water loss (Taiz & Zeiger, 2006). Stomata- opening creates a cooling effect through the latent heat loss of ET (Taiz & Zeiger, 2006). Stomata closure is one of the first signs of water stress, whereas degradation of photosynthesis efficiency occurs as the water stress worsens (Taiz & Zeiger, 2006). This is because mesophyll, cells containing chloroplasts needed for photosynthesis, do not exhibit metabolic slowdown until water stress becomes more severe (Taiz & Zeiger, 2006).

These breakdowns in the plant's physiology can be detected via remote sensing techniques. For example, Zhang et al. (2013) reviewed literature focusing on remote sensing of drought impacts on forested landscapes. Zhang et al. (2013) noted that for vegetation droughts, physiological changes within the affected plants can be remotely sensed. Zhang et al. (2013) noted that as stomata closure interrupts the cooling ET process, the temperature of the canopy begins to rise. Thus, remote sensing of Land Surface Temperature (LST) can be used to examine water stress in plants, at early stages. As effects on photosynthesis occur at the mid-stage, vegetation indices can be utilized to examine more pronounced stages of water deficiency. The Normalized Difference Vegetation Index (NDVI) is a commonly employed vegetation index used to examine plant health, as well as to differentiate healthy vs. stressed or diseased vegetation. It can also be used in conjunction with LST to determine ET (Zhang et al., 2013).

NDVI is relatively straight forward to generate:

$$NDVI = \frac{NIR - R}{NIR + R}$$

where, NIR is the near infrared band, and R is the red band.

NIR and R bands are common and available in many commercial and public satellites in very coarse (over 200 m) to very fine (less than 10 m) resolution. LST is not as straight forward to calculate, as the formulas involved require thermal bands, which are not as common in satellite sensors, and may require outside meteorological data (Pu et al., 2006). Furthermore, algorithms can be very complex, some needing more than one thermal band, and multiple coefficients that differ depending on climate and location (Pu et al., 2006). For instance, Pu et al. (2006) assessed the use of satellite and airborne thermal sensors to detect urban LST. They used Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) thermal data to measure and compare LST with LST products generated by MODerate resolution Imaging Spectroradiometer (MODIS). They used a Split Window Algorithm (SWA) with two ASTER thermal bands, 13 and 14, to calculate LST. The algorithm requires transmittance (τ), water vapor, using MODTRAN4, a code used to approximate water vapor and its relationship to transmittance, a flat emissivity (ε) value for urban areas, interpolation of the relationship between brightness temperature ((Bi(Ti)), the temperature Ti "seen" at the satellite sensor for band i, using the formula:

$$Bi(Ti) = ai \cdot Ti - bi$$

as inputs in the SWA for LST. The SWA is defined as:

$$Ts = \frac{[C14 \cdot (B13 + D13) - C13 \cdot (D14 + B14)]}{(C14 \cdot A13 - C13 \cdot A14)}$$

where

$$A13 = a13 \cdot \varepsilon13 \cdot \tau13,$$

$$B13 = a13 \cdot T13 + b13 \cdot \varepsilon13 \cdot \tau13 - b13,$$

$$C13 = (1 - \tau13) \cdot [1 + (1 - \varepsilon13) \cdot \tau13] \cdot a13,$$

$$D13 = (1 - \tau13) \cdot [1 + (1 - \varepsilon13) \cdot \tau13] \cdot b13$$

$$A14 = a14 \cdot \varepsilon14 \cdot \tau14,$$

$$B14 = a14 \cdot T14 + b14 \cdot \varepsilon14 \cdot \tau14 - b14$$

$$C14 = (1 - \tau14) \cdot [1 + (1 - \varepsilon14) \cdot \tau14] \cdot a14$$

$$D14 = (1 - \tau14) \cdot [1 + (1 - \varepsilon14) \cdot \tau14] \cdot b14$$

where T13 and T14 are brightness temperature of ASTER thermal bands 13 and 14, respectively.

Despite using only 2 bands and a flat emissivity value, when compared to the formal LST product generated from ASTER, the SWA provided comparable results, with only a small difference in LST. Also, Pu et al. (2006) stated that previous literature revealed a negative correlation between LST and NDVI, something they themselves were also able to reproduce using the SWA, further supporting their use of the SWA. These results indicate that LST from basic ASTER data can be retrieved in a cost efficient way.

While Pu et al., (2006) were able to generate LST, the resultant image was 90 m resolution. For large areas this is suitable, but for many small areas this results in mixed pixel values that may not accurately reflect the LST of the targeted feature (Pu et al., 2006; Agam et al., 2007; Anderson et al., 2012).

Agam et al. (2007)'s study examined a way to improve the spatial resolution of the thermal band through sharpening. Utilizing the well-known relationship between NDVI and LST, they examined four algorithms used to sharpen thermal imagery to a higher resolution. By testing the algorithms over a corn and soybean field in Iowa, Agam et al. (2007) found that the simplified fractional vegetation cover (fc_s) resulted in one of the lowest Root Mean Square Error (RMSE). A least square regression between LST and NDVI, where NDVI is aggregated to the resolution of the LST ($\mathrm{NDVI}_{\mathrm{low}}$) imagery, was performed. Then, the sharpening process was applied using the following formulas (Agam et al., 2007):

$$\widehat{T}_s(\mathrm{NDVI}_{low}) = f(\mathrm{NDVI}_{low})$$

$$\widehat{T}_s(\mathrm{NDVI}_{high}) = f(\mathrm{NDVI}_{high})$$

$$\Delta\widehat{T}_{s\ low} = T_{s\ low} - \widehat{T}_s(\mathrm{NDVI}_{low})$$

$$\widehat{T}_{s\ high} = \widehat{T}_s\left(\mathrm{NDVI}_{high}\right) + \Delta\widehat{T}_{s\ low}$$

where NDVI_{high} = NDVI at its original spatial resolution

$\widehat{Ts}$ = temperature generated from NDVI regression *f(NDVI)* which is defined below, and where *low* and *high* are defined as low and high resolution (pixel size), respectively

$$f(NDVI) = a0 - a1(1 - NDVI)^{0.625}$$

where *f* = a function performed on (x)

a0 and a1 = scene specific parameters defined from a least square regression analysis

While the fc_s (related to NDVI and further to LST) was found to be the most accurate, Agam et a. (2007) noted that sharpening methods were only able to provide estimates of LST (Agam et al., 2007).

Water, Drought, and Evapotranspiration

As seen in the above section, there is a negative correlation between NDVI and LST, which can be explained by the cooling effect of ET from healthy plants (Taiz & Zeiger, 2006; Petropoulos et al, 2009). Thus this relationship between NDVI and LST can be used to examine the ET rate of areas.

Anderson et al. (2012) reviewed the application of remote sensing of ET. ET measurements using satellite remote sensing technology are primarily dependent on the thermal bands. Multiple studies were found to successfully approximate ET or ET-related variables based on thermal response of the area. Thermal remote sensing of areas to generate ET measurements were able to examine water rights violations, drought indices, recovery of the landscape after water rights buyouts, etc. (Anderson et al., 2012). These methods were found to be more applicable to mapping water stressed areas than non LST measurements that instead rely on crop coefficients or vegetation index (VI) measurements (Anderson et al., 2012).

As has been frequently noted, unique relationship between NDVI and LST allows for the examination of water stress and ET measurements of an area. Petropoulos et al. (2009) reviewed the use of this relationship to determine ET rates of an area using satellite remote sensing. Examining the efficiency and error of different methodologies using the NDVI and LST relationship to generate ET, their review found that the multiple studies were successful in using the Vegetation Index Temperature Trapezoid (VITT) as a method for estimating ET at a regional scale. VITT is a scatterplot technique that proposes plotting the NDVI vs. LST relationship to identify pixels of maximum (wet edge) and minimum (dry edge) ET (Petropoulos et al., 2009).

Yang et al. (2011) study aimed to use a modified VITT to calculate ET, using LST – Air temperature (Ts – Ta) rather than LST alone. Examining groundwater dependent ecosystems in Australia, they examined the effect of groundwater pumping on ET rates. Using the formulas:

$$(Ts - Ta)\,\mathrm{max} = a0 + a1NDVI$$

$$(Ts - Ta)\,min = \ b0 + b1NDVI$$

where a0 and a1 are the slope and offset of the wet edge, and b0 and b1 the slope and offset of the dry edge (seen in Figures A1 – A2), and the moisture availability index (*Ma*) is defined as:

$$Ma = 1 - WDI = \frac{(Ts - Ta)max - (Ts - Ta)r}{(Ts - Ta)max - (Ts - Ta)min} = \frac{ET}{ETp}$$

where r is the observed pixel value, and ETp is potential ET (Yang et al., 2011). Results showed ET rates were lower for groundwater dependent ecosystems within the cone of depression of production wells, than those that were outside of the cone of depression (Yang et al., 2011).

Remote Sensing to Analyze NTBA Wetlands

Literature reviewed shows only partial recovery of wetlands within the NTBA, without particular spatial distribution (Metz, 2011; Haag & Pfeiffer, 2012). The wetlands recovery is primarily due to the increase in potentiometric surface of the FloridanAquifer (Metz, 2011). The pattern of wetland recovery does not necessarily follow expected trends. For example, wetlands expected to have short flood duration, such as those in an active wellfield, still maintained longer durations of flooding than others further from the wellfield (Nilsson et al., 2013). Literature also shows an interesting insight as to overall hydrology of the area, as numerous papers reported multiple wetland types at the same time, finding recovery and hydrology similar, despite differing vegetation types (Metz, 2011; Haag & Pfeiffer, 2012; Nilsson et al., 2013). For this case, it could be concluded that further research needs to be applied to the NTBA. All of the studies but Craig et al. (2001) were able to examine only a small number of wetlands, and their results were ambiguous as to the overall recovery of the wetlands in the NTBA. Furthermore, Craig et al. (2001) was only able to examine the NTBA wetlands prior to reductions in pumping.

Anderson et al. (2012), Petropoulos et al. (2009), Yang et al. (2011) and Zhang et al. (2013) demonstrated the applicability of NDVI, LST, and ET in examining water stressed ecosystems, with Taiz & Zeiger (2006), Zhang et al. (2012) and others explaining the theoretical framework as to why these metrics are suitable for examining water stressed areas. As the NTBA wetlands' status as water stressed is still under question due to the ambiguity of the results listed above, and remote sensing is able to examine large regional areas, it is felt that a remote sensing analysis of the area post groundwater withdrawal reductions is warranted.

Therefore, was proposed that remote sensing analysis of NDVI, LST and ET of isolated wetlands within the NTBA be conducted. Results of such analysis would provide further insight into the overall recovery of the wetlands within the NTBA following policies enacted to reduce groundwater pumping of the Upper Floridan Aquifer. Results would also provide additional, large scale knowledge as to the efficacy of the current groundwater withdrawal reductions impact on the recovery of the wetlands within the NTBA.

PROBLEM STATEMENT AND OBJECTIVE

The overall goal of the study is to observe and map the spectral and thermal characteristics of wetlands within the NTBA overtime in response to the reduction in groundwater withdrawals.

Objectives were to:

1. Map the spectral and thermal characteristics of the wetlands to assess the recovery of the wetlands after the reduction in groundwater withdrawals over the time period of 2005 - 2014
2. Study whether the spectral and thermal characteristics do or do not relate with the current ground evaluation strategy; the Wetland Evaluation Procedure (WAP), used by the SWFWMD.

Therefore, the corresponding research questions addressed here are:

- Based on the spectral and thermal characteristics of the wetlands in the study area, have the overall wetland conditions been improved after the reduction in groundwater withdrawals?
- Based on the WAP scores, have overall wetland conditions been improved after the reduction in groundwater withdrawals?
- Do the spectral and thermal characteristics of the wetlands relate with the WAP scores?

STUDY AREA

The NTBA is located in west-central Florida, USA, in the counties of Hernando, Hillsborough, Pasco, Pinellas, and Sumter County. The study area focuses on the middle of Hernando, Hillsborough, and Pasco counties (Figure 1). The area is subtropical climate characterized by a warm humid summer, and mild dry winter. The wet season is during the summer months, June- September, and accounts for about 60% of the rainfall (Metz, 2011; Nilsson et al., 2013). While yearly rainfall can vary, average annual rainfall is about 1371.6 mm (Metz, 2011; Haag & Pfeiffer, 2012; Nilsson et al., 2013). The area is relatively flat in topography, with some sand hills located in the eastern part of the area (Metz, 2011). The underlying aquifer is a complex karst system, with various levels of confinement from north to south (Metz, 2011; Haag & Pfeiffer, 2012).

The study focused on the WAP scored wetlands, shown in green patches in Figure 1. Wetland types ranged from arboreal hardwood bays and cypress domes, to short herbaceous marshlands. The study examined only wetlands that were categorized as isolated, as the WAP procedure is only compatible with isolated wetlands (WAP Instruction Manual for Isolated Wetlands, 2005).

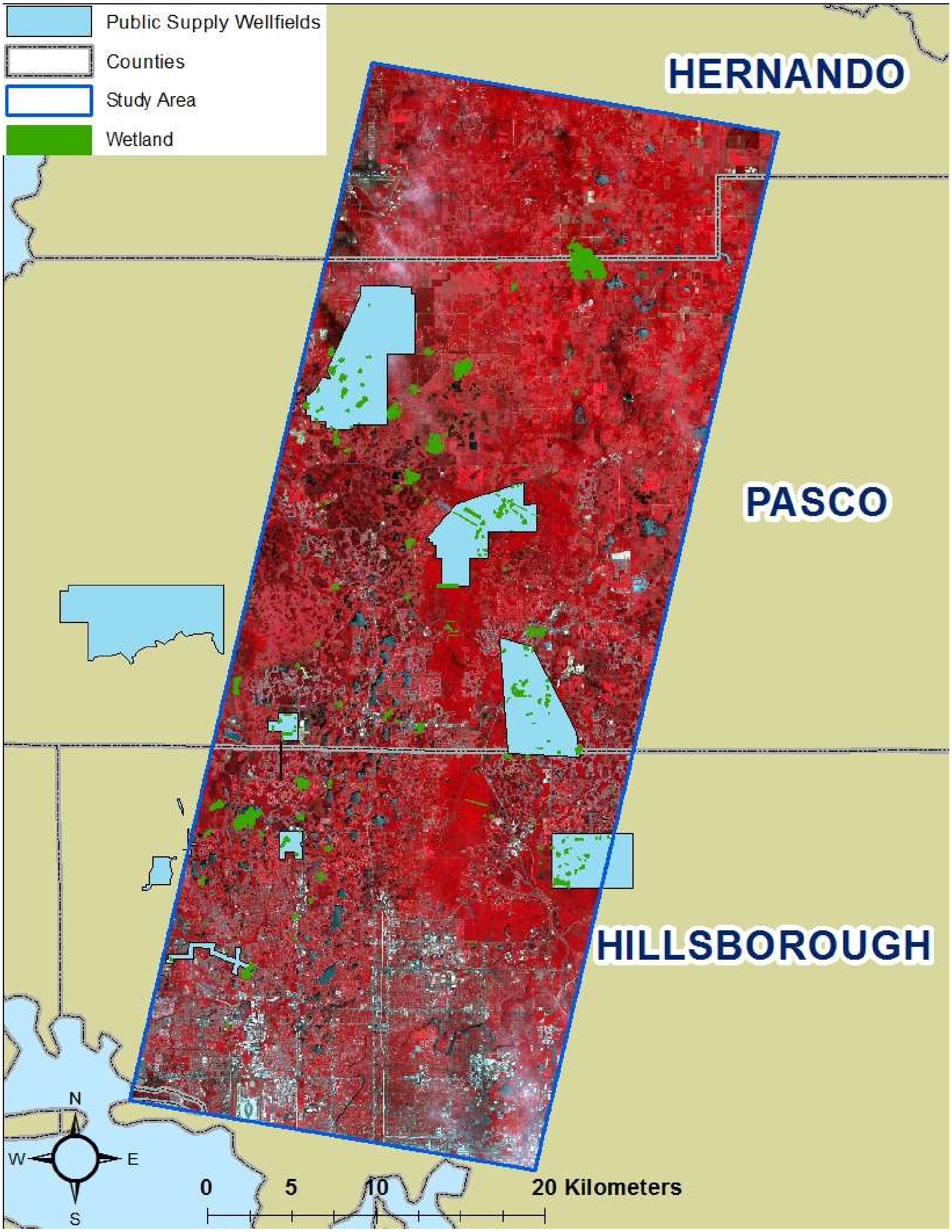

Figure 1. Map of Study Area. The Map showing the study area.

DATA

Wetland Assessment Procedure (WAP)

WAP transects, wetland boundaries, and scores were downloaded from SWFWMD's Water Management Information System (WMIS), or directly emailed by SWFWMD staff. WAP was created in 2000, with the most recent major revision in 2005. Every May – June, data are collected on various wetland variables and scored. Scores are collected from a 10m wide transect, which stretches from just outside the wetland boundary to the deepest part of the wetland. The main scores are based on plant species location, and are categorized based on 3 classes: herbaceous, shrub, and tree. Scores are high when obligate and facultative wetland species are within their correct place in the wetland, and low if upland species are found within the wetland. These scores are dependent on groundwater availability, as wetland species are adapted to inundated conditions, whereas the upland species die due to flooding (WAP: Instruction Manual for Isolated Wetlands, 2005).

The WAP scores used in the analysis were the biological scores:

- Tree Zonation – Scoring of tree species locations within the wetlands
- Shrub Zonation – Scoring of shrub and small tree species locations within the wetlands
- Groundcover Zonation – Scoring of herbaceous species locations within the wetlands

Satellite Imagery

Table 1. ASTER band characteristics (NASA, 2004a).

Band Number	**Band Name**	**Wavelength (µm)**	**Spatial Resolution (m)**	**Notes**
1	Green	0.52 - 0.60 µm	15	
2	Red	0.63 - 0.69 µm	15	
3	Near Infrared Forward	0.76 - 0.86 µm	15	
3	Near Infrared Backwards	0.76 - 0.86 µm	15	
4	SWIR	1.600 - 1.700 µm	30	**Nonfunctional since 2008**
5	SWIR	2.145 - 2.185 µm	30	**Nonfunctional since 2008**
6	SWIR	2.185 - 2.225 µm	30	**Nonfunctional since 2008**
7	SWIR	2.235 - 2.285 µm	30	**Nonfunctional since 2008**
8	SWIR	2.295 - 2.365 µm	30	**Nonfunctional since 2008**
9	SWIR	2.360 - 2.430 µm	30	**Nonfunctional since 2008**
10	Thermal	8.125 - 8.475 µm	90	
11	Thermal	8.475 - 8.825 µm	90	
12	Thermal	8.925 - 9.275 µm	90	
13	Thermal	10.25 - 10.95 µm	90	
14	Thermal	10.95 - 11.65 µm	90	

ASTER bands1-3, and 13 and 14, were used in the analysis (Table 1). Bands 4-9 were not used due to the failure of the sensor in 2008 (NASA, 2004a, 2004b).

Two cloud free or minimal cloud ASTER L1B scenes from 2005 and 2014 were collected for analysis. Scenes were captured on May 7, 2005 and May 16, 2014, as they had the lowest percentage of cloud cover, were captured during the end of the dry season, and coincided with the WAP collection time frame.

Meteorologic Data

Hydrologic condition reports for May 2005 and May 2014 were downloaded from SWFWMD, to provide a general idea of the study area's rainfall and groundwater conditions during the ASTER scene (Hydrologic Conditions May 2005, 2005, & Hydrologic Conditions for the month of May 2014, 2014). Additionally, NexRad Rainfall Radar Grid measurements were acquired from the SWFWMD to provide further rainfall information. The 2 km × 2 km grids were collected for the day the images were captured, plus the two preceding days. USGS 2 km × 2 km grids of daily reference evapotranspiration (ET_{r24}) were downloaded for use in the VITT model. Finally, air temperature data from nearby Florida Automated Weather Network (FAWN) stations were collected at or around the time of image capture (Figure 2).

Other Data

Groundwater well locations and data monitoring the Upper Floridan Aquifer and Surficial Aquifer in and around the study site were acquired from SWFWMD. From these wells a potentiometric surface map was created, using a method provided by a SWFWMD scientific data analyst (Crowell, 2014). To aid in the georectification of the two ASTER scenes, 2014 aerial imagery mosaics of the underlying counties were collected from the SWFWMD. ASTER Spectral libraries were used to atmospherically correct the spectral images (Baldridge et al, 2009).

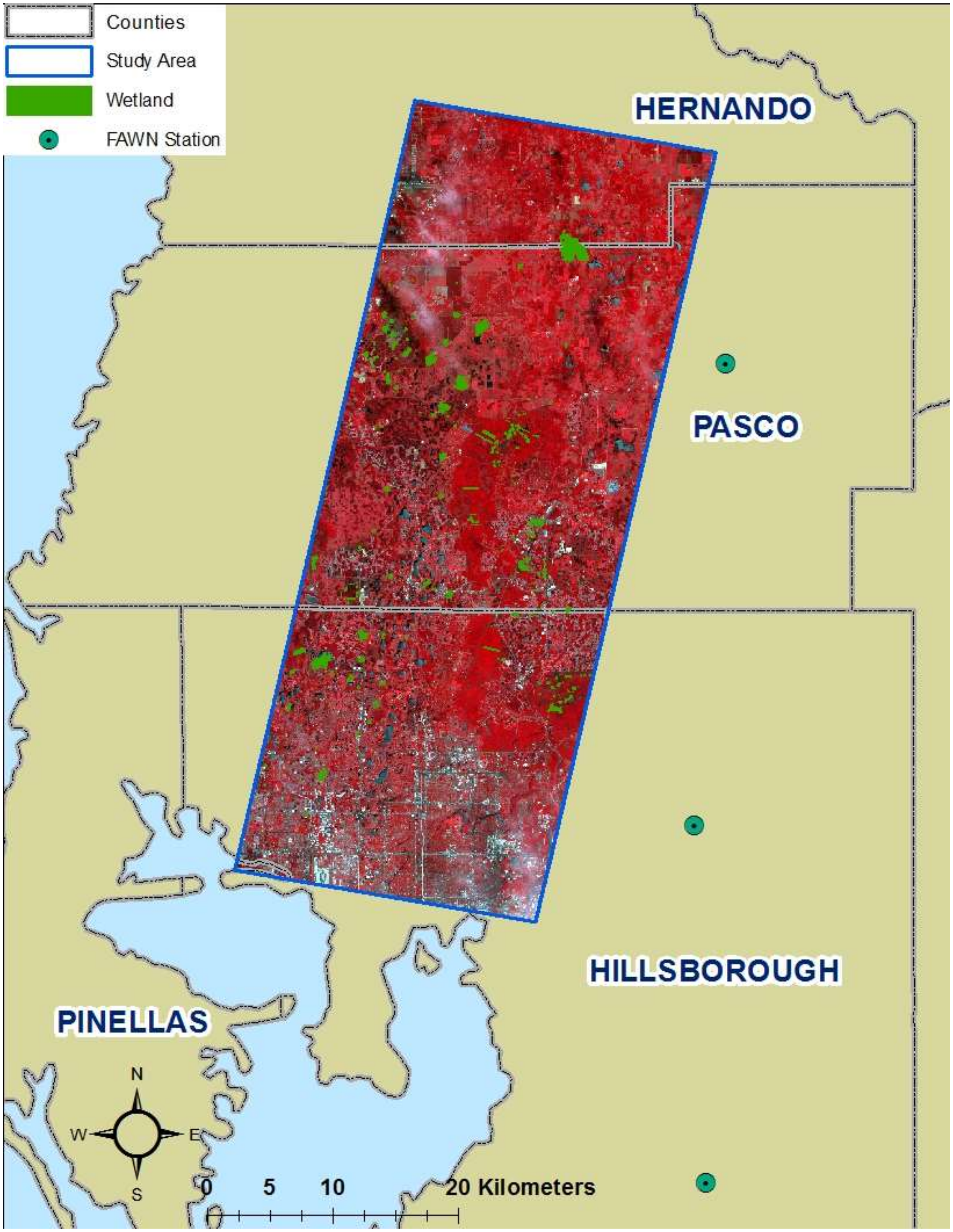

Figure 2. Fawn Station Locations. Location of the FAWN stations used in the VITT process

METHODS

Pre-Processing

Both ASTER scenes were georeferenced against 2014 aerial imagery. The geometrically corrected images were clipped to the size of the overlap of the two scenes. Atmospheric correction of the visible and near infrared bands were conducted using ENVI software (Exelis Visual Information Solutions, Boulder, Colorado), utilizing the Empirical Line Calibration (ELC) function, and the ASTER spectral libraries of tap water and limestone [fine $CaCO_3$] (Baldridge et al, 2009). Two NDVI images were generated from the corrected scenes.
Using the SWA method by Pu et al. (2006), a C script provided by Dr. Pu, and LST was calculated from ASTER imagery's band 13 and 14. As Florida is a subtropical area, the tropical formula for Transmittance (τ):

$$Tropical: \tau = 0.061099w + 0.987200, \qquad R^2 = 0.990,$$

$$0.1 < w < 5.4$$

and air temperature (Ta):

$$Tropical: \tau = 10.573150 - 1.957187\mathrm{H} + 0.964805\mathrm{T0}, \qquad R^2 = 0.999,$$

$$\mathrm{T0} : 280 - 340\ \mathrm{K}$$

was used (Pu et al, 2006). For the 2005, scene a water vapor value of 3.5 and forest emissivity were used; the 2014 scene used a 5.0 water vapor value and forest emissivity. The calibrated thermal imagery, along with the NDVI created by the student, were used to generate a thermally sharpened LST scene, using the fc_s sharpening method described in Agam et al. (2007).

ET was calculated using the VITT method used in Yang et al. (2011), and converted to daily ET using the following formula found in Colaizzi et al, 2006:

$$ET_{24} = (\frac{ET}{ET_r}) * ET_{r24}$$

where the subscript 24 denotes the total number of hours the ET value represents (Colaizzi et al 2006, Yang et al 2011). The VITT used the thermally sharpened LST, NDVI products generated above, the USGS provided 2 km × 2 km grids of ET_{r24}, and average air temperature from the nearby weather stations. As the average air temperature was found to be 24.05C^o in 2005, and 22.63C^o in 2014, normalization of temperature between the two years was not necessary. The wet and dry edges (Petropoulos et al., 2009) used to generate the VITT ET are plotted in Figures A1−A2.

Wetland polygons were converted into raster format, with pixel values representing their wetland ID number. Images for 2005 and 2014 were composited together in to multiple TIF – format images, and clipped to the wetland polygon boundaries.

Main Analysis

The composite .TIFF image was loaded in open source *R* statistical software (R core team), and converted into a data frame, where null data values were omitted. Boxplots of NDVI, LST, and ET were generated for each wetland for 2005 and 2014. Histograms with density lines were generated for NDVI, LST, and ET of all the wetland pixels for both 2005 and 2014, to visualize the spread of the data, and check for normality. As the overall data were found to be non-normally distributed, non-parametric tests were selected for analysis of overall changes in wetland spectral responses (Figures A6−A8). A Wilcox Rank Sign Test was run in *R* on the change between NDVI, LST, and ET from 2005 to 2014, and the resulting p-values were recorded. Z-values from the Wilcox Rank Sign Test were used to generate effect sizes in *R*

(Yatani, 2014). A table of the results of the statistical tests were joined to the wetland shapefile and mapped.

The WAP scores collected from SWFWMD via various sources (website, annual reports, and emailed PDFs) were entered into a spreadsheet and examined for changes from 2005 to 2014. The results were tallied and used to create pie charts, as well as joined to wetland shapefiles to examine and map changes in WAP scores in regards to the study area. The spreadsheet data were also imported to *R*, where two sets of boxplots comparing the WAP score to the thermal and spectral responses were created. The first set used all pixels within all wetlands, to see if all wetland pixels response values could be used to differentiate the 0-5 WAP scores. The second set used only the median of the spectral and thermal responses, to reduce the affect of wetland size on the relationship between remotely sensed values and WAP.

Other Analysis

As Metz (2011) noted, the level of the potentiometric surface of the Upper Floridan Aquifer was the primary influence in improvement in wetland flooding and WAP scores (Metz, 2011). WAP wetland shapefiles were loaded into ArcGIS 10.x and examined against the difference in potentiometric surface (herein referred to as POT) generated by the student for simple correlation. The difference POT raster was then loaded into R and plotted against the difference in NDVI, LST, and ET for all wetlands; examining for trends that these factors truly reflect any changes in hydrologic condition.

Because there was a rainfall event within 3 days of the images for both years, a scatterplot of the difference in the two year's rainfall vs. the ET was generated, to examine if rainfall impacted the changes in ET between the two years. 2km rainfall rasters were generated from SWFWMD's NEXRAD Rainfall grids in ArcGIS 10.x, and a rainfall difference raster created. The rainfall difference raster was examined in ArcGIS 10.x against the WAP wetland shapefiles. The difference rainfall raster was then loaded into R and plotted against the difference NDVI, LST, and ET for all wetlands; examining for trends that these factors truly reflect any changes in hydrologic condition.

RESULTS

Change in Spectral and Thermal Response

84 of the 211 wetlands showed a statistically significant increase in NDVI at 95% confidence. Of the 84 wetlands that showed an increase in NDVI, 37 of them had an effect size of greater than or equal to 0.5.

189 of the 211 wetlands showed a statistically significant decrease in LST at 95% confidence. Of the 189 wetlands that showed a decrease in LST, 159 of them had an effect size less than or equal to -0.5.

198 of the 211 wetlands showed a statistically significant increase in ET at 95% confidence. Of the 198 wetlands that showed an increase in ET, 183 of them had an effect size greater than or equal to 0.5.

The median change in NDVI was 0.004, with a 95% confidence interval of 0.0032 to 0.0051. The median change in LST was -3.636 ^{o}C, with a 95% confidence interval of -3.674 to -3.596 ^{o}C. The median change in ET was 1.268 mm/day, with a 95% confidence interval of 1.261 to 1.277 mm/day. Overall, most of the wetlands showed both a statistically significant, and practical significant increase in ET, and decrease in LST. Most wetlands did not have a statistical or practical increase in NDVI. The wetlands showed a large amount of variance in response values within their individual boundaries for all three remotely sensed values. Boxplots of 2005 and 2014 spectral responses can be seen in Figure 3, and maps of the wetlands' p-values and effect size seen in Figures 4 - 6. The variance in remotely sense values is seen in Figures A3−A5.

Change in WAP Scores

Of the 211 wetlands, WAP scores from 69 wetlands were examined for change from 2005 to 2014. The net changes between the two years are shown in the Tables 2 - 4.

Overall, the selected wetlands showed a net decrease in WAP score whether they were forested or herbaceous. Groundcover scores had the highest decrease overall, while Tree scores had the lowest decrease. When examined as percentages, the general trend was that a little under half the WAP scores showed no change, around a third showed a decrease in WAP, with the remainder of the scores showing an improvement in WAP for groundcover, shrub, and tree scores. Furthermore, because of the unique compositions of herbaceous vs. forested wetlands, the numbers and percentages were examined where wetland type was taken into account. Herbaceous wetlands should be devoid of trees and most shrubs, with groundcover being the main if not only score. Therefore, herbaceous wetlands' groundcover WAP scores were further analyzed. Forested wetlands should have all 3 WAP scores, as it is appropriate to have understory plants in forested wetlands. The focus of this study was on the WAP tree score, as majority of the wetlands were classified specifically as Cypress wetlands, where Cypress trees are the main species. The tree score was also chosen because trees would be the main component of the remotely sensed values, as the understory reflectance would be blocked by the canopy cover. When broken down by wetland type, the breakdowns were still in line with the general trend, though herbaceous wetlands did have a larger percentage of WAP decline (Figure 7). Location and change in status by wetland type are shown in Figures 8 - 10.

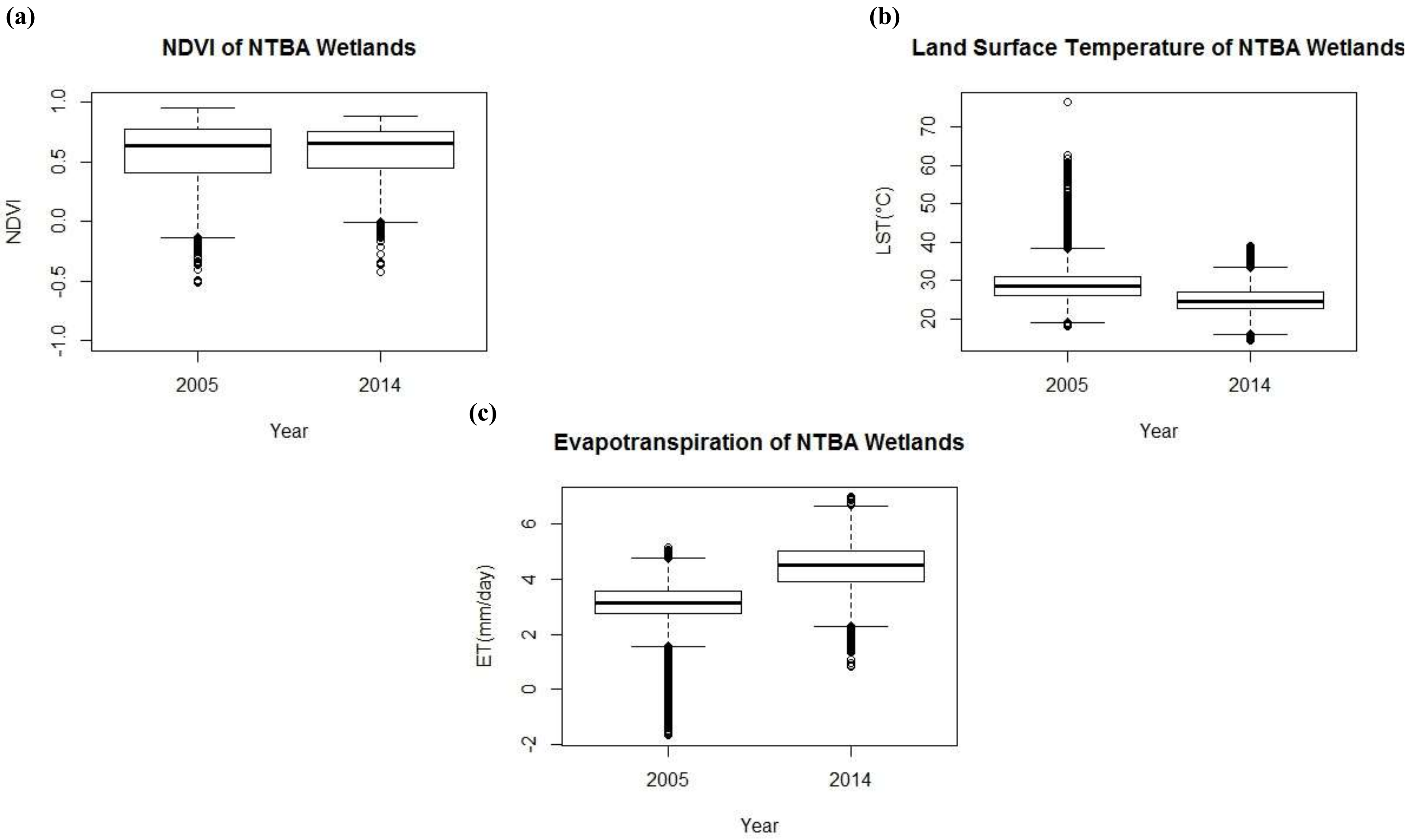

Figure 3. Boxplots of (a) ET, (b) LST, and (c) NDVI. ET and LST showed significant improvements from 2005 to 2014. ET showed increases from 2005 to 2014, with less areas of deposition (negative ET) and less ET values falling below 2 mm/day. LST declined from 2005 to 2014, and had fewer extreme values in 2014 than they did in 2014. NDVI did not show noticeable improvement.

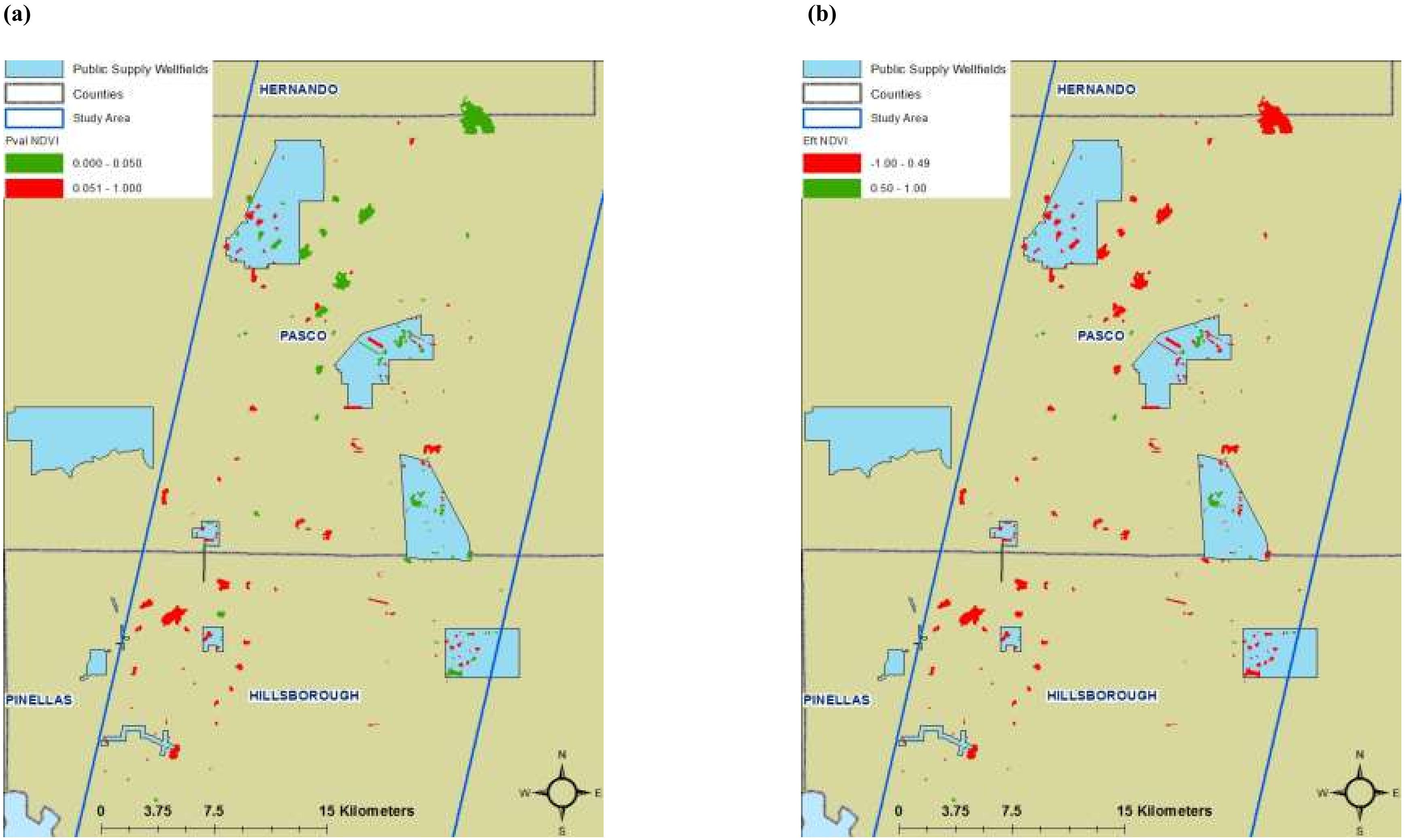

Figure 4. Map of NDVI Pvals and Effect size. The majority of the wetlands failed to show statistical or practical significance improvement in NDVI. (a) Green wetlands are where median NDVI in 2014 was greater than in 2005, and statistically significant at 95%. Red Wetlands are where median NDVI in 2014 was less than than 2005, or the increase from 2005 to 2014 was not statistically significant at 95%. (b) Green wetlands are where median NDVI in 2014 was greater than in 2005, and pratically signifcant at 0.5 or greater. Red Wetlands are where median NDVI in 2014 was less than than 2005, or the increase from 2005 to 2014 was not practically significant at 0.5 or greater.

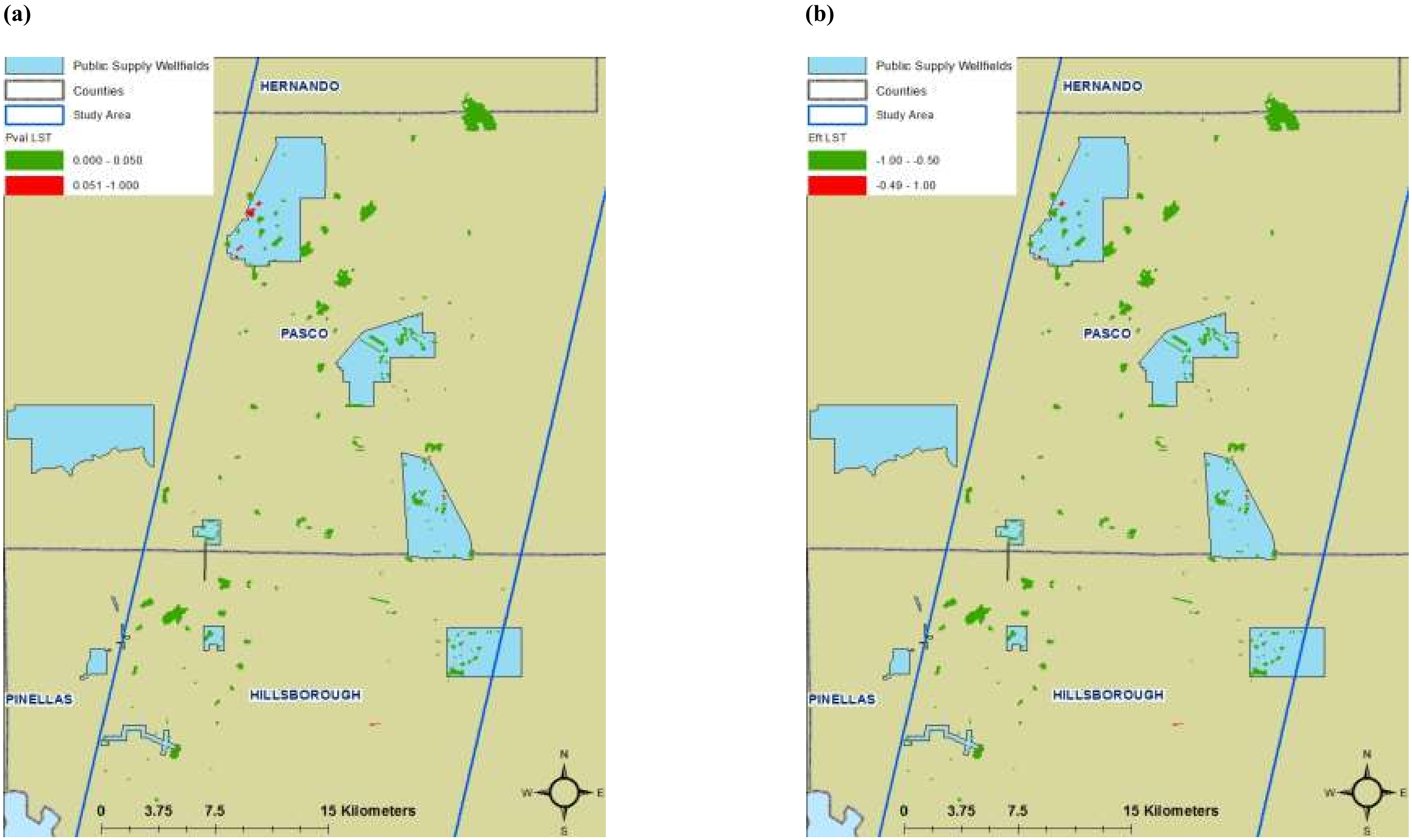

Figure 5. Map of LST Pvals and Effect size. Majority of the wetlands showed a statistical and pratical significance improvement in LST. (a) Green wetlands are where median LST in 2014 was less than in 2005, and statistically significant at 95%. Red Wetlands are where median NDVI in 2014 was less than than 2005, or the decrease from 2005 to 2014 was not statistically significant at 95%. (b) Green wetlands are where median LST in 2014 was less than in 2005, and pratically signifgant at 0.5 or greater. Red Wetlands are where median LST in 2014 was greater than 2005, or the decrease from 2005 to 2014 was not practically significant at 0.5 or greater.

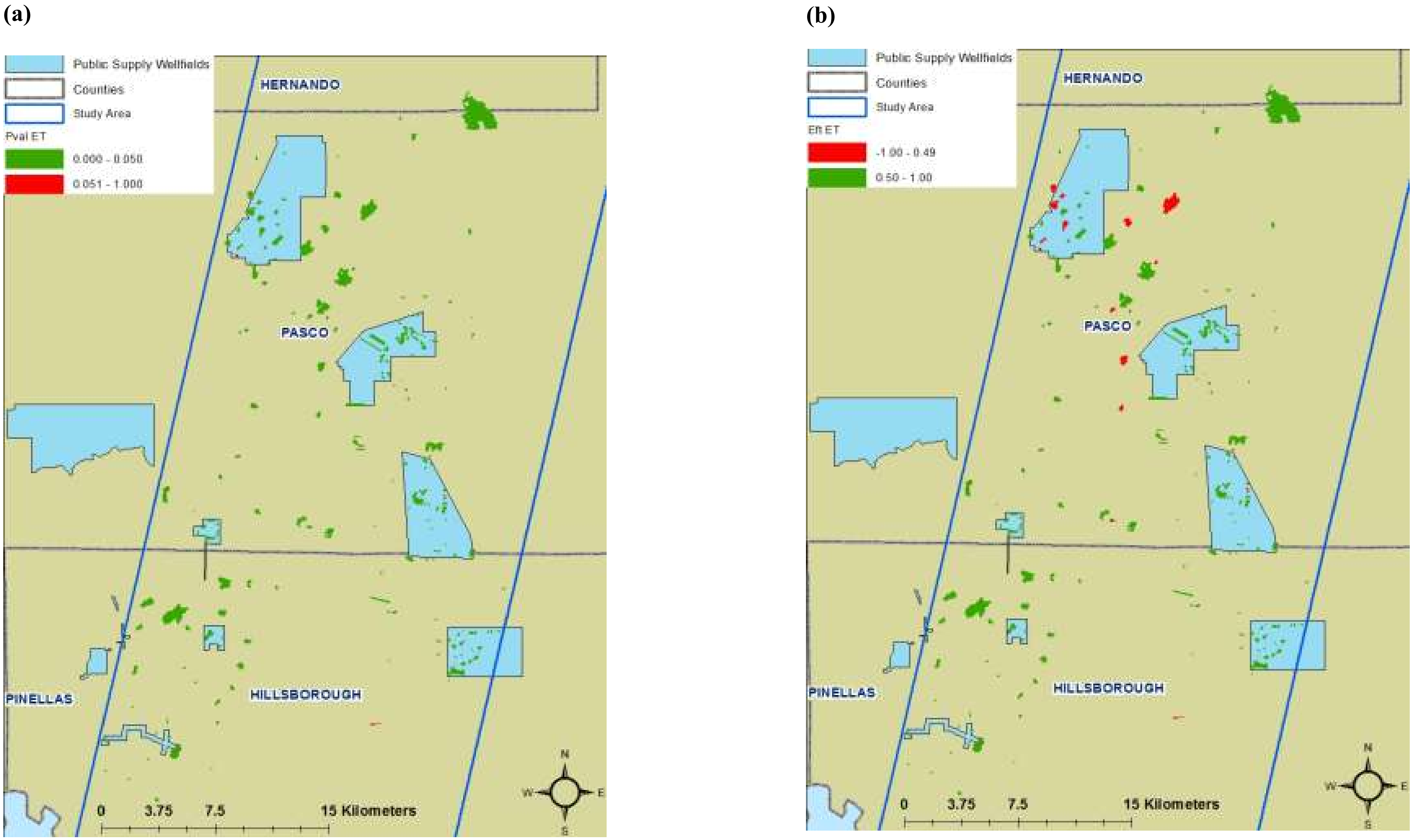

Figure 6. Map of ET Pvals and Effect size. Majority of the wetlands showed a statistical and pratical significance improvement in ET. (a) Green wetlands are where median ET in 2014 was greater than in 2005, and statistically significant at 95%. Red Wetlands are where median ET in 2014 was less than than 2005, or the increase from 2005 to 2014 was not statistically significant at 95%. (b) Green wetlands are where median ET in 2014 was greater than in 2005, and pratically signifgant at 0.5 or greater. Red Wetlands are where median ET in 2014 was less than than 2005, or the increase from 2005 to 2014 was not practically significant at 0.5 or greater.

Table 2. All Wetlands (n = 69)*

	Groundcover	Shrub	Tree
Total Net Change in Score	-18	-8	-4
# Wetlands No Change	33	32	38
# Wetlands Improvement	12	16	11
# Wetlands Decrease	24	21	20
Max Score Change All	+2	+5	+5
Min Score Change All	-3	-5	-3

*Overall counts and net changes in WAP scores from 2005 to 2014 for all wetland types, combined, in the NTBA.

Table 3. Herbaceous Wetlands (n = 18)*

	Groundcover	Shrub	Tree
Marsh Net Change in Score	-15	-5	+12
# Wetlands No Change	7	9	11
# Wetlands Improvement	1	4	5
# Wetlands Decrease	10	5	2
Max Score Change Marsh	+1	+4	+5
Min Score Change Marsh	-3	-5	-3

*Overall counts and net changes in WAP scores from 2005 to 2014 for herbaceous type wetlands in the NTBA.

Table 4. Forested Wetlands (n = 51)*

	Groundcover	Shrub	Tree
Forested Net Change in Score	-3	-3	-16
# Wetlands No Change	26	23	27
# Wetlands Improvement	11	12	6
# Wetlands Decrease	14	16	18
Max Score Change Forested	+2	+5	+2
Min Score Change Forested	-2	-5	-3

*Overall counts and net changes in WAP scores from 2005 to 2014 for forested type wetlands in the NTBA.

Figure 7. Pie charts showing percentage of wetlands change in status. Pie charts showing percentage of wetlands that improved, declined, or had no change from 2005 to 2014.

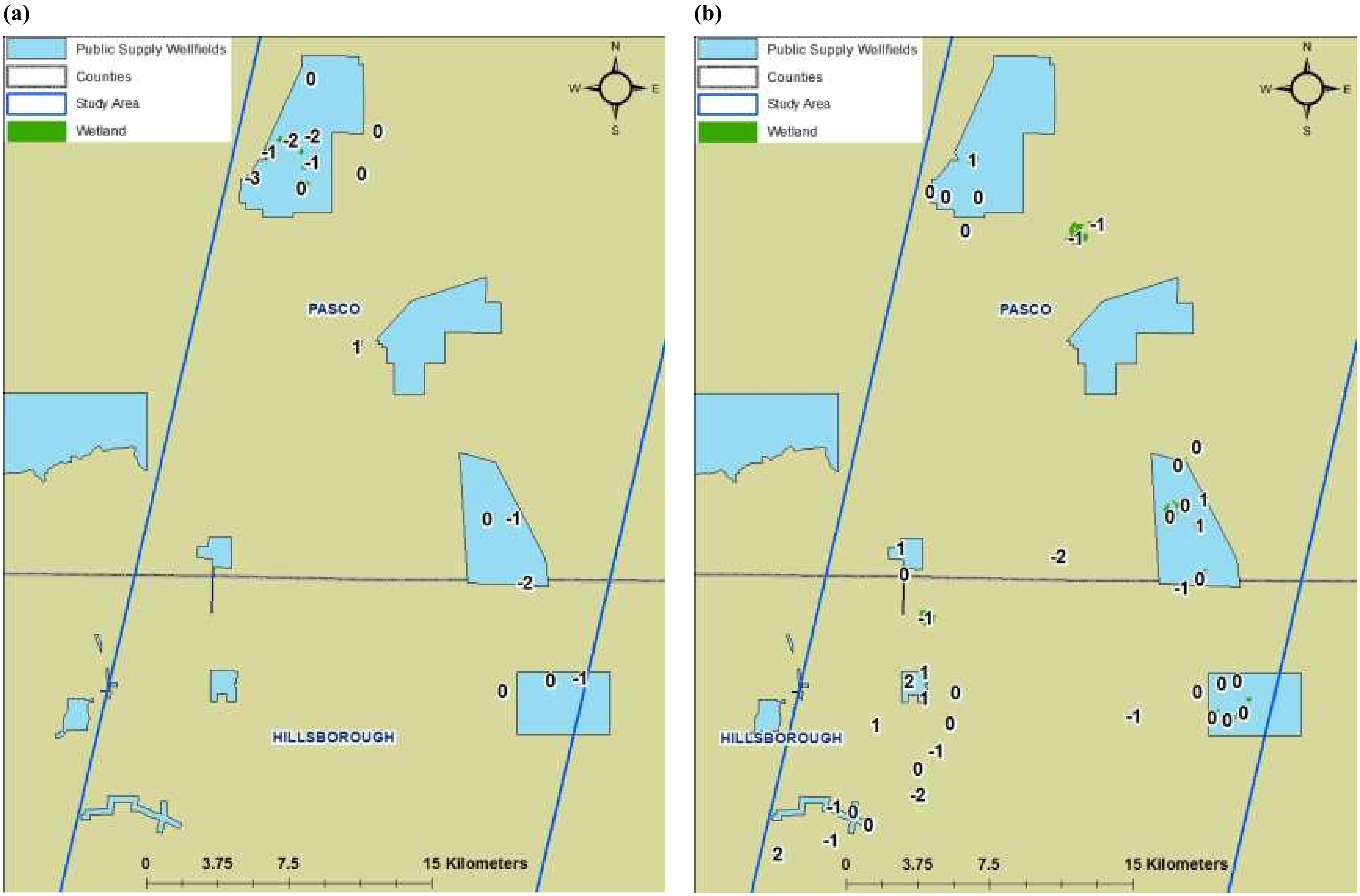

Figure 8. Map of WAP groundcover score changes. Map showing the locations of (a) Herbaceous, (b) Forested wetlands WAP groundcover score changes.

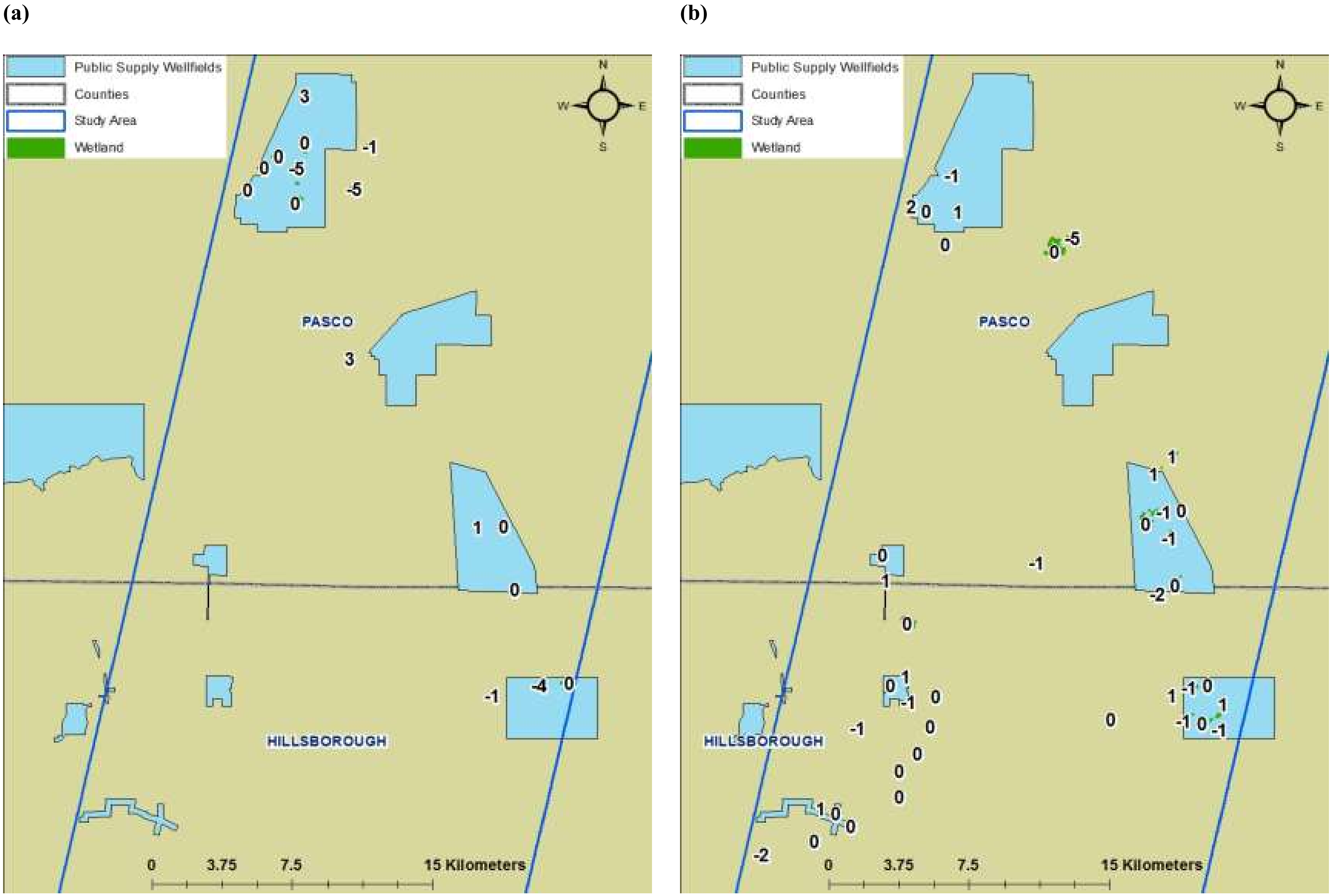

Figure 9. Map of WAP shrub score changes. Map showing the locations of (a) Herbaceous, (b) Forested wetlands WAP shrub score changes.

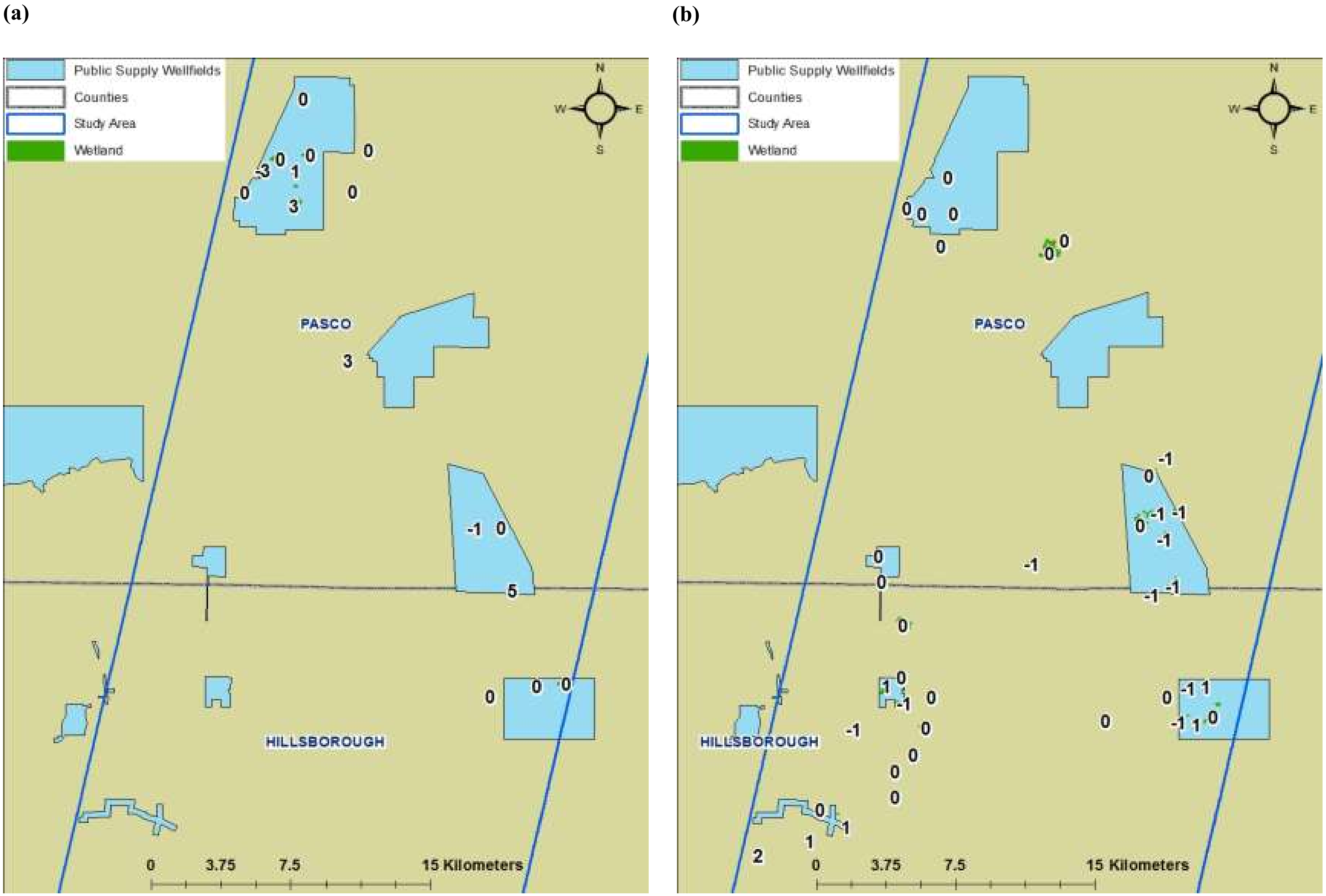

Figure 10. Map of WAP tree score changes. Map showing the locations of (a) Herbaceous, (b) Forested wetlands WAP tree score changes.

WAP scores showed that there was a net decrease in WAP score during the timeframe between 2005 and 2014, however, Figures 7a–7i showed that just a little under half the wetlands had a net change of zero. A net change of zero could be a lack of improvement from a low score, but it could also be because of wetlands maintaining a high score. More so, the increase or decrease in scores could be as little as going from 4 to 5, so already wet wetlands improving, or decreasing from 5 to 3, healthy wetlands taking a steep drop in hydrologic conditions. To determine which cases the changes fell into, WAP scores were placed in 3 groups: Good (4-5), OK (3), Poor (1-2), and compared to the net change.

Of the herbaceous wetlands that showed no change in their groundcover scores, 29% were in good condition, 42% were in OK condition, and 29% were in poor condition. Of the wetlands that declined, 50% went from good to OK condition, 30% went from good to poor, 10% declined but still stayed in good condition, and 10% went from OK to poor condition. Of the wetlands that improved, 100% went from poor condition to OK condition.

Of the forested wetlands that showed no change in their tree scores, 48% were in good condition, 37% were in OK condition, and 15% were in poor condition. Of the wetlands that declined, 22% declined but still stayed in good condition, 39% went from good to OK condition, 28% went from OK to poor condition, and 11% went from good to poor condition. Of the wetlands that improved, 50% went from OK to good, 16% improved their already good score, 17% went from poor to OK condition, and 17% went from poor to good condition.

Remote Sensing vs. WAP Comparison

The 69 wetlands that were examined for changes in WAP were also assessed against remotely sensed responses of 2005 and 2014. Boxplots of herbaceous wetlands did not show an obvious trend between the groundcover WAP score and NDVI, LST, or ET (Figures 11 – 13), with no discernable difference found between scores. Boxplots of the forested wetlands showed similar results, with no real trend of tree WAP score vs. NDVI, LST, and ET (Figures 14- 16). This lack of trend continues, even when just the median values for each wetland are used. While the 2014 herbaceous scores may appear to show a difference for the two extreme scores of 1 and 5, these each consisted of only 1 wetland (Figures 11b&d, 12b&d, 13b&d), and only a total of 18 wetlands were classed as marsh overall. Forested wetlands did not have any wetlands with a tree score below 2, and consisted of a total of 51 wetlands.

Other Analysis

The median change in POT over only NTBA wetlands was -1.1m, with a maximum change of 0.4m and a minimum change of -2.2m. The median change in rainfall 2 days before, and the day of the image acquisition was 13.3 mm/3days, with a maximum change of 57.0 mm/3days, and a minimum change of -8.8 mm/3day. Changes in rainfall and POT for the entire study area are mapped in Figure 17. The change in spectral and thermal responses of the wetlands when linearly regressed against changes in rainfall between the two study years showed little to no fit, with r^2 values under 0.1 (Figure 18). The spectral and thermal responses of the wetlands also showed r^2 values under 0.1 when linearly regressed against the change in POT of the Upper Floridan Aquifer (Figure 19).

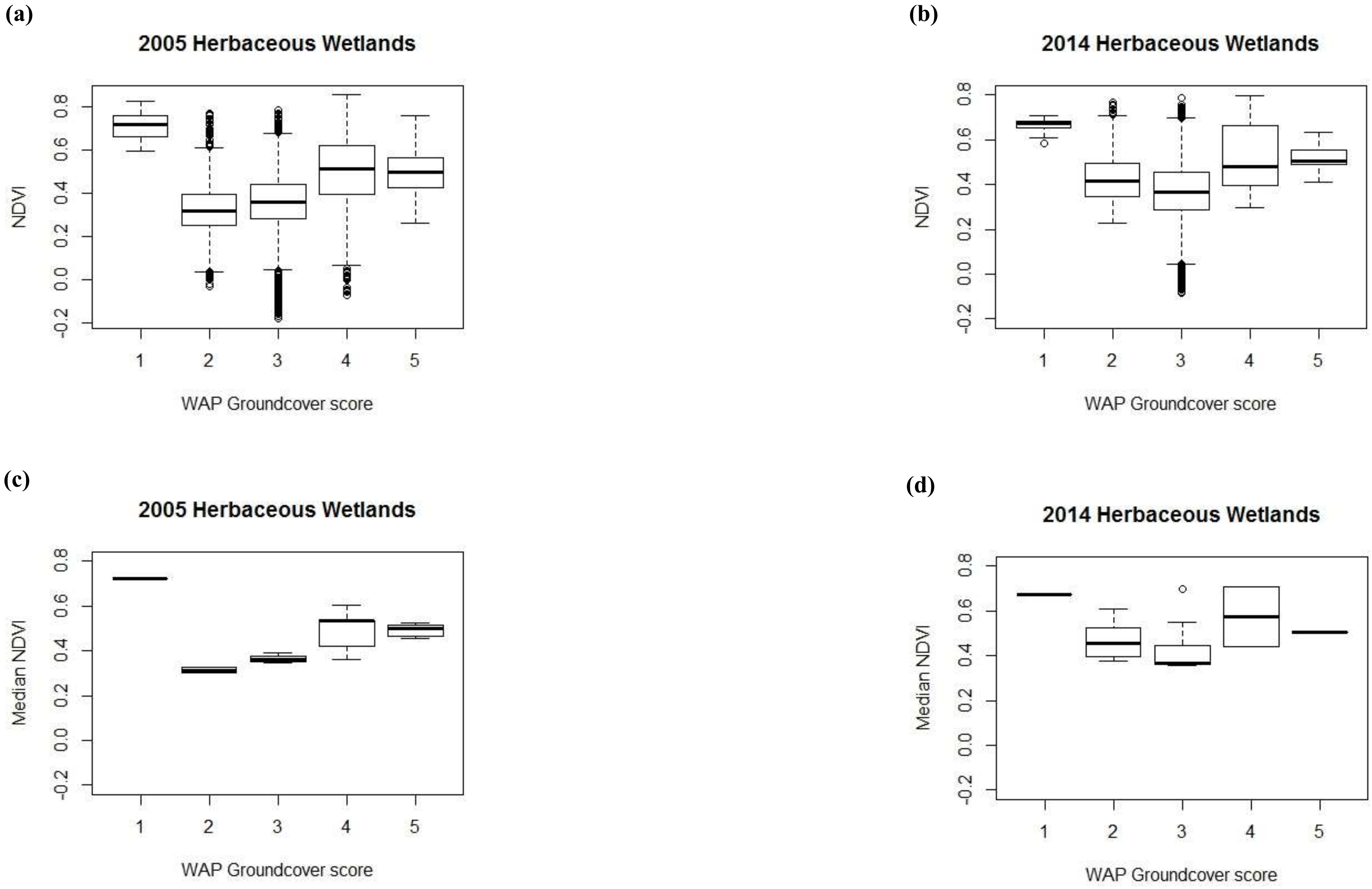

Figure 11. Boxplots of NDVI vs. Herbaceous wetlands groundcover score. Boxplots of (a) NDVI vs. 2005 herbaceous wetlands WAP groundcover score, (b) NDVI vs. 2014 herbaceous wetlands WAP groundcover score, (c) Median NDVI vs. 2005 herbaceous wetlands WAP groundcover score, (d) Median NDVI vs. 2014 herbaceous wetlands WAP groundcover score.

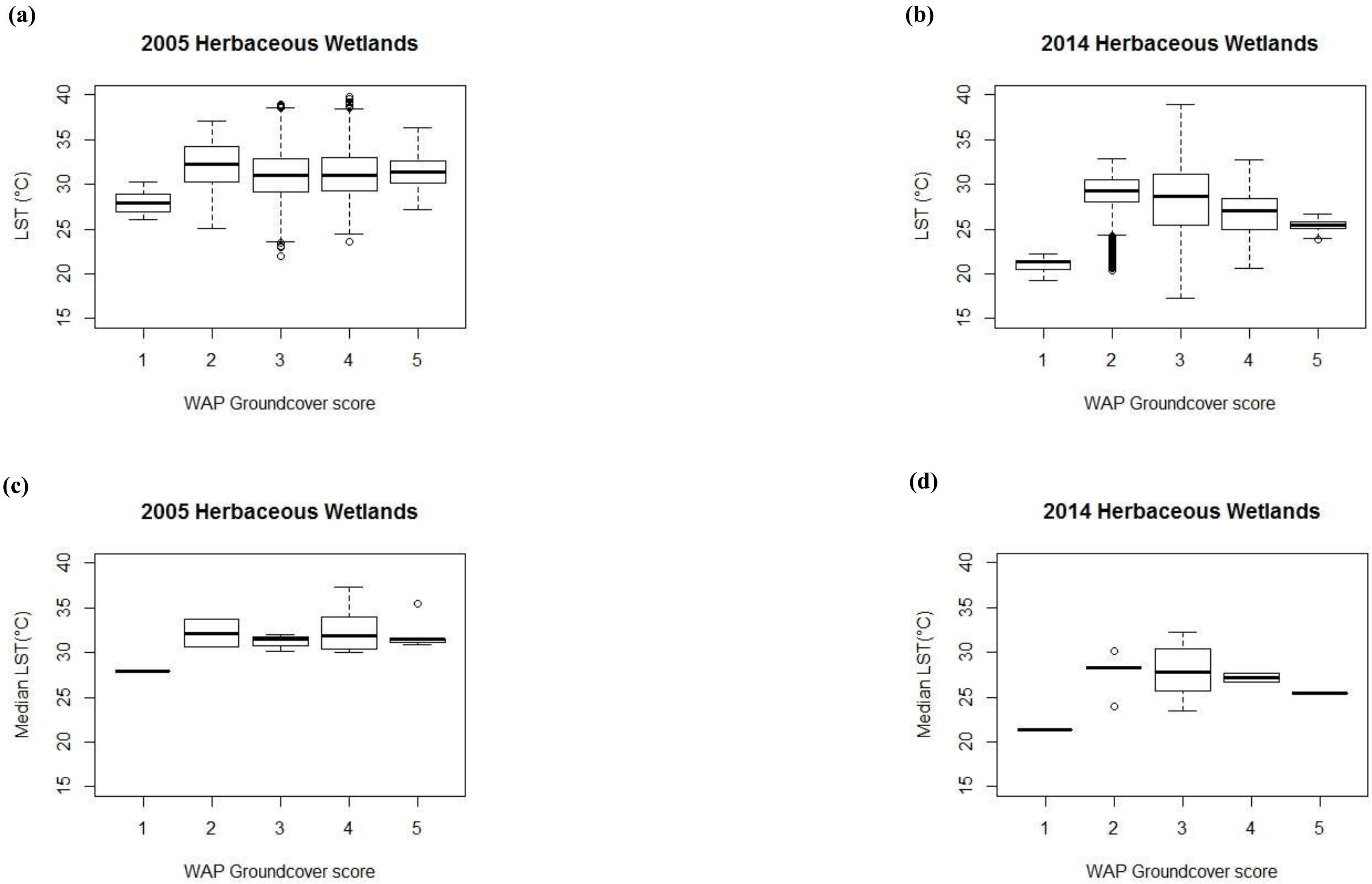

Figure 12. Boxplots of LST vs. Herbaceous wetlands groundcover score. Boxplots of (a) LST vs. 2005 herbaceous wetlands WAP groundcover score, (b) LST vs. 2014 herbaceous wetlands WAP groundcover score, (c) Median LST vs. 2005 herbaceous wetlands WAP groundcover score, (d) Median LST vs. 2014 herbaceous wetlands WAP groundcover score.

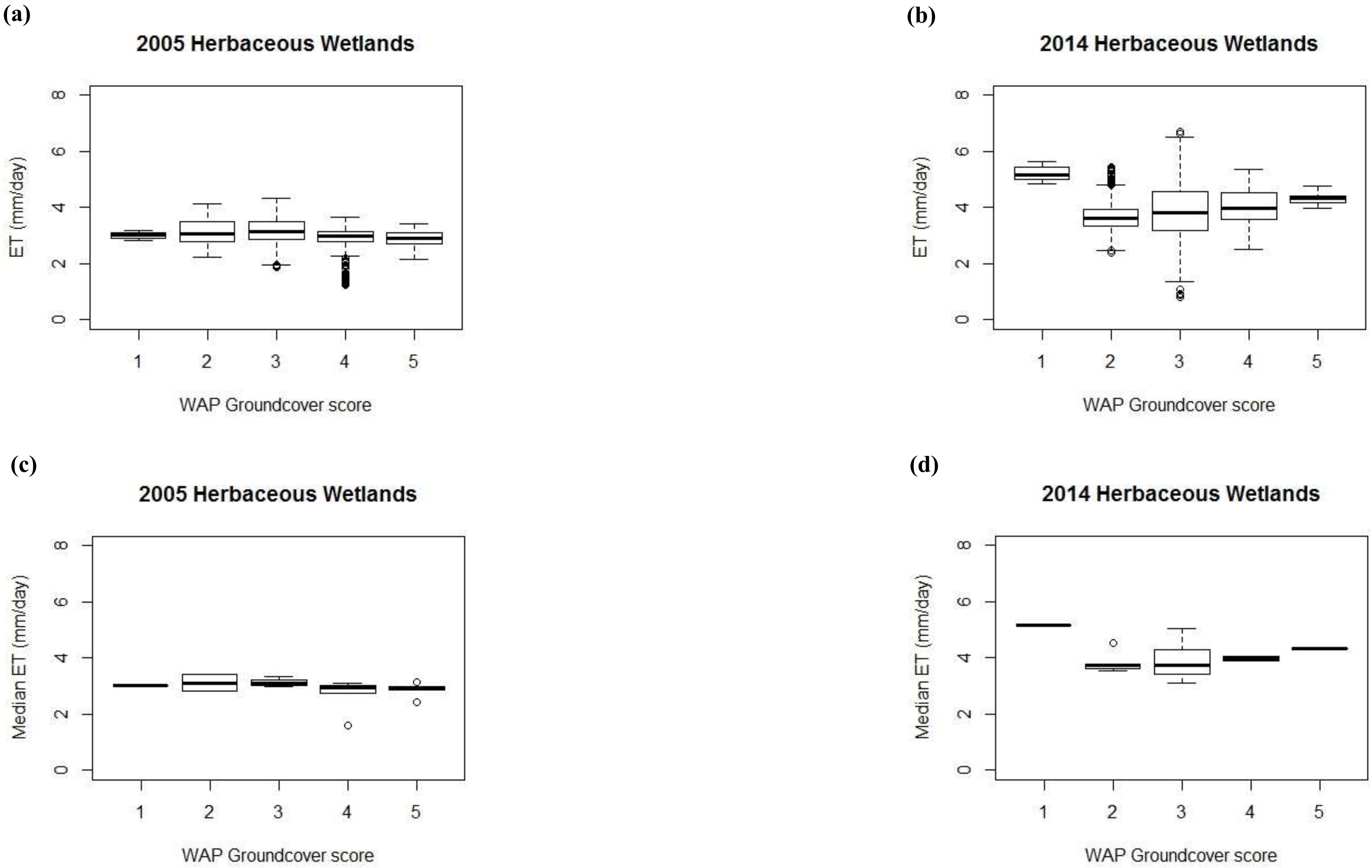

Figure 13. Boxplots of ET vs. Herbaceous wetlands groundcover score. Boxplots of (a) ET vs. 2005 herbaceous wetlands WAP groundcover score, (b) ET vs. 2014 herbaceous wetlands WAP groundcover score, (c) Median ET vs. 2005 herbaceous wetland WAP groundcover score, (d) Median ET vs. 2014 herbaceous wetland WAP groundcover score.

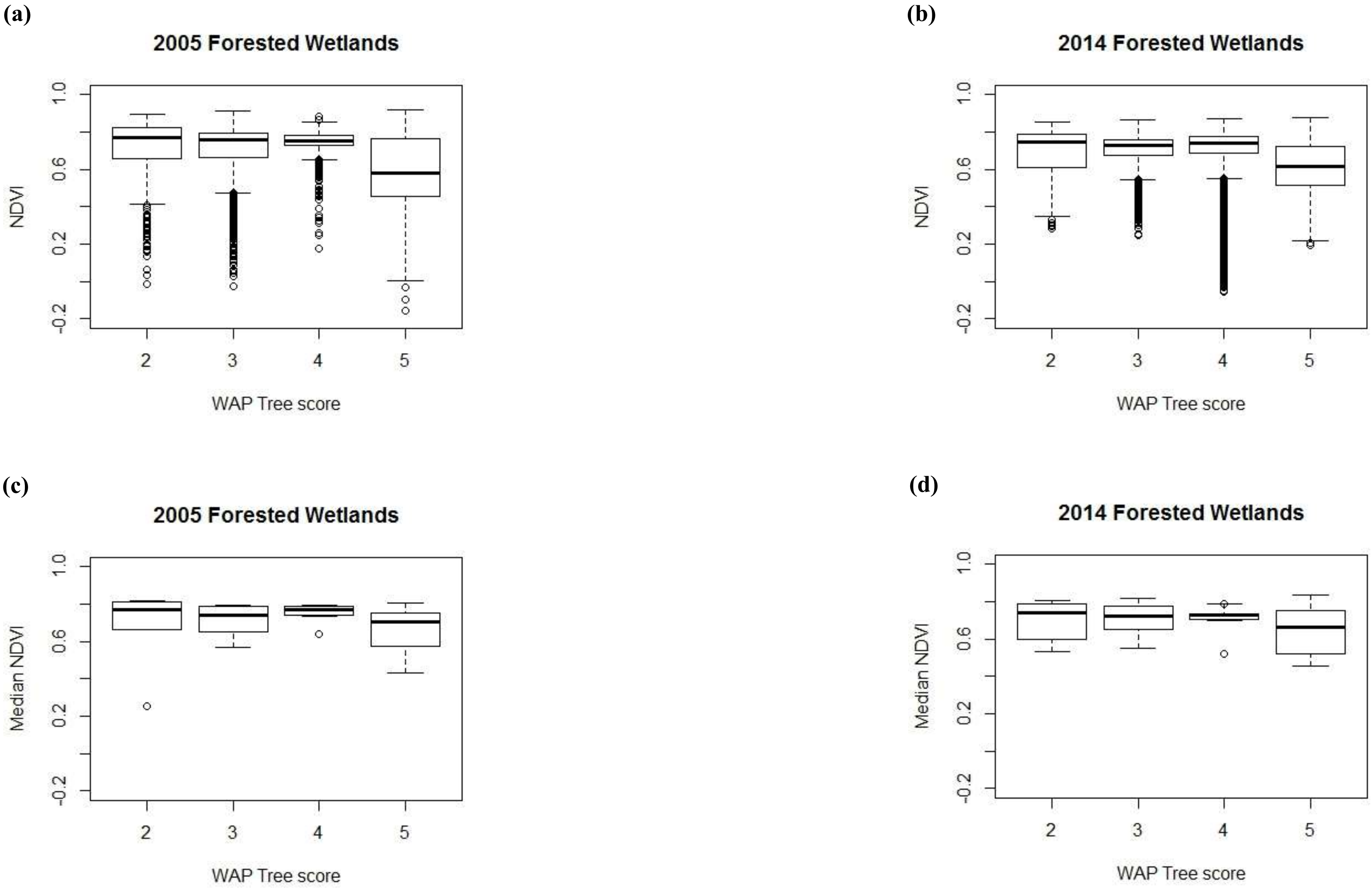

Figure 14. Boxplots of NDVI vs. Forested wetlands tree score. Boxplots of (a) NDVI vs. 2005 forested wetlands WAP tree score, (b) NDVI vs. 2014 forested wetlands WAP tree score, (c) Median NDVI vs. 2005 forested wetlands WAP tree score, (d) Median NDVI vs. 2014 forested wetlands WAP tree score.

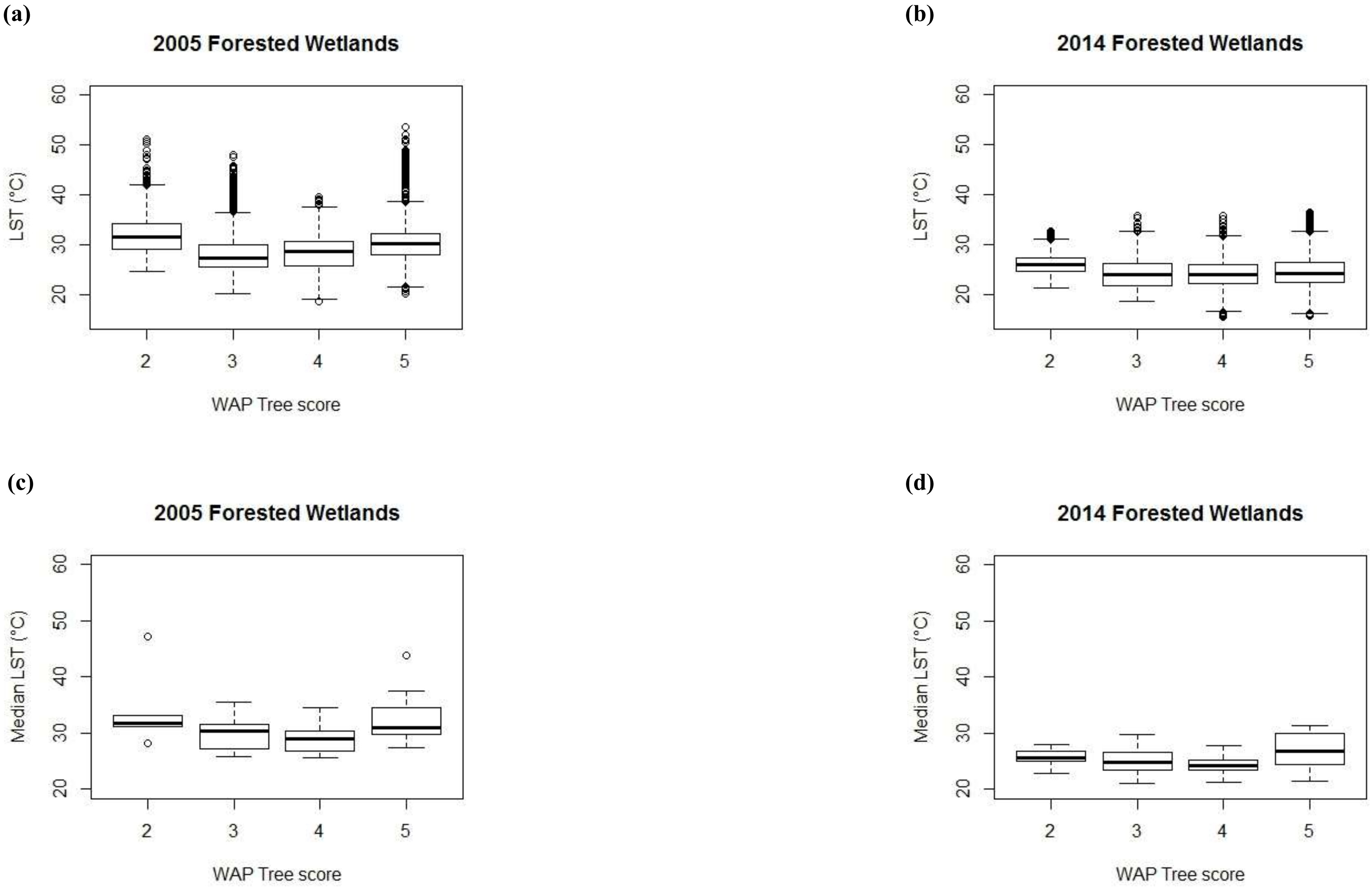

Figure 15. Boxplots of LST vs. Forested wetlands tree score. Boxplots of (a) LST vs. 2005 forested wetlands WAP tree score, (b) LST vs. 2014 forested wetlands WAP tree score, (c) Median LST vs. 2005 forested wetlands WAP tree score, (d) Median LST vs. 2014 forested wetlands WAP tree score.

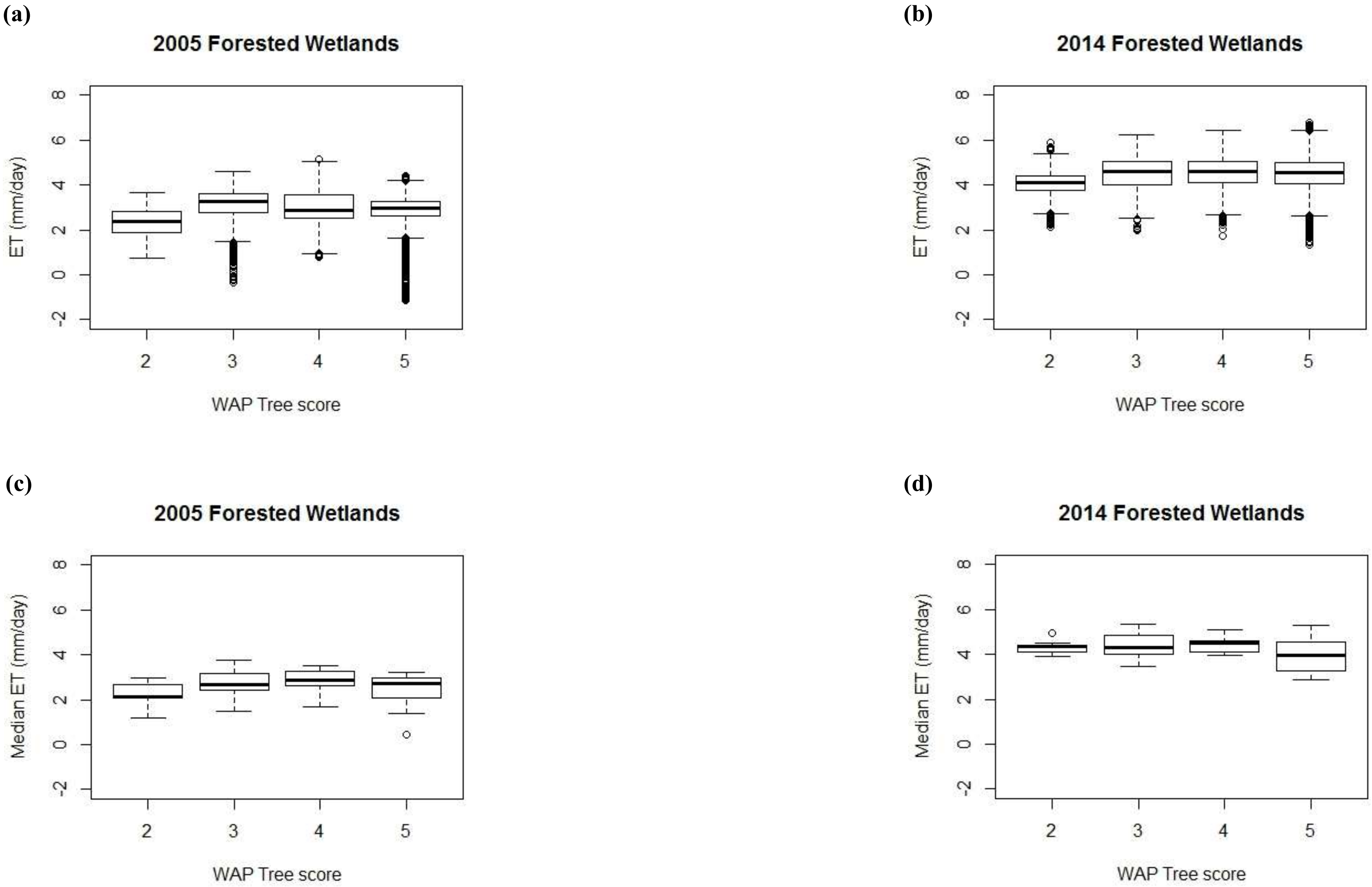

Figure 16. Boxplots of ET vs. Forested wetlands tree score. Boxplots of (a) ET vs. 2005 forested wetlands WAP tree score, (b) ET vs. 2014 forested wetlands WAP tree score, (c) Median ET vs. 2005 forested wetlands WAP tree score, (d) Median ET vs. 2014 forested wetlands WAP tree score.

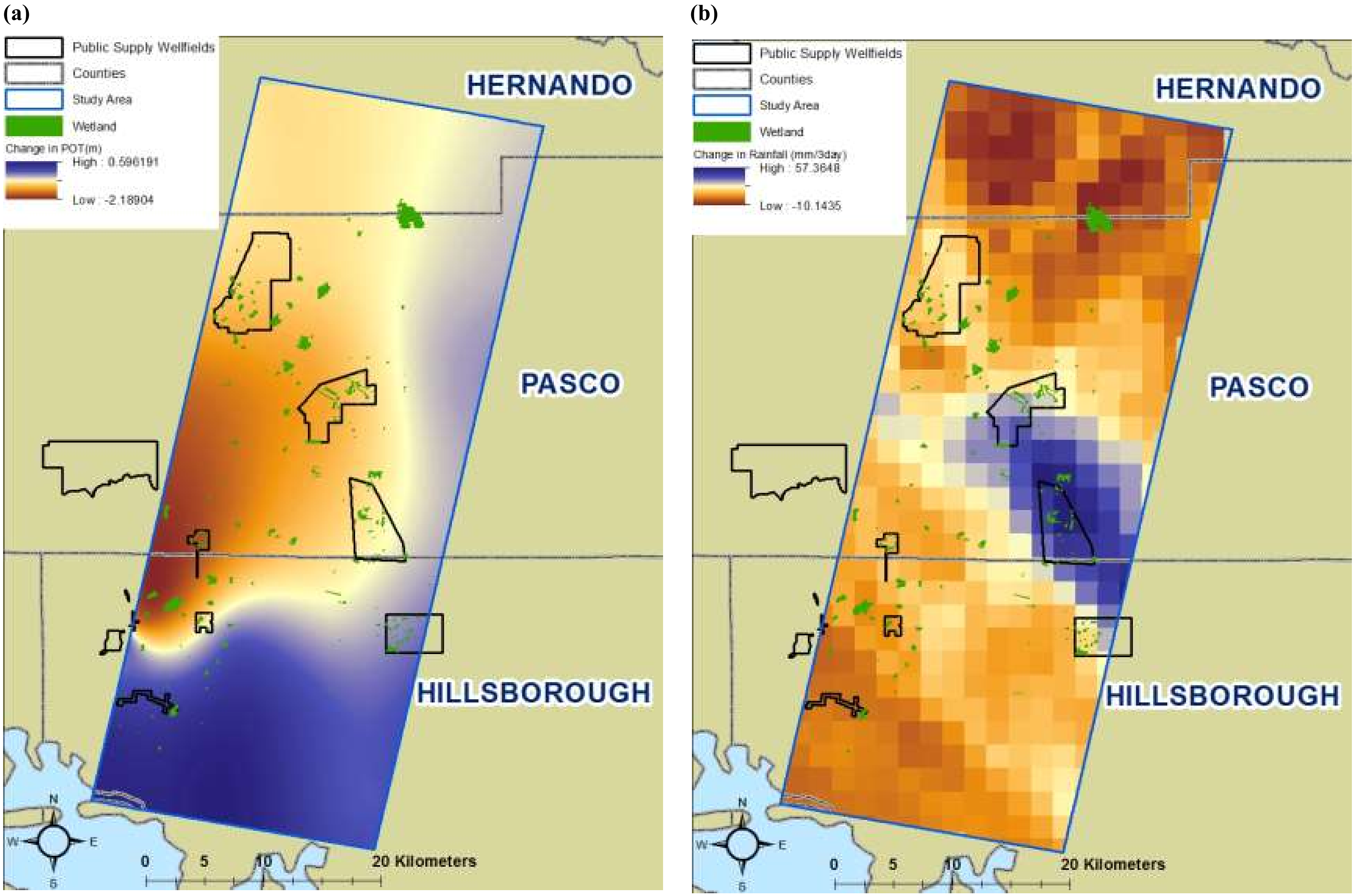

Figure 17. Maps of change in POT and Rainfall**.** Maps of (a) change in POT, (b) change in Rainfall in relation to study area and wetlands

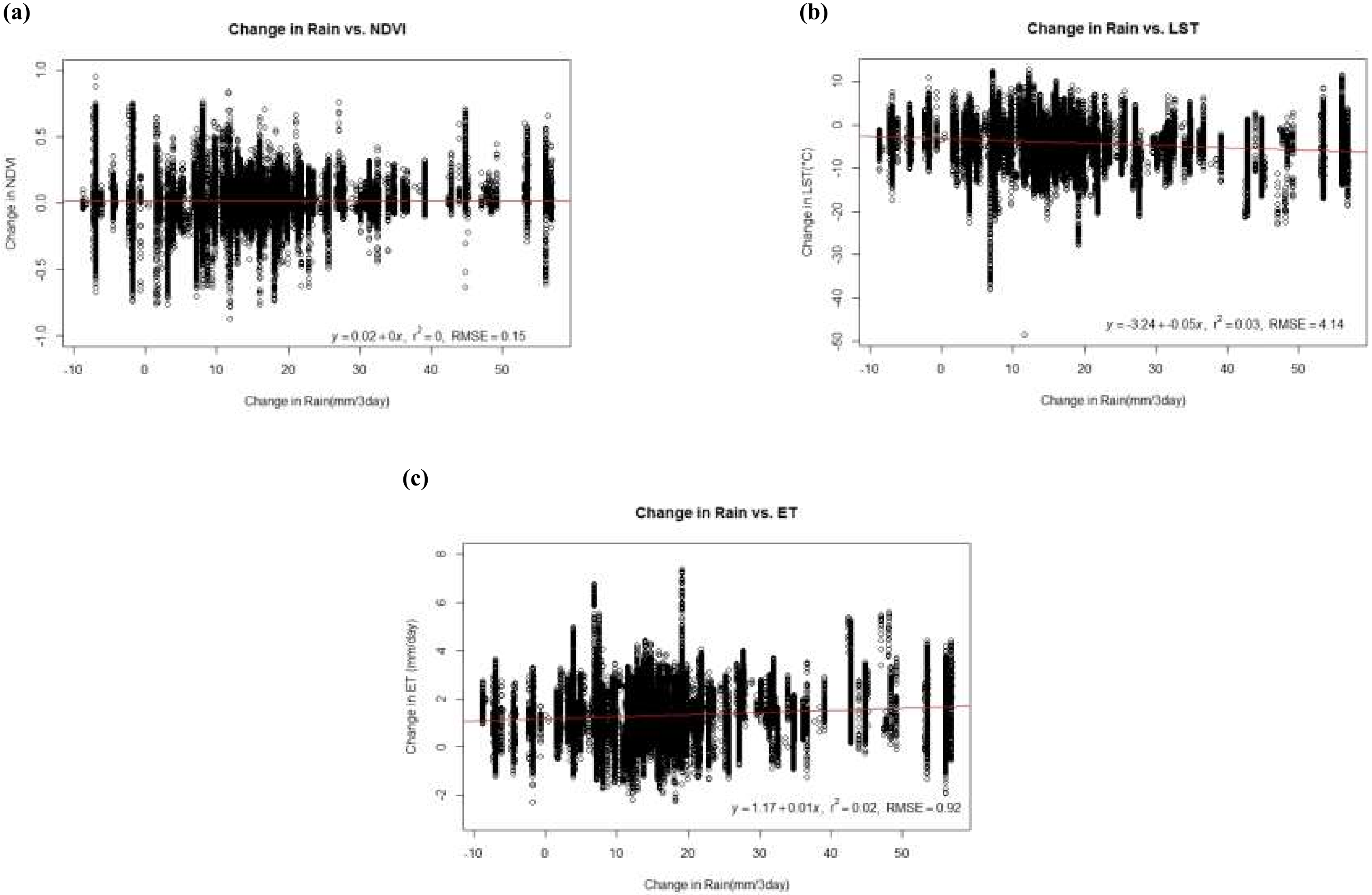

Figure 18. Scatterplots of change in Rainfall vs. change in NDVI, LST, and ET. Scatterplot of change in Rainfall vs. (a) Change in NDVI, (b) Change in LST, and (c) Change in ET

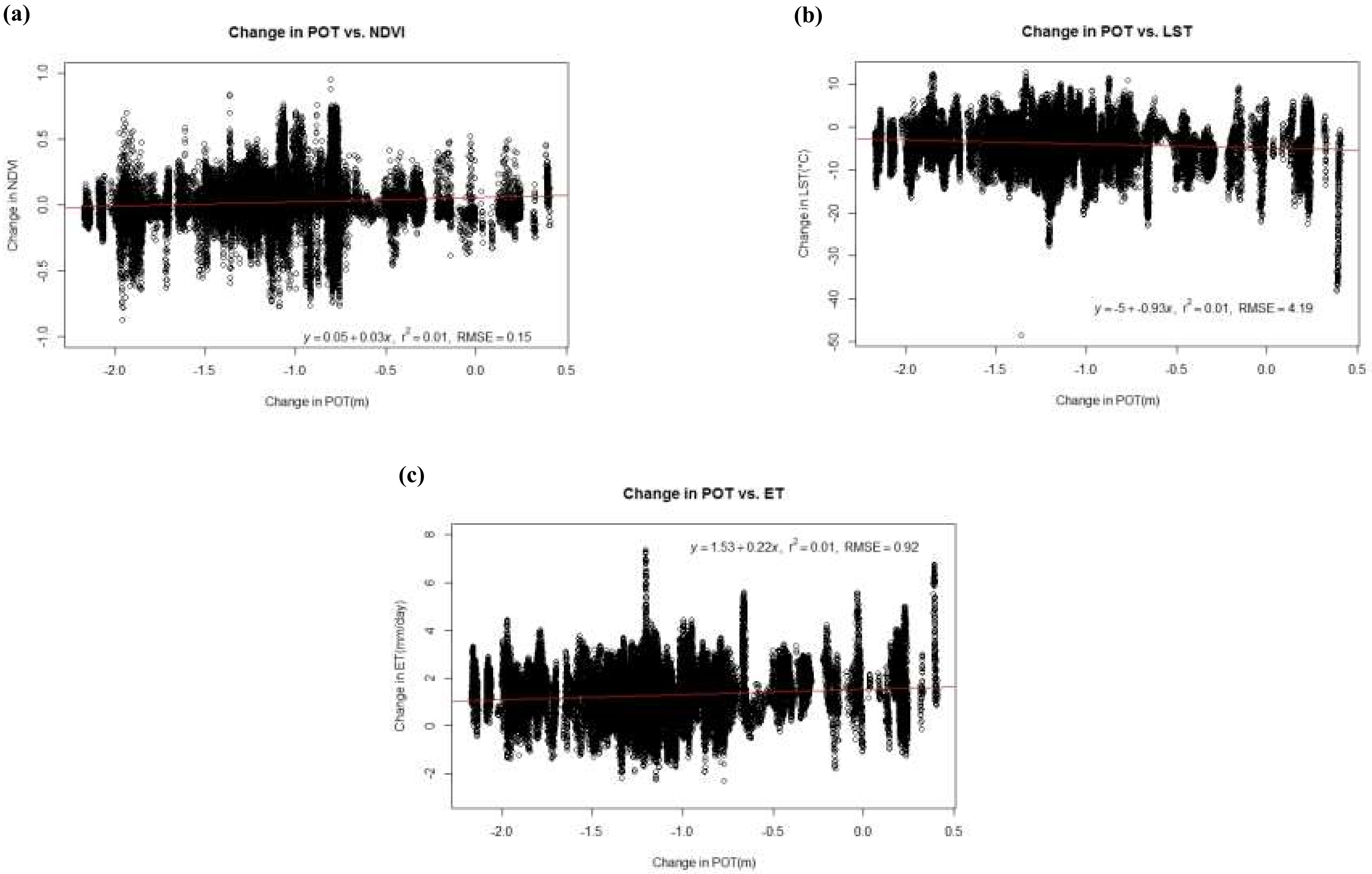

Figure 19. Scatterplots of change in POT vs. change in NDVI, LST, ET. Scatterplot of change in POT vs. (a) Change in NDVI, (b) Change in LST, and (c) Change in ET

DISCUSSION

The results of the analysis show a mismatch between the remotely sensed apparent recovery and the slight degradation indicated by the WAP scores and POT decreases. The results do not support the hypothesized belief that WAP scores would display a relationship with remotely sensed values. The results do fit the overall narrative of mixed, conflicting results of wetland recovery in the NTBA (Metz, 2011; Haag & Pfeiffer, 2012; Nilsson et al., 2013).

Changes in Spectral and Thermal Properties

The thermal and spectral responses showed an overall increase in wetland status, despite an overall decrease in POT of the Flordian Aquifer. The reasons for this increase in ET are unknown. Examination of one of the most likely reasons, the increase in rainfall, showed low r^2 scores, as seen in Figure 19. Another reason examined was the change in the elevation of the Surficial Aquifer (SWL). The SWL of the NTBA wetlands showed an overall increase in elevation, with a median change of 0.9m, a minimum change of -1.6m and a maximum change of 4.0m, with the change over the entire study area mapped in Figure 20. As the surficial aquifer is closer to land surface and plant root zones, it was believed that the increase in ET would be show a positive relationship with the increase in SWL. However, when changes in SWL were plotted against changes in ET, no trend emerged, as seen in Figure 21.

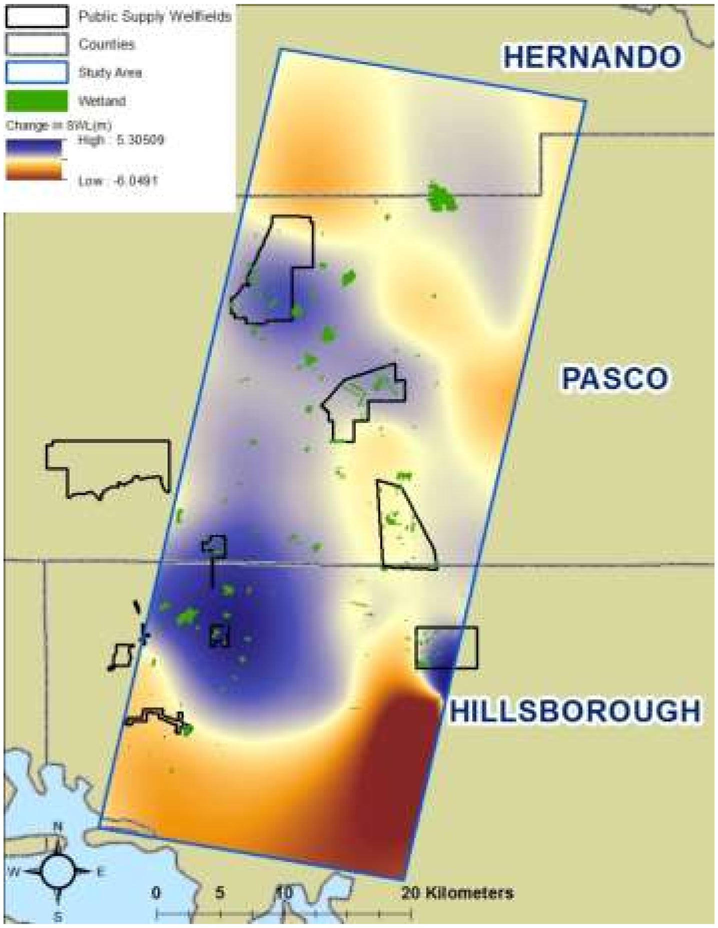

Figure 20. Map of change in SWL in relation to study area and wetlands

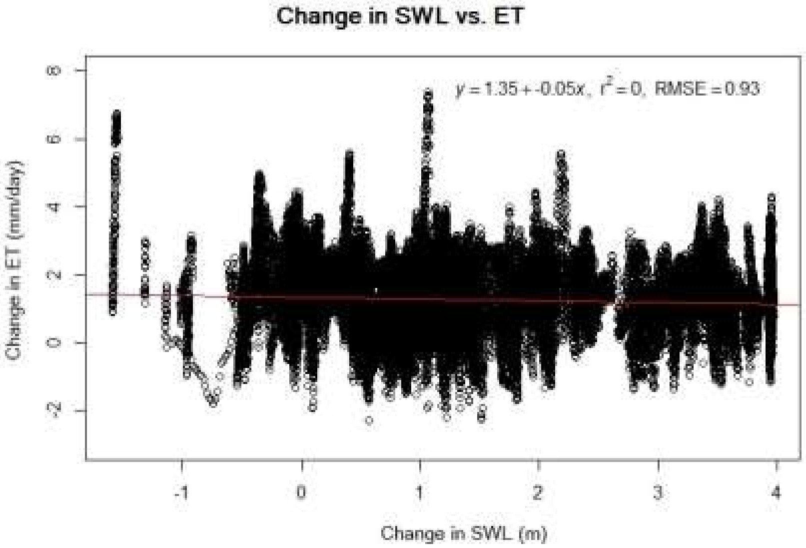

Figure 21. Scatterplot of change in SWL vs. change in ET

Based on these trends, the overall increase in ET cannot be fully explained by the variables examined in this study. The graphs show a large range in ET change regardless of the other variables, a likely indicator of other variables playing a part into water availability. Therefore, while it is likely that at least some of the increase in ET is due to the increase in part SWL and rainfall, based on the conflicting results with POT, the overall increase in ET cannot be fully explained by these two variables alone.

Change in WAP Scores

The overall trend of the wetlands ranged from generally no change, to a slight decline in WAP score from 2005 to 2014, regardless of type. The reasons for the decline in WAP despite decreases in pumping could be for a variety of reasons.

First, the NTBA wellfields began a staggered reduction in groundwater withdrawals in 2002, but the amount reduced varied from wellfield to wellfield (Haag & Pfeiffer, 2012). As the WAP scores showed a range in improvement to decline, it was believed that the amount reduced by nearby wellfields played some role in the trends in WAP between the two study years. Therefore, the May average MGD of 9 public supply groundwater wellfields within 2 miles of the study areas boundary (Water & Air Research et al., 2006) was analyzed for the two study years, with the results displayed in Figure 22. Furthermore, the annual pumping records of the 9 wellfields were examined for the change in MGD.

Three of the wellfields (Cypress Creek, Cypress Bridge, and Morris Bridge) showed an increase in pumping in 2014 compared to 2005, with Cypress Bridge having an especially large increase in pumping, going from approximately 5.5MGD to approximately 11MGD. The rest of the wellfields showed decreases in MGD. It is important to note that despite the decrease in MGD for majority of the well fields, three, almost four, wellfields had a MGD greater than 10 in

2014. When the locations of wetlands that showed a decrease in relevant WAP score were compared to wellfields, it was seen that many of the wetlands that declined are located in or near those wellfields that had a MGD of about 10 or more (Figures 8-10). The wetlands that showed declines also tended to be in areas where the change in POT was negative, which also happened to be in the areas where withdrawals were around 10 MGD. Based on these results, it is believed that the decline in WAP scores of the wetlands examined in this study is at least partially a result of the uneven and in some cases lack of reduction in groundwater withdrawals across the study area.

The other factor that might help explain the decline in WAP scores is the weather experienced in the area between the two years. As it turns out, the weather patterns in the NTBA since the establishment of the new WAP were on the extreme ends, and more than likely affected WAP scores. The 2005 establishment of WAP came at the end period of an extreme rainfall and heavy hurricane activity during 2003 and 2004 (Granville Kinsman, personal communication, 2015). These abnormally heavy precipitation events led to higher than mean groundwater and surface water levels, and much more suitable conditions for wetland flora. These wet conditions were followed by many years of abnormally dry conditions for the majority of the temporal skip from 2005 to 2014 (Granville Kinsman, personal communication, 2015). As 2005 can be seen as the new “baseline” for WAP, it is believed that scores were set high due to the abnormal wet years. It is also reasonable to believe that the excessively dry conditions of the gap years led to decreases in WAP scores.

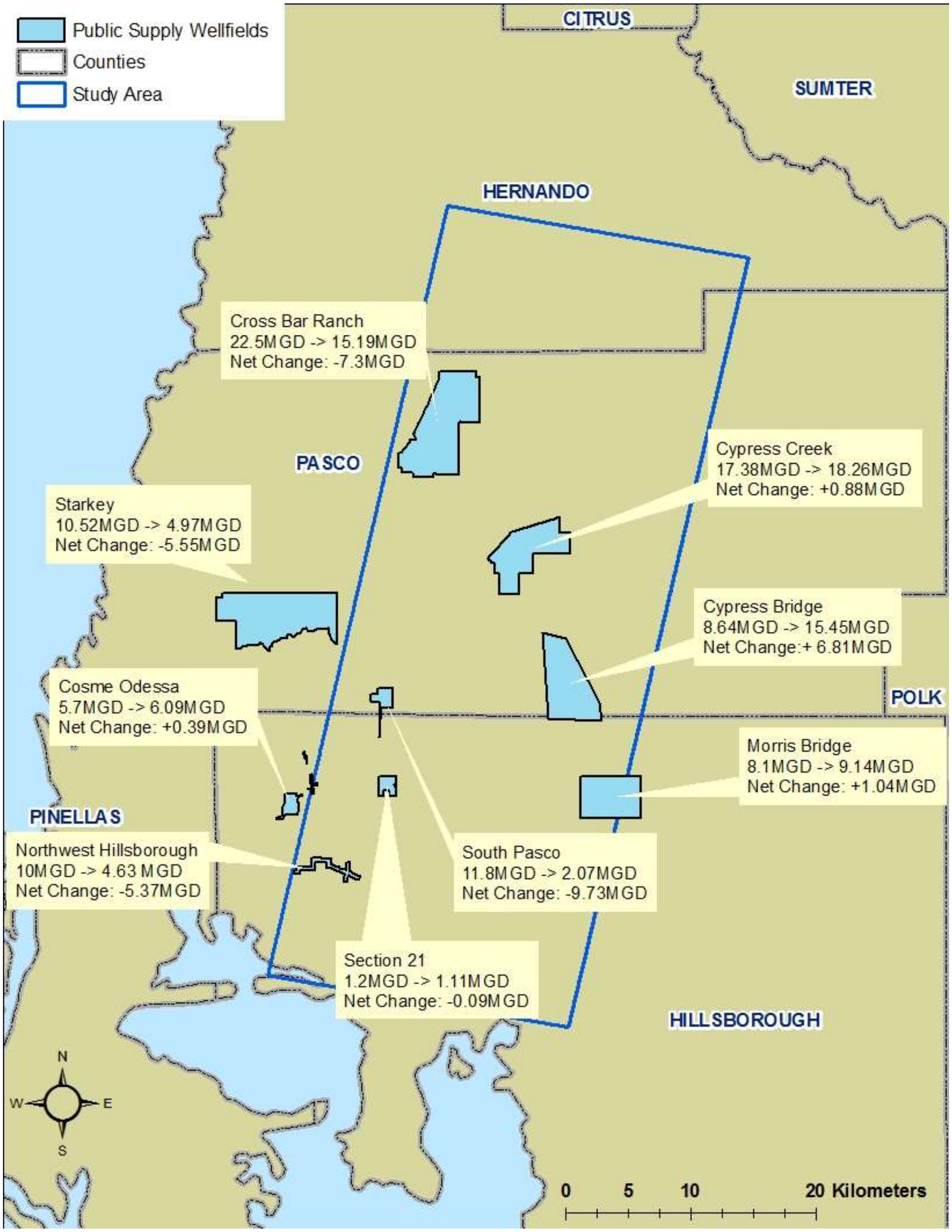

Figure 22. Map of wellfields within two miles of the Study area with changes in MGD. Map of wellfields within two a miles of the Study area boundary, and their pumping rates for the two years included in the study.

Mismatch of Remotely Sensed Responses vs. WAP Scores

Remotely sensed values had large ranges in most WAP scores, leading one to believe that there is no relationship between the two assessment methods. The lack of a relationship also leaves questions as to whether the wetlands of the NTBA recovered after reductions in groundwater withdrawals.

The first possibility that comes to mind is that the spatial resolution was too coarse for the purposes of this study. ASTER scenes had a spatial resolution of 15 m at the finest, and 90 m at the coarsest. WAP transects are 10 m wide and variable length depending on the size of the wetland. So while the transects are similar to the 15 m pixel size, it could be that the pixel resolutions are still too coarse in differentiating wetlands intermixed or overtaken by exotics and non-wetland plants from those that are mostly obligate and facultative wet species. (WAP: Instruction Manual for Isolated Wetlands, 2005). It is also important to remember that WAP is scored based on presence and location of upland vs. wetland plants in the wetland, not the condition they are in (WAP: Instruction Manual for Isolated Wetlands, 2005). Scores may be high or low due to the location of species in the wetland, but not reflected in the catchall pixel, which only describes the health. There is also the fact that WAP scores are originally scored based off transects, which t are divided into zones. These zones may or may not completely match up with the catchall pixel. If the zones both overlap the same pixel, their results are mixed together for the remote sensing assessment, while they are initially collected and judged separately using WAP. Furthermore, the transect is at face value a sample of the wetland, albeit one that is supposed to represent the entire wetland. Meanwhile the remotely sensed method used in this study actually utilized the entirety of the wetland. The results of the remotely sensed method showed wetlands had a large variance in pixel values (Figures A3−A5), so it could be that areas outside of the transect are showing improvement or decline, but are not represented in the WAP score.

Another thing to consider is the temporal differences between the two methods. Remote sensing methods, while they can be used to study long-term trends, are based off instantaneous data. The remotely sensed values of this study show the hydrologic conditions of the wetland at the time of capture, and are sensitive to acute changes in the local environment, such as cloud cover, incoming radiation, very recent changes in water levels, etc. WAP scores on the other hand, are based off values that are much less susceptible to acute changes, and are affected by different variables than remotely sensed values. Plant presence and numbers would not lower immediately due to a drop in ET rates caused by a short-term decline in water levels. Plant presence would however, change due to prolonged drops in water levels making the wetland areas unsuitable for obligate and facultative wet plants to continue to survive and reproduce. As WAP scores measure plant presence, the changes in WAP scores are more likely to represent the long-term improvement or lack thereof. This of course is also dependent on other factors, such as the type of plants themselves, the rate and intensity of change of hydrologic conditions of the area, etc. This brings up the next possible reason as to why there was a mismatch between WAP scores and remotely sensed values.

A third possible reason for the mismatch in spectral values vs. WAP scores could be that there was not enough hydrologic improvement to change the makeup in species within the wetlands. Plants can and will adapt to stressors, such as too little water, before they succumb to the stress. For example, Taiz & Zeiger (2006) explain that when water scarcity is gradual and moderate in intensity, plants will grow deeper roots to reach the lower water levels (Taiz & Zeiger 2006). However as the lack of water continues to worsen, roots will eventually begin to shrivel, lowering the ability to reach and absorb water. The opposite is not true, as plants not suited for flooding have very little tolerance for extended periods of inundation, and will die off very quickly if flooded. So it is believed that the increase in ET represents plants that are currently in the wetlands having more moisture available in 2014, but the saturation has not reached a high enough level and long enough duration to kill off upland species that bring the WAP score down. This can be seen in some of the results by Haag & Pfeiffer (2012), where a few wetlands had increases in flooded duration and extent, but no increase in WAP scores (Haag & Pfeiffer, 2012). Furthermore, the wetland plants of the NTBA may have adjusted to prolonged water limitations, and therefore are slow to die off due to poor hydrologic conditions. This is supported by the large number of wetlands that had no change in WAP score between the two study years, especially those with a score of 3. Of course this would vary across community types, with herbaceous shallow rooted plants being less tolerant than trees, which ideally should be able to grow deeper roots to reach the lower water tables. Therefore, there is a possibility that decreases in herbaceous wetlands groundcover scores would reflect short-term changes in water scarcity, while decreases forested wetland tree scores reflect a more extreme water stress.

Nonetheless, the above reason does not fully explain the wetlands that showed no change in WAP, had a score of 4 or 5 for both years of the study despite years of drought that impacted other nearby wetlands, and still had lower LST and higher ET. As such, it is believed that on top of the moisture increase not being enough for the area to drive off non-wetland species, other variables played a larger role in the conflict between remotely sensed values and WAP values.

The most likely missing variable affect the mismatch would be the hydrogeological properties of the wetlands and their immediate surroundings. Metz (2011) noted that underlying karst subsidence was a large factor in wetland recovery (Metz, 2011). It is possible that from

2005 to 2014, local subsidence occurred, altering flow of water into and out of the wetlands. This idea is supported by the facts that the POT of the Upper Floridan aquifer was lower in May 2014, that there were periods of drought between the two study years, the scattered distribution of wetlands with no change in WAP, and that Metz's findings of subsidence were not uncommon (Metz, 2011). Metz (2011) and Nilsson et al. (2013) noted that materials that make up the bottom or underlie the bottom of the wetland affected water flow within the wetland boundary area, specifically the presence of the confining unit, clay, and other low permeable sediments (Metz, 2011, Nilsson et al., 2013). Furthermore, clay is known to absorb water and slowly release it over time, creating a lag between drier surface conditions in the wetlands and the physiological effects on the plants. As sediment sampling was not a part of this study it is possible that mismatch could be explained by the inclusion of this data, something that also suggested by Nilsson et al. (2013), who also found stressed and non-stressed wetlands spread throughout the NTBA area (Nilsson et al., 2013).

This is not to say that the reasons addressed above are the sole explanations of the remotely sensed WAP mismatch. The lack of correlation found in this study could be due to many other reasons such as: not enough time has elapsed between reductions in groundwater withdrawals for the wetlands to show recovery, preprocessing errors (poor fitting empirical line calibration, over or under sharpening of thermal band, etc.), human error, etc.

Overall Wetland Recovery

Based on the results of the study, it cannot be shown definitively that the wetlands of the NTBA have improved or declined in hydrologic condition. When previous studies are taken into account, the results appear to show a complex area, where slow transitions are taking place. This transition looks in part like the transition noted by Haag & Lee (2012), where drier conditions have converted the northeastern half of the study area's herbaceous wetlands into forested wetlands. Figures 8a & 10a shows herbaceous wetlands WAP groundcover scores declining and tree scores increasing in the northwest to southeast diagonal, area where nearby wellfields had an increase in MGD. These areas are still wet enough to provide habitat for wetlands species, but more so woody species that have shown themselves more resilient against dry weather periods and higher MGD than herbaceous species (Haag & Pfeiffer, 2012). This transition also shows large swaths of the NTBA wetlands morphing or already transformed from strict wetland, to more transitional wetlands that are more habitable to facultative wet and weedy facultative species that can survive wet conditions for some time, but are also well suited to drier conditions.

The NTBA has proven to be much more complex than what could be examined in this study, with many variables and influences that greatly affect the ability to monitor and understand recovery of either methodology. Past studies have shown mixed results, with this work continuing that trend (Metz. 2011; Haag & Pfeiffer, 2012; Nilsson et al., 2012).

CONCLUSION

The purpose of this study was to examine the recovery of wetlands in the NTBA after the reduction in pumping from 2005 to 2014. Specifically, three questions were asked:

- Based on the spectral and thermal characteristics of the wetlands in the study area, have the overall wetland conditions been improved after the reduction in groundwater withdrawals?
- Based on the WAP scores, have overall wetland conditions been improved after the reduction in groundwater withdrawals?
- Do the spectral and thermal characteristics of the wetlands relate with the WAP scores?

The experimental results indicate that the answer to the first question is yes, as the overall median ET and LST, as well as majority of the individual wetlands median ET and LST values showed improvement. To the second question the answer is no, as there was a net decrease in the overall WAP scores, though this decrease might be due to outside factors. Moreover, to the third question the answer is no again, for reasons that cannot be fully explained, but likely due to other variables not included in this study playing a large role in wetland responses, as well as incompatibility between the responses measured by each of the two methodologies. Because of the conflicting results between the two methodologies used in this study to evaluate wetland recovery, it cannot be determined with absolute certainty whether the NTBA wetlands truly recovered after the reduction in pumping at some of the wellfields in the area. With this, it is believed that by itself, this methodology of remote sensing is not able to determine hydrologic improvement based on the current method of mapping biological indicators. It is suggested that it be used as a supplement to field based methods at this time.

It is suggested in future studies that high-density field sampling of underlying geologic variables be collected in any future studies, as there has been a continued mention of complex hydrogeological variables playing a large part in the hydrologic recovery of wetlands. It is also recommended that future remotely sensed studies be a time series of images taken at peak dry and wet season to better identify and associate changes in spectral response with changes in pumping vs. other influences.

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DATA SOURCES

2005 Natural Color Aerial Imagery - Originator: Southwest Florida Water Management District. Publication Date: n.d. Data Type: Mosaic Dataset. Presentation format: Not presented, used as image. Retrieved from: SWFWMD internal Image server

2014 Natural Color Aerial Imagery - Originator: Southwest Florida Water Management District. Publication Date: n.d. Data Type: Mosaic Dataset. Presentation format: Not presented, used as image. Retrieved from: SWFWMD internal Image server

ASTER Imagery – ASTER imagery was downloaded from the USGS Earth Explorer website. Scenes were retrieved for ASTER L1B data, based on date availability for both years, overall coverage of study area, and lowest level of cloud cover. Images selected for use were georectified and clipped to the area of overlap between the two image years. The clipped image was then used for all subsequent analysis. https://earthexplorer.usgs.gov/.

ASTER Spectral Library - Baldridge, A. M., S.J. Hook, C.I. Grove and G. Rivera, 2009. The ASTER spectral library version 2.0. Remote Sensing of Environment, vol 113, pp. 711-715. Data Retrieved from :< https://speclib.jpl.nasa.gov/>.

ENVI version 4.8 & 5.1 software. Exelis Visual Information Solutions. Boulder, Colorado. Copyright © 2017 Exelis Visual Information Solutions. <www. http://www.harrisgeospatial.com/Home.aspx>.

ESRI. Webmap Services. **World Imagery** - Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community. Maps throughout this thesis were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.

Florida Automated Weather Network weather stations – Weather station data for the sites closest to the study area boundary (Balm, Dover, and Dade City) were collected from the FAWN website in .csv format the days of the imagery collection. Data was in 15minute format, and used 2m above ground temperature at the time of imagery collect. Desired records were placed in a separate sheet, and converted into ^{o}C. The.csv sheet was added to ArcMap, converted into points, and mapped. https://fawn.ifas.ufl.edu/.

Groundwater Data Collection Sites – Originator: Southwest Florida Water Management District. Publication Date: 01-30-2008. Data Type: Shapefile. Presentation format: vector digital data. Retrieved from: SWFWMD internal SDE database. Later versions available from: http://data-swfwmd.opendata.arcgis.com/.

Groundwater level data – Groundwater levels were collected upon request by SWFWMD staff members: Patrick Casey, Margit Crowell, and Asmita Shukla from the internal WMIS website. Groundwater data came in .csv format, and was joined to the Groundwater Data Collection Sites shapefile.

Microsoft Office 2010 - 2016. Microsoft Excel, Powerpoint, and Word. Copyright © 2017 Microsoft. < https://www.microsoft.com/en-us/>.

NEXRADGRIDDISTRICT – Originator: Southwest Florida Water Management District. Publication Date: 10-27-2011 Data Type: Shapefile. Presentation format: vector digital data. Retrieved from: SWFWMD internal SDE database

NexRad daily rainfall – NexRad rainfall were collected from the SWFWMD internal Water Management Information System (WMIS) website. Total daily rainfall was collected for the day of the image collected and the two days preceding image collection. All rainfall came in .csv format, and were joined to the NEXRADGRIDDISTRICT shapefile, converted to raster format, and clipped to only include grid cells included in the study area boundary.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing,Vienna, Austria. URL https://www.R-project.org/

Reference Evapotranspiration – Reference evapotranspiration data was downloaded from the USGS Caribbean-Florida Water Science Center's Evapotranspiration Information Data website. Data for 2005 and 2014 were downloaded in .csv format, and data for the day of image copied and combined into one excel file. Excel files of the data used were converted to point format, joined to the NEXRADGRIDDISTRICT shapefile, converted to raster format, and clipped to only include grid cells included in the study area boundary. < https://fl.water.usgs.gov/et/>.

PUBLICSUPPLYWELLFIELDS– Originator: Southwest Florida Water Management District. Publication Date: 10-27-2011 Data Type: Shapefile. Presentation format: vector digital data. Retrieved from: SWFWMD internal SDE database

PUBLICSUPPLYDISPERSED– Originator: Southwest Florida Water Management District. Publication Date: 10-27-2011 Data Type: Shapefile. Presentation format: vector digital data. Retrieved from: SWFWMD internal SDE database

WAP_WETLANDS. – Originator: Southwest Florida Water Management District. Publication Date: 10-27-2011 Data Type: Shapefile. Geospatial Data Presentation format: vector digital data. Retrieved from: SWFWMD internal SDE database

WATERMANAGEMENTDISTRICTS– Originator: Southwest Florida Water Management District. Publication Date: 10-27-2011 Data Type: Shapefile. Presentation format: vector digital data. Retrieved from: SWFWMD internal SDE database

Wetlands Assessment Procedure Scores – WAP scores for both years were collected from a variety of sources including:

- SWFWMD external WMIS website < http://www18.swfwmd.state.fl.us/ResData/Search/ExtDefault.aspx>.
- SWFWMD internal WMIS website
- Personal communication with SWFWMD Staff member David Carr
- Manually extracted from the following internal SWFWMD reports:
    - Biological Research Associates, LLC. & SDI Environmental Services, Inc. (2006a). Annual hydrological and ecological environmental assessment report for the Cross Bar Ranch wellfield: water year 2005. Tampa, Florida. Biological Research Associates, LLC.
    - Biological Research Associates, LLC. & SDI Environmental Services, Inc. (2006b). Annual hydrological and ecological environmental assessment report for the Morris Bridge wellfield: water year 2005. Tampa, Florida. Biological Research Associates, LLC.
    - Bureau Veritas/Berryman & Henigar. & SDI Environmental Services, Inc. (2006). J.B. Starkey wellfield and North Pasco regional wellfield ecological/hydrological monitoring program: water year 2005 annual monitoring report (October 1, 2004 - September 30, 2014).
    - Tampa Bay Water. (2006). Annual meter report, Cypress Creek wellfield monthly comparison. Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.
    - Tampa Bay Water. (2015a). Annual hydrological and ecological environmental assessment report for the Cosme-Odessa wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.
    - Tampa Bay Water. (2015b). Annual hydrological and ecological environmental assessment report for the Cross Bar Ranch wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015c). Annual hydrological and ecological environmental assessment report for the Cypress Bridge wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015d). Annual hydrological and ecological environmental assessment report for the Cypress Creek wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015e). Annual hydrological and ecological environmental assessment report for the Morris Bridge wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015f). Annual hydrological and ecological environmental assessment report for the Northwest Hillsborough regional wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015g). Annual hydrological and ecological environmental assessment report for the Section 21 wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015h). Annual hydrological and ecological environmental assessment report for the South Pasco wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015i). Annual hydrological and ecological environmental assessment report for the J.B. Starkey/North Pasco wellfields: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Terra Environmental Services, Inc. & HDR Engineering, Inc., Cypress Bridge wellfield: water year 2005 (October 2004 – September 2005) annual report. (2006). Tampa, Florida. Terra Environmental Services, Inc. Internal report: unpublished.

- Water & Air Research., HSW Engineering Inc., Ormiston, B. G. (2006). Comprehensive annual ecological monitoring and environmental assessment report for the Cosme-Odessa, Eldridge Wilde, Northwest Hillsborough, Section 21, and South Pasco wellfield regions: water year 2005. Gainesville, Florida. Water & Air Research. Internal report: unpublished.

All WAP values were combined into an excel file, which was joined to the WAP_WETLANDS shapefile. All subsequent analysis used this excel file or the joined WAP_WETLANDS shapefile.

Wellfield pumping rates- Wellfield pumping rates were manually extracted into a word document from the following internal SWFWMD reports:

- Biological Research Associates, LLC. & SDI Environmental Services, Inc. (2006a). Annual hydrological and ecological environmental assessment report for the Cross Bar Ranch wellfield: water year 2005. Tampa, Florida. Biological Research Associates, LLC.
- Biological Research Associates, LLC. & SDI Environmental Services, Inc. (2006b). Annual hydrological and ecological environmental assessment report for the Morris Bridge wellfield: water year 2005. Tampa, Florida. Biological Research Associates, LLC.
- Bureau Veritas/Berryman & Henigar. & SDI Environmental Services, Inc. (2006). J.B. Starkey wellfield and North Pasco regional wellfield ecological/hydrological monitoring program: water year 2005 annual monitoring report (October 1, 2004 - September 30, 2014).
- Tampa Bay Water. (2006). Annual meter report, Cypress Creek wellfield monthly comparison. Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.
- Tampa Bay Water. (2015a). Annual hydrological and ecological environmental assessment report for the Cosme-Odessa wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.
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- Tampa Bay Water. (2015e). Annual hydrological and ecological environmental assessment report for the Morris Bridge wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

- Tampa Bay Water. (2015f). Annual hydrological and ecological environmental assessment report for the Northwest Hillsborough regional wellfield: water year 2014 (October 1, 2013- September 30, 2014). Clearwater, Florida. Tampa Bay Water. Internal report: unpublished.

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- Water & Air Research., HSW Engineering Inc., Ormiston, B. G. (2006). Comprehensive annual ecological monitoring and environmental assessment report for the Cosme-Odessa, Eldridge Wilde, Northwest Hillsborough, Section 21, and South Pasco wellfield regions: water year 2005. Gainesville, Florida. Water & Air Research. Internal report: unpublished.

All pumping rates were recorded in a word document, and later placed in new attribute fields of the PUBLICSUPPLYWELLFIELDS shapefile.

APPENDICES

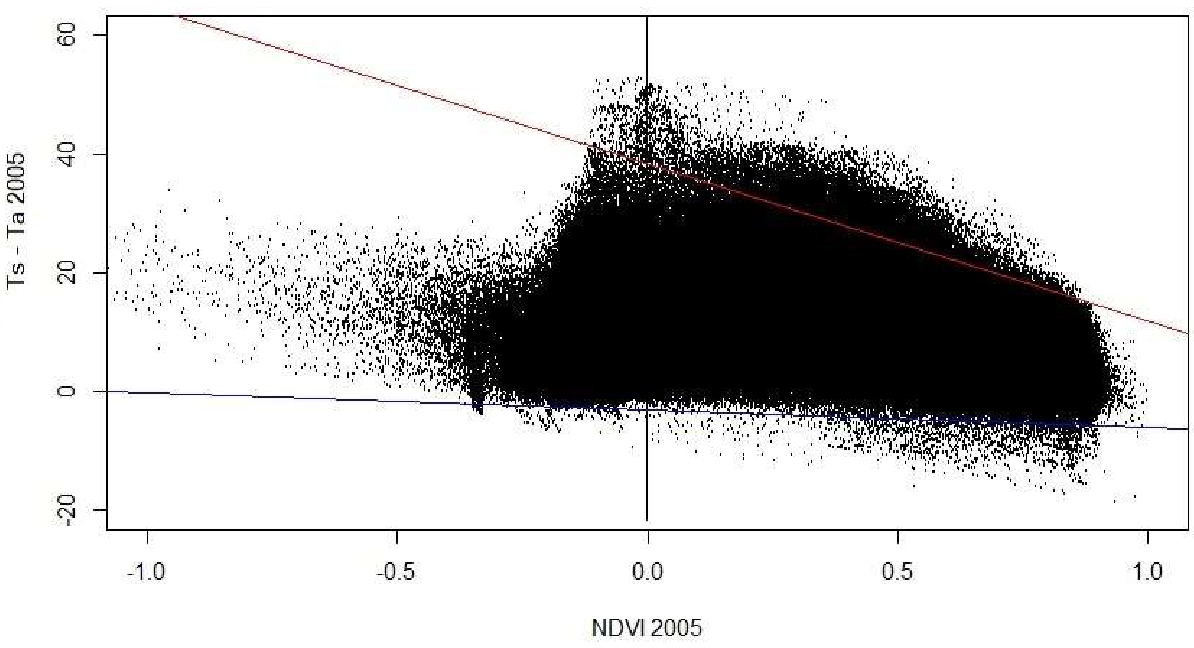


Figure A1. Scatterplot of Ts-Ta vs. NDVI 2005. The blue line represents the wet edge, and the red line represents the dry edge.

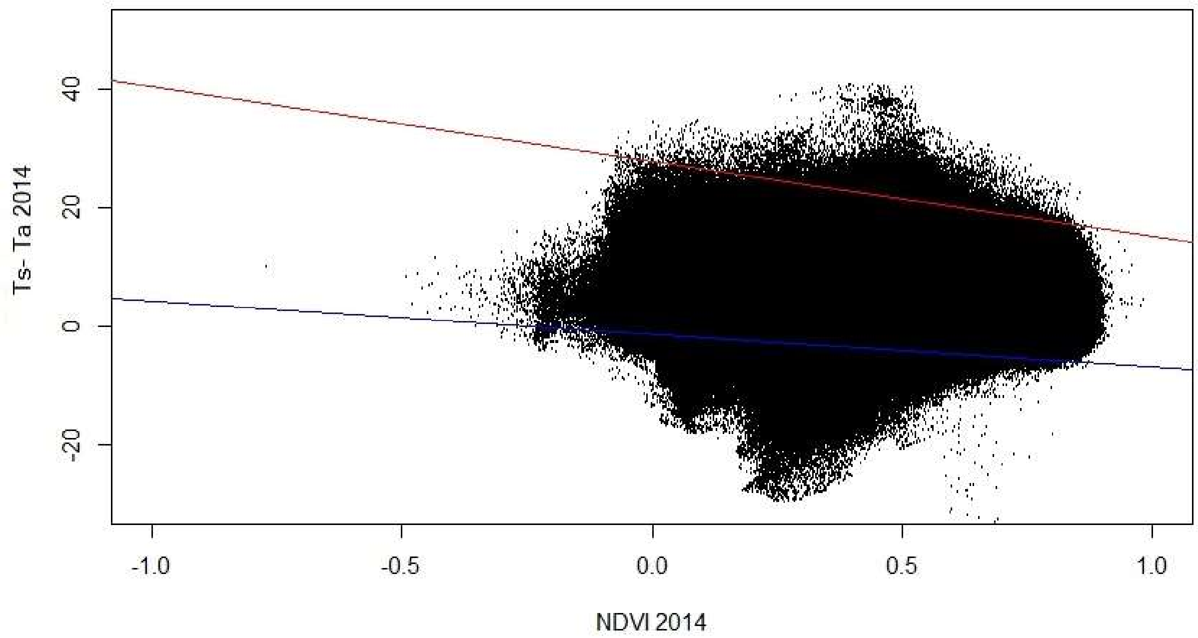


Figure A2. Scatterplot of Ts-Ta vs. NDVI 2014. The blue line represents the wet edge, and the red line represents the dry edge.

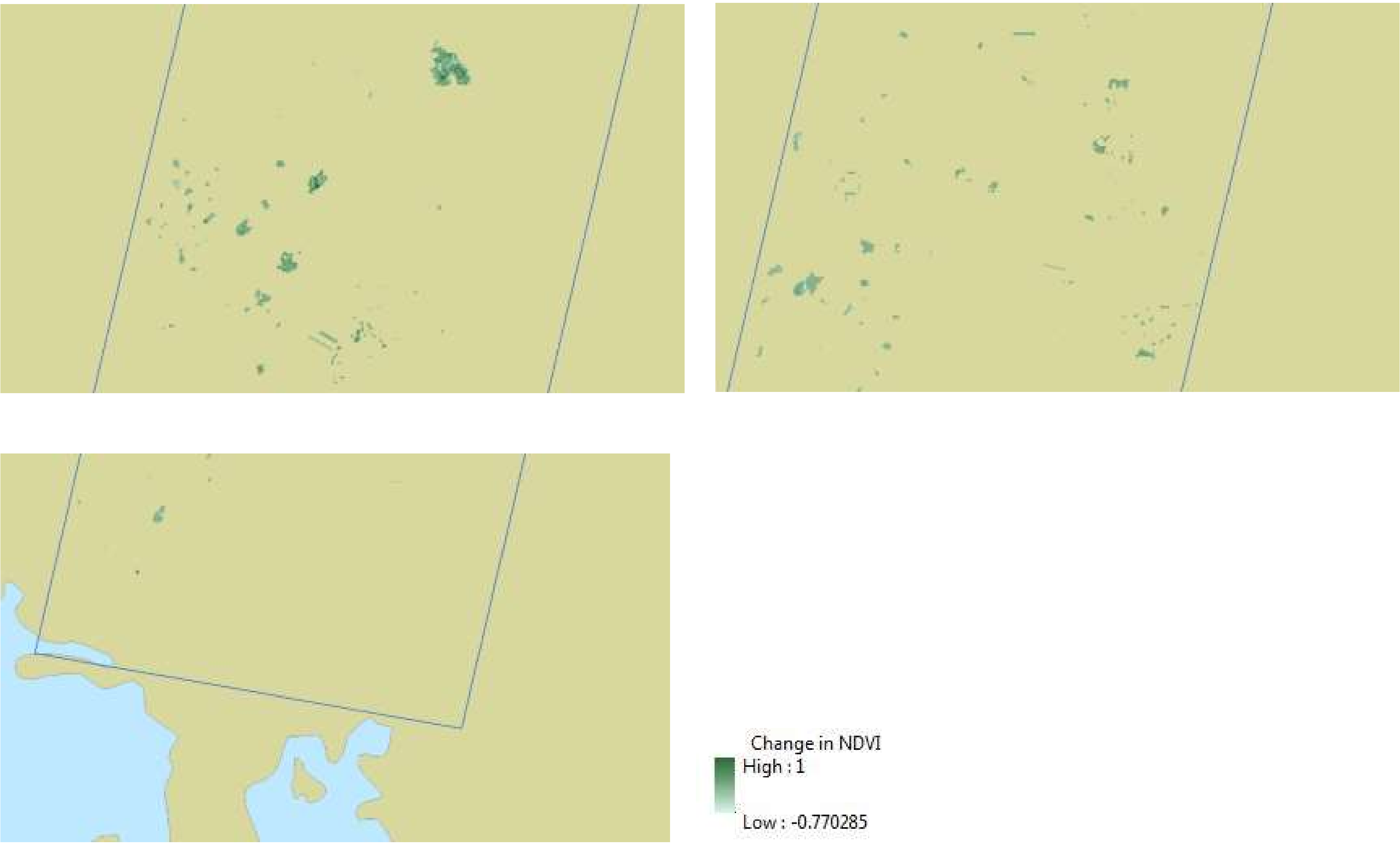


Figure A3. Screenshots of inter-wetland variance of change in NDVI

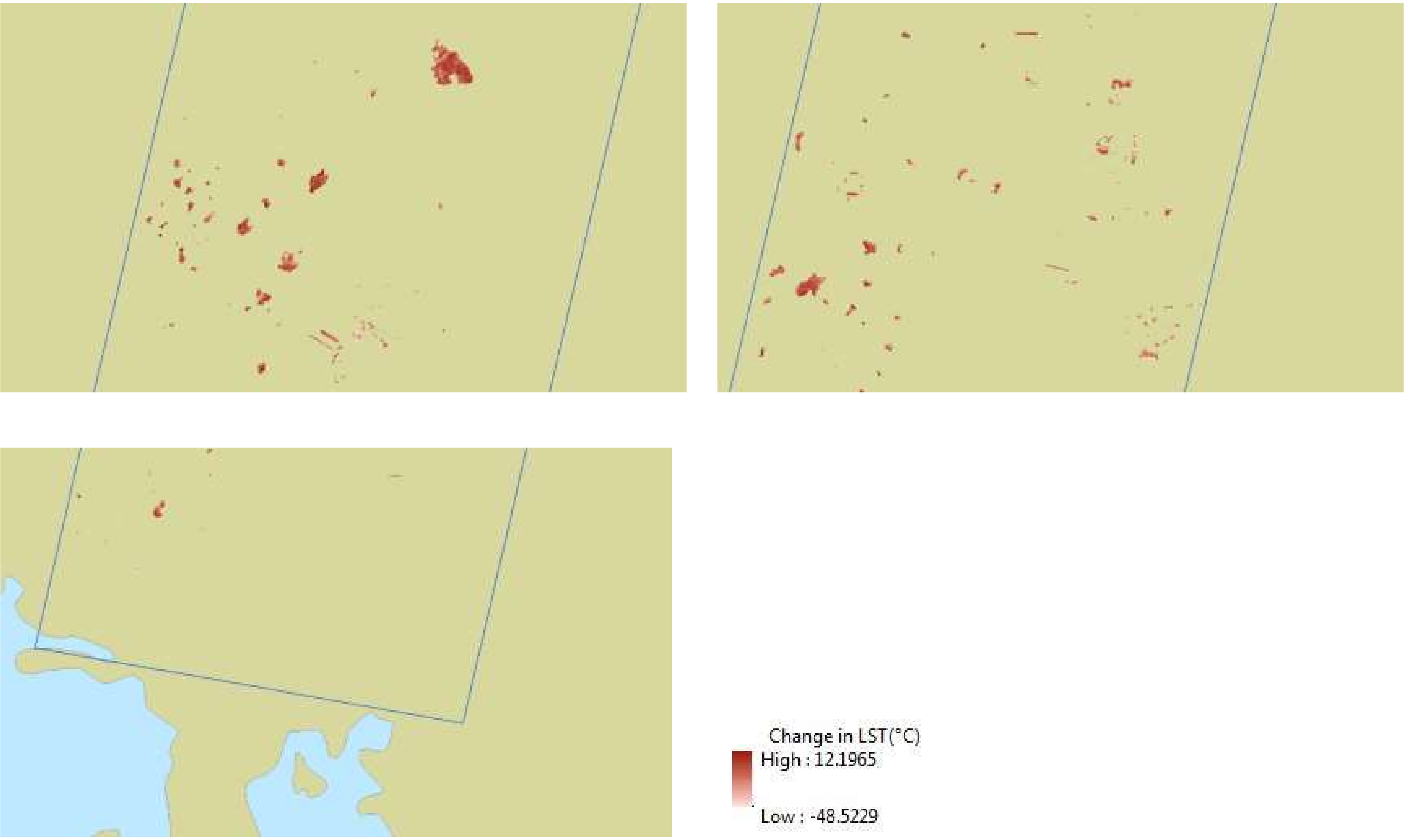


Figure A4. Screenshots of inter-wetland variance of change in LST (^{o}C)

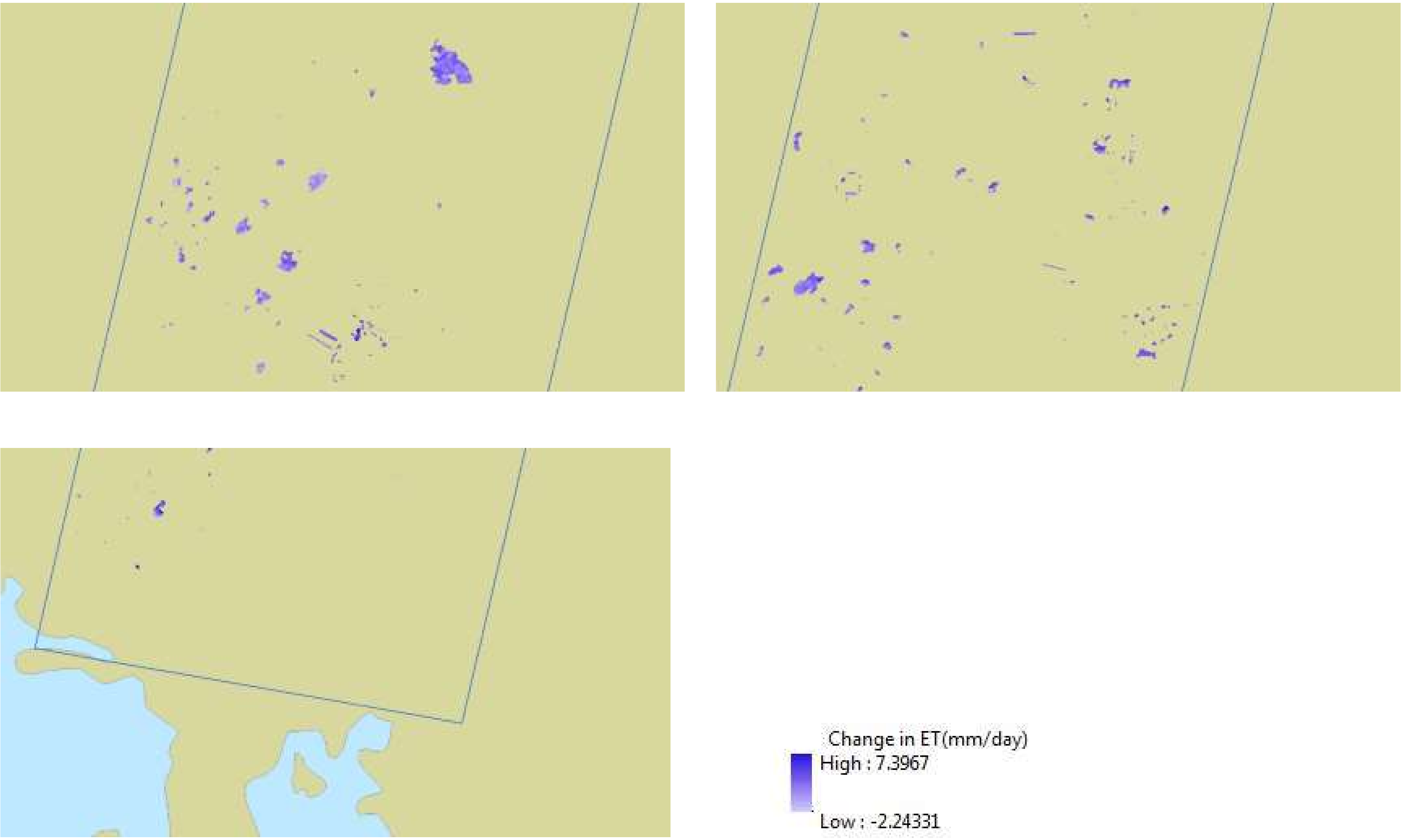


Figure A5. Screenshots of inter-wetland variance of change in ET (mm/day)

Table A1. WAP scores for all years.*

Wetland ID	Wetland Type	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2	Cypress Isolated	4	4	4	4	4	4	4	4	4	4
38	Cypress Isolated	5	5	5	5	5	5	5	5	5	5
121	Cypress Isolated	3	3	3	3	3	3	3	3	3	3
122	Cypress Isolated	2	2	2	2	2	2	2	2	2	2
124	Cypress Isolated	5	5	5	5	3	3	4	5	5	5
131	Cypress Isolated	5	4	4	3	4	3	4	4	3	4
132	Cypress Isolated	3	3	3	4	3	2	3	2	2	2
133	Cypress Isolated	5	5	5	5	5	5	5	5	5	5
138	Cypress Isolated	5	4	4	5	4	4	3	4	4	3
140	Cypress Isolated	4	3	3	4	3	3	3	4	3	3
142	Cypress Isolated	5	5	5	4	4	3	4	3	4	4
147	Cypress Isolated	4	4	4	4	4	3	3	3	3	3
149	Cypress Isolated	5	5	5	4	5	5	4	4	4	4
153	Cypress Isolated	4	5	4	5	3	3	3	5	3	2
260	Cypress Isolated	4	4	3	4	3	3	3	3	3	3
261	Cypress Isolated	3	3	4	4	3	3	3	3	4	4
263	Cypress Isolated	5	5	5	5	5	5	5	3	3	3
273	Cypress Isolated	3	3	3	3	3	3	3	3	2	2
274	Cypress Isolated	3	3	5	3	5	4	4	4	4	4
276	Cypress Isolated	4	3	3	3	3	3	3	3	3	3
280	Cypress Isolated	5	5	5	5	5	5	5	5	5	5
367	Cypress Isolated	2	5	4	4	4	4	4	4	4	4
372	Cypress Isolated	3	3	3	2	2	2	2	2	2	2
374	Cypress Isolated	3	3	3	3	3	3	3	3	3	3
378	Cypress Isolated	5	5	5	5	5	5	5	5	5	5
379	Cypress Isolated	3	3	3	4	3	3	3	3	3	3
381	Cypress Isolated	4	4	3	3	3	3	3	5	5	5

Table A1 (Continued)

383	Cypress Isolated	2	2	2	2	2	2	2	2	2	2
385	Cypress Isolated	3	3	3	3	3	3	3	3	3	3
387	Cypress Isolated	2	2	2	2	2	2	3	3	3	2
388	Cypress Isolated	3	3	3	3	3	3	3	3	3	3
390	Cypress Isolated	2	3	2	3	2	0	2	2	2	2
392	Cypress Isolated	3	4	3	4	4	4	4	4	4	4
393	Cypress Isolated	3	3	3	4	3	3	3	3	3	2
394	Cypress Isolated	3	2	2	2	2	2	2	2	2	2
395	Cypress Isolated	3	3	3	3	4	3	3	3	3	3
396	Cypress Isolated	3	3	3	3	3	3	3	3	3	3
401	Cypress Isolated	5	5	5	5	5	5	5	4	4	5
404	Cypress Isolated	5	4	4	4	5	5	4	5	5	5
9	Cypress Marsh Isolated	3	3	3	3	3	3	3	3	3	3
10	Cypress Marsh Isolated	3	3	4	3	3	2	2	2	3	3
11	Cypress Marsh Isolated	5	5	5	5	5	5	5	5	5	5
17	Cypress Marsh Isolated	5	5	5	5	5	5	5	5	5	5
39	Cypress Marsh Isolated	5	5	5	5	5	5	5	5	5	5
156	Cypress Marsh Isolated	5	5	5	5	5	5	3	4	4	4
262	Cypress Marsh Isolated	3	3	3	5	4	3	5	4	3	3
279	Cypress Marsh Isolated	5	5	5	5	5	5	5	5	5	5
366	Cypress Marsh Isolated	2	3	3	3	2	2	2	2	2	3
123	Hardwood Isolated	5	5	5	4	3	3	3	2	2	2
127	Hardwood Isolated	5	4	5	5	5	5	4	4	4	5

Table A1 (Continued)

134	Tupelo marsh Isolated	4	3	3	3	4	3	3	3	3	3
37	Lake Fringing Marsh	3	3	3	3	3	2	3	3	3	3
4	Marsh Isolated	5	3	3	2	3	2	3	3	3	4
5	Marsh Isolated	4	2	2	2	3	2	2	2	2	2
7	Marsh Isolated	5	2	3	3	3	2	2	2	2	3
8	Marsh Isolated	4	3	3	2	2	2	2	2	3	3
14	Marsh Isolated	2	3	3	2	3	3	3	2	2	2
18	Marsh Isolated	1	2	2	1	1	1	1	1	1	1
23	Marsh Isolated	5	3	3	3	3	3	2	2	2	2
34	Marsh Isolated	4	2	2	2	2	2	2	2	2	2
35	Marsh Isolated	3	3	3	3	3	3	3	3	3	3
126	Marsh Isolated	4	5	2	3	2	4	3	3	3	3
130	Marsh Isolated	4	4	4	5	3	4	5	4	3	4
151	Marsh Isolated	5	3	5	4	5	3	4	3	3	3
161	Marsh Isolated	2	2	3	3	3	2	2	2	3	3
258	Marsh Isolated	3	2	3	2	3	3	3	3	3	3
259	Marsh Isolated	3	2	4	3	3	3	3	2	2	2
267	Marsh Isolated	4	2	3	3	3	4	4	3	3	3
281	Marsh Isolated	5	5	4	4	4	4	4	4	4	5

*Table showing WAP scores of the 69 wetlands examined in this study. Forested wetlands scores are Tree scores, Non-forested Herbaceous wetlands are groundcover scores.

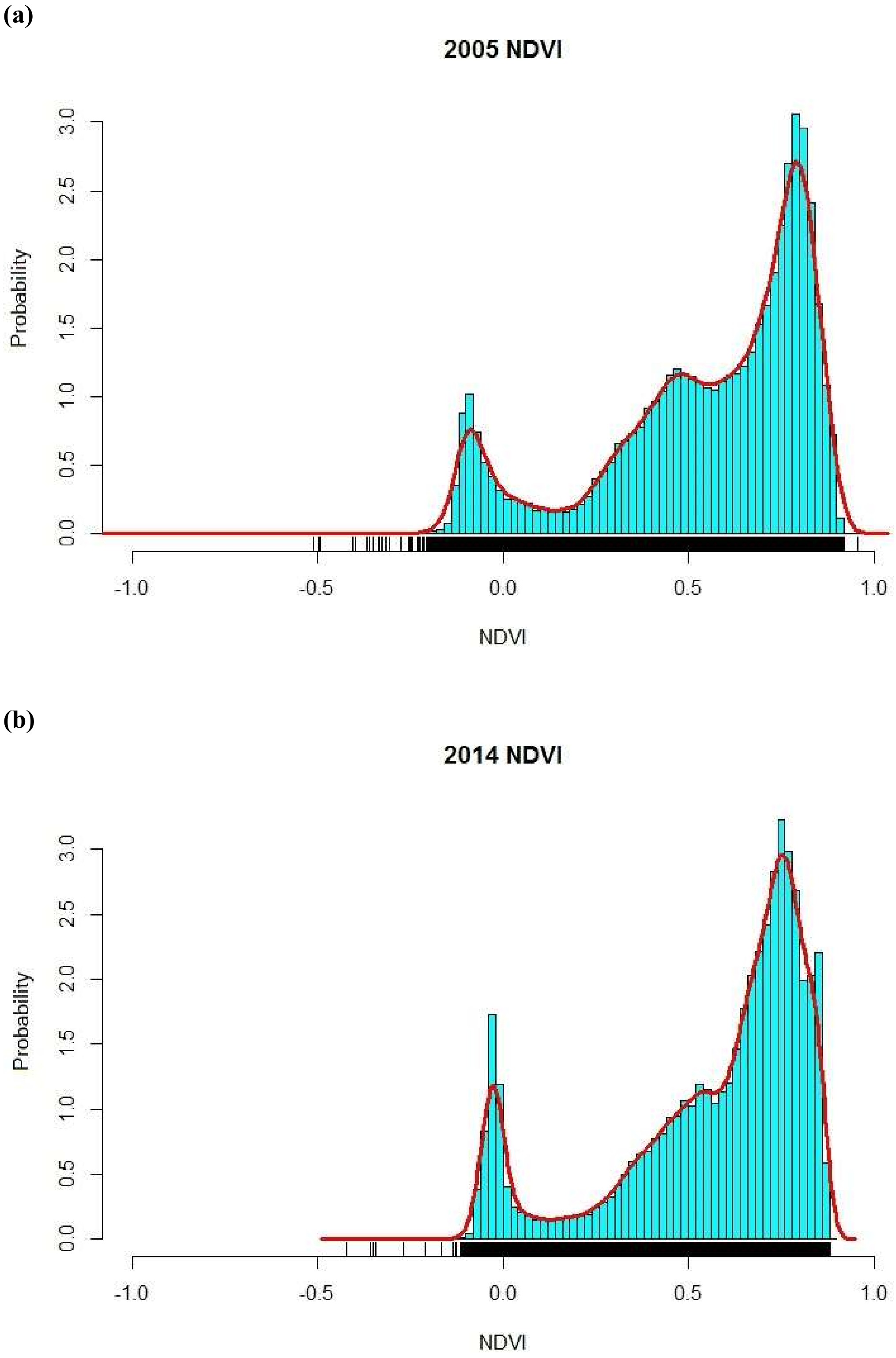
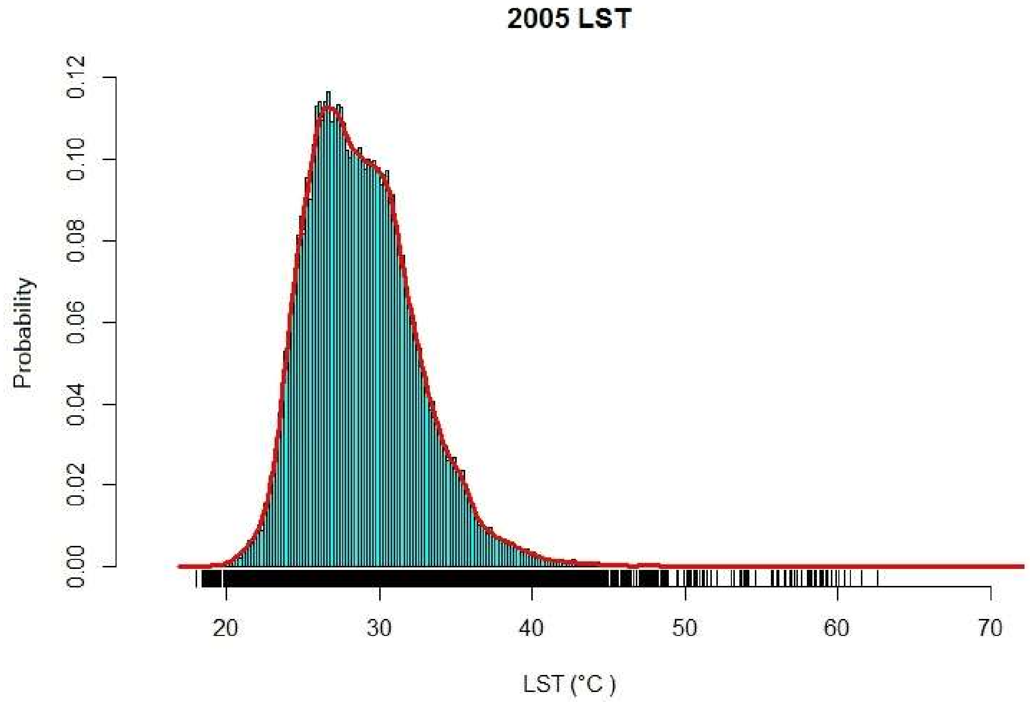


Figure A6. Histograms of NDVI. Histograms with probability line of NDVI for (a) 2005, (b) 2014

(a)



(b)

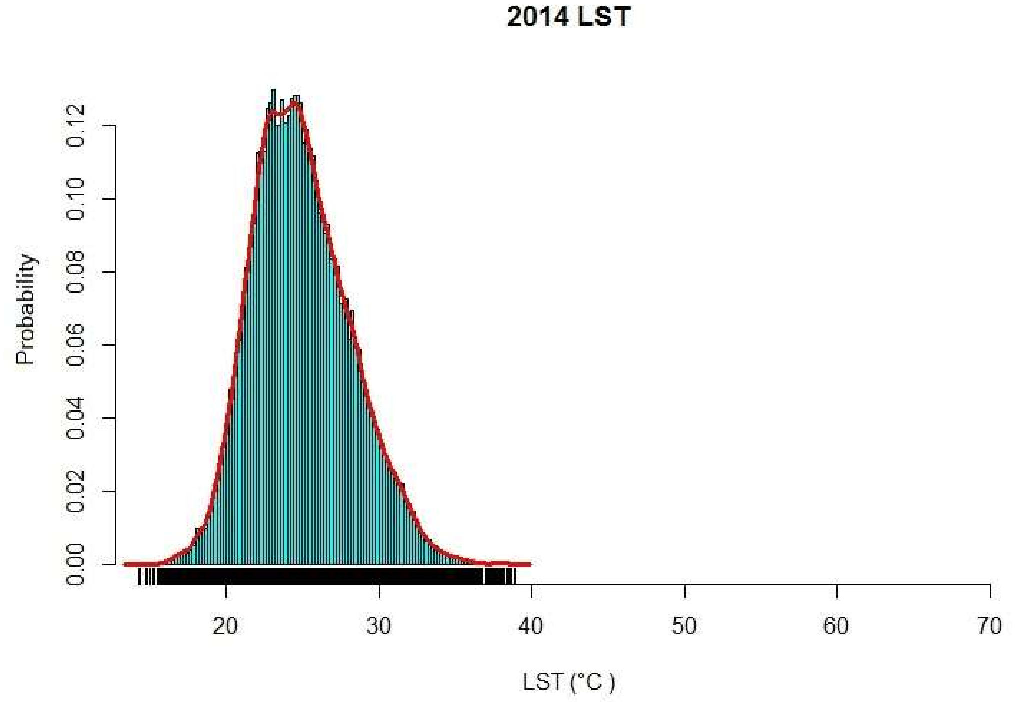
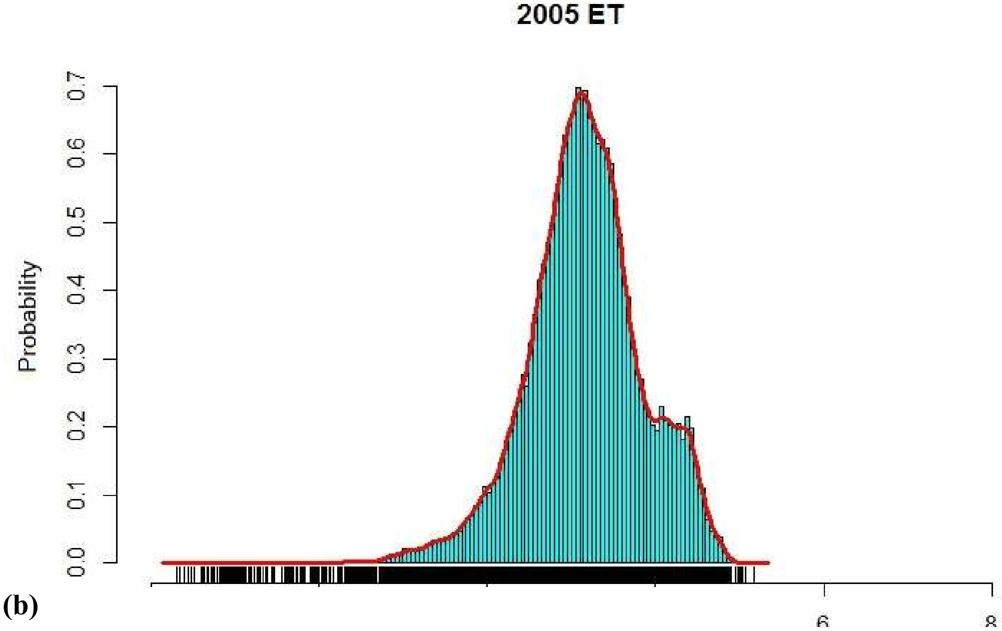


Figure A7. Histograms of LST. Histograms with probability line of LST for (a) 2005, (b) 2014

(a)



(b)

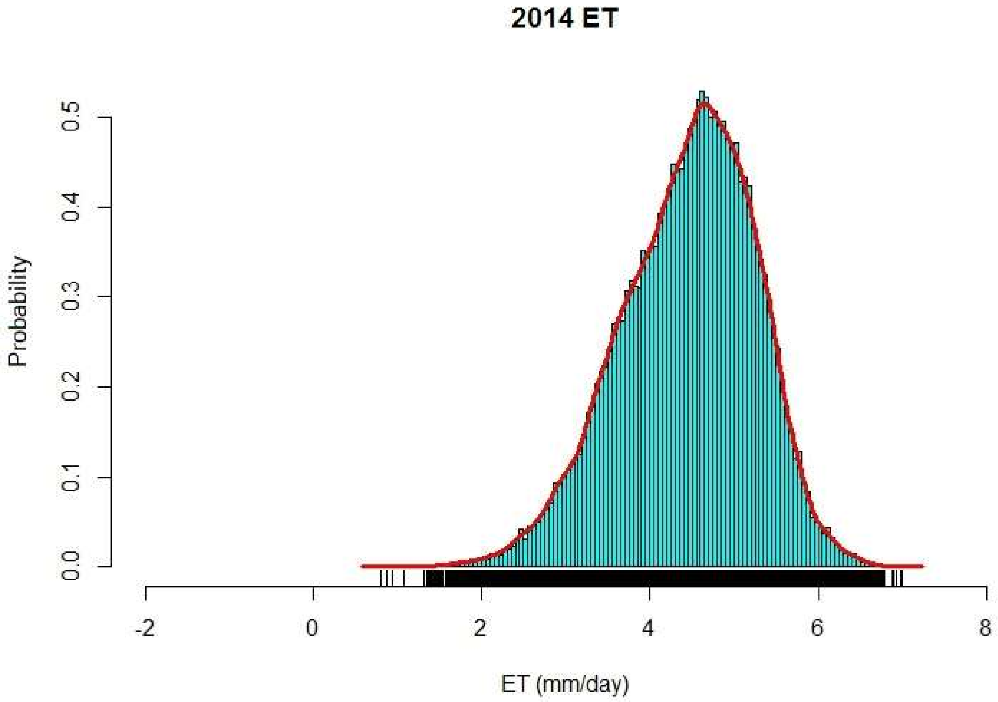


Figure A8. Histograms of ET. Histograms with probability line of ET (a) 2005, (b) 2014