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Vegetative Responses to Hydrology and Ground Water Extraction in West-Central Florida Cypress Domes

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Vegetative Responses to Hydrology and Ground Water Extraction in West-Central Florida

Cypress Domes

by

Paul E. Thurman

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy Department of Integrative Biology with a concentration in Ecology College of Arts and Sciences University of South Florida

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The increasing demand for and limited supply of fresh water necessitates an understanding of how human actions affect aquatic ecosystems. Anthropogenic impacts to these ecosystems occur in many forms including eutrophication, invasive species removals, and hydrologic alterations. Ground water extraction is one such action that can dramatically impact wetland hydrology and is increasing in occurrence globally as clean surface water resources are exhausted. Despite the importance of ground water extraction to meet human demand, little information is available concerning the response of vegetation communities to chronic ground water extraction. Over extraction is known to result in reduced water levels and duration, resulting in a shift towards more upland tolerant species; however, detailed information concerning the response of the individual species comprising these communities and how wetlands shift along with pumping regime remains unavailable. The following dissertation combines historical hydrology and ground cover vegetation data with recent monitoring to describe how ground cover (herbaceous species) and canopy (tree species) vegetation respond to fluctuations in hydrology and ground water extraction.

Ground cover communities were extremely diverse with a total of 103 species being sampled in the historical ground cover vegetation dataset. *Juncus repens* was the most widely distributed species and was observed in 36% of all samples. The 29 species most widely observed in the ground cover strata (<1 m height) displayed relatively narrow ranges of preferred
water depth and duration with *Amphicarpum muhlenbergianum* being found in the driest areas and *Pontederia cordata* and *Ludwigia repens* the wettest. In general species found in shallower water depths also tended to be found in locations with shorter hydroperiods, although woody species tended to found in areas with relatively shallow water depths with extended hydroperiod. Ground cover vegetation is extremely useful as an indicator of recent hydrology, although the hydrologic preference of the species in the current study does not reflect the assumed ecology of the species utilized by Florida Administrative Code 62-340.450. Additional research to validate and improve the accuracy of this classification system is required.

When ground water extraction volumes in well fields was significantly reduced, ground cover communities were responsive, as was indicated by Permanova results (Before After Control Impact). All ground cover at wetlands located within well fields became more indicative of wetter conditions while control wetlands responding only to climate and weather all became drier. In contrast, several well fields displayed reductions in water levels and hydroperiod following extraction reductions. The shift in ground cover community indicates that ground water extraction has not produced an alternative stable state and restoration of these ecosystems is possible through alterations in ground water extraction volumes alone.

As ground water extraction volumes were increased, tree communities responded by displaying increased occurrence of non-*Taxodium* sp. trees, mortality of wetland tree species, and light availability. All wetlands remained dominated by mature *Taxodium* sp. regardless of the amount of ground water impact indicating that each wetland has not yet shifted into a new community type as a result of non-*Taxodium* tree encroachment; however, recruitment and mortality patterns of both *Taxodium* and non-*Taxodium* species indicate this may occur in the
future. Changes in light availability at the wetland floor associated with tree species is likely providing an additional feedback mechanism on ground cover communities.

Results from this dissertation indicate that vegetation communities are extremely responsive to changes in hydrology and have shown significant changes associated with ground water extraction. These changes may not be permanent; however, and alterations in extraction volumes and timing can provide changes in vegetation communities even after decades. Routine long term monitoring should be conducted, in addition to critical assessments of current extraction volumes, to assess the current status of vegetation ecosystems and allow for individuals to best manage aquatic resources for all uses.
CHAPTER ONE

GENERAL INTRODUCTION

Wetlands are exceptionally dynamic systems that experience large fluctuations in the climatological conditions that help determine what biota can live there. Hydrology is one such abiotic component, which fluctuates annually as a result of differences in precipitation associated with natural cycles such as El Nino or La Nina (van der Valk 2005). Precipitation is a primary hydrologic input for many wetlands including those in southern Florida and as precipitation levels increase or decrease, water depth and duration change accordingly. As a result, the biota inhabiting these wetlands must be capable of surviving routine hydrologic fluctuations and new communities can arise if conditions persist.

Changes in community structure often result from variations in the flood-tolerance and growth rate of the individual species located within a community (Megenigal 1997; Wilcox 1995). As a result, as the duration and intensity of flooding is increased, a community will shift towards more flood-tolerant species (Malecki et al., 1983; King 1995, Young et al., 1995). As water levels recede the species composition can shift to the species capable of surviving and reproducing under particular environmental conditions (Makarewicz and Likens 1975). For example, Taylor Slough in the Florida Everglades regularly fluctuates between systems dominated by muhly grass (*Muhlenbergia capillaris* var. *filiipes*), sawgrass (*Cladium*
and spikerush (*Eleocharis cellulosa*) depending on manipulated water levels (Armentano et al., 2006, David 1996, Busch et al., 1998, Nott et al., 1998, Ross et al., 2003).

Although the connection between hydrology and vegetation is well established, the hydrologic ranges and most ecological information concerning most wetland species, especially ground cover species, remain unknown.

As human populations encroach into areas surrounding wetlands, the hydrology is often altered. These changes result in the alteration of water depth and stage duration from the direct installation of surface structures such as ditches and levees to drain wetlands (Marois and Ewel 1983); as well as indirect impacts such as reduced wetland surface water levels resulting from the over extraction of ground water (Stewart 1968, Stewart and Hughes 1974, USGS unpublished data). This altered hydrology resulted in a shift in ground cover vegetation to species more characteristic of shallower, shorter hydroperiod wetlands; in addition to mass mortality of mature cypress, *Taxodium* sp., trees (Rochow 1994).

Despite the global importance of ground water extraction to meet human demand and the numerous adverse impacts associated with it, virtually no information exists concerning the restoration of vegetation communities to chronic ground water extraction. Vegetation should become more indicative of deeper water, longer hydroperiod conditions as water levels increase; however, predicting the new vegetation communities remains difficult. Many vegetation species are thought to have optimum ranges of water depth/duration, soil organic matter, and light levels which may display large differences following extended periods of pumping. For example, the hydrologic and nutrient range of most species has not been described and the depth and amount of organic material present in the soils can change following extended periods of drought (Laanbroeck 2990). Understanding cypress dome succession is further complicated by findings
that as environmental stress, such as hydrology, many vegetation species undergo positive species interactions promoting survival (Bertness and Callaway 1994; He et al. 2013) and the potential for alternative stable states of vegetation to arise following the restoration of hydrology (Scheffer et al. 2001; Scheffer and Carpenter 2003).

The Tampa Bay area is ideally suited to study the interaction between ground water extraction and vegetation. Ground water extraction began during 1932 with the establishment of the Cosme Odessa well field, with 12 additional well fields being brought on line (Tampa Bay Water, 2016). Historically more than 190 million gallons per day (mld) was extracted at peak production; however this volume was reduced to 90 mld following 1998 in response to observed adverse impacts to surface ecosystems. Detailed information concerning the volume of ground water withdrawn, wetland hydrology, and wetland vegetation communities was collected beginning in 1977 and was conducted annually through 2002. Additional monitoring conducted between 2011 and 2013, provided unique insight into the effectiveness of reductions in ground water extraction volumes in producing more hydrophilic communities in addition to describing long-term trends in tree communities.

The following dissertation answers three questions regarding ground cover vegetation, hydrology, and ground water extraction. 1- What are the hydroperiod, mean annual water depth, and maximum annual water depth ranges of the species most commonly observed in the ground cover stratum? 2- Were reductions in ground water extraction volumes successful in producing a shift in ground cover vegetation to species indicative of longer hydroperiods and deeper water levels? 3- Have tree species composition and light availability changed since the initiation of ground water extraction? The results presented in this dissertation have direct implications
globally and provide much needed information for promoting the long-term viability of wetland ecosystems.
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Armentano TV; Say JP; Ross MS; Jones DT; Cooley HC; Smith CS (2006) Rapid responses of vegetation to hydrological changes in Taylor Slough, Everglades National Park, Florida, USA. Hydrobiologia 569: 293-309.


CHAPTER TWO

UTILIZING A HISTORICAL DATABASE TO IMPROVE HERBACEOUS
VEGETTION AND HYDROGIC MODELS IN CYPRESS (*TAXODIUM SP.* ) SWAMPS
NORTH OF TAMPA BAY, FLORIDA

Abstract

Understanding wetland responses to fluctuations in hydrology is increasingly important as the effects of climate change and other human impacts to aquatic resources increase. In many cases, fluctuations in the stage, timing and duration of water levels are likely to exceed extremes typically experienced by wetlands resulting in systems becoming considerably wetter or drier. To predict and counter unacceptable changes in ecosystem structure and function, a thorough understanding of the distribution of plant species relative to hydrological conditions and patterns is needed; however, this requires monitoring that can be prohibitively time consuming and expensive. This study utilized a historical plant database to describe the hydrologic (hydroperiod, average water depth, maximum water depth) ranges of 29 ground cover species common to isolated cypress domes in subtropical central Florida. *Amphicarpum muhlenbergianum* were observed in wetlands containing the shallowest water depths and shortest hydroperiod. *Pontederia cordata* and *Ludwigia repens* were characteristic of wetlands with the deepest water and longest hydroperiods. Several species were quite variable in their responses to
hydrological parameters with some species inhabiting wetlands with long hydroperiods, but shallow depths, etc. The ecology of the herbaceous species included in this study was not reflected by Florida Administrative Code 62-340.450 and demonstrated that significant changes should be made, with approximately half of the 29 species requiring reassignment. The historical database utilized for this study provided valuable information for numerous species common to the Tampa Bay region for which little to no ecological information was previously available. The methodology and results reported in this paper highlight the urgent need for and possible solution to the validation of any regulatory system used to quantify environmental impacts and restoration regardless of locale.

**Introduction**

Wetlands are naturally dynamic systems displaying wide fluctuations in ecosystem structure and function. Often biotic changes occur in response to variations in abiotic factors, particularly hydrology. In Florida, changes in hydrology arise from inter-annual climatic variation from events such as El Nino/La Nina and seasonal changes in precipitation, evaporation, and transpiration associated with distinct wet/dry seasons (Abtew and Trimble 2010; Hwang et al. 2011; Teegavarapu et al. 2013). Ground cover and woody plant communities at a single location will often shift towards more flood-tolerant species during wet periods and drought-tolerant species during drier periods (Chapin and Paige 2013; King 1995; Makarewicz and Likens 1975; Malecki et al. 1983; Megonigal et al. 1997; Wilcox and Meeker 1991; Young et al. 1995).

In recent years, numerous human-induced changes in wetland hydrology have been observed, including both direct manipulations of wetland hydrology (water control structures,
groundwater extraction, storm water storage) and indirect actions such as climate change. Global human population will continue to increase (World Population Balance 2015) concurrent with changes in precipitation and temperature patterns associated with climate change (Hartmann et al. 2013), placing increased stress on aquatic resources. To predict how chronic changes in hydrology may affect wetlands, an understanding of the hydrological requirements of the plant species inhabiting the wetlands is vital. This is becoming increasingly important as the number and quality of wetlands present in areas such as Tampa Bay continue to decline (Rains et al. 2013).

Tree species, such as cypress, (*Taxodium* sp.) are not good indicators of short to moderate term hydrologic changes. While fluctuations in hydrology do affect their growth and reproductive success, mature trees are capable of surviving major fluctuations in hydrology (Casey and Ewel 2006; Demaree 1932; Dickson and Broyer 1972; Ewel 1990; Harms et al. 1980; Palta et al. 2012) and even upland conditions provided adequate hydration. As a result, changes in mature cypress survival and health are more indicative of long-term hydrologic averages as opposed to short term or relatively small fluctuations. Cypress and many other wetland trees, however, are susceptible to catastrophic, long-term loss of hydrology, such as can be associated with excessive ground water pumping (Rochow 1994).

Ground cover species, in contrast, are more sensitive to short term changes in hydrology. For example, Taylor Slough in the Florida Everglades regularly fluctuates among communities dominated by different ground cover species depending on the stage of manipulated water levels (Armentano et al. 2006; Busch et al. 1998; David 1996; Murray-Hudson et al. 2014; Nott et al. 1998; Ross et al. 2003; Todd et al. 2010). In many cases, these changes can be relatively rapid compared to tree species, with observable changes in ground cover vegetation occurring within
three to four years of changes in manipulated water levels (Armentano et al. 2006, Murray-Hudson et al. 2014, Todd et al. 2010).

Despite the potential use of herbaceous species in predictive models, their use in predicting responses to hydrological conditions exceeding expected values is hindered by a paucity of ecological information for most species (Whigham 2004), especially responses to hydrology. Given the often rapid and sensitive response to altered hydrology, detailed information on the hydrological responses of a suite of species could provide an early warning system for ecosystems undergoing hydrologic stress and allow sufficient time for restoration activities.

In an effort to address this lack of information, the State of Florida assigned common tree, shrub, and ground cover species into five groups based on their expected hydrologic tolerance (Fla. Admin. Code 62-340). This system (state system) is used to help characterize hydrological and ecological conditions in wetlands and to determine the severity of wetland impacts and subsequent restoration required. The U.S. Army Corps of Engineers uses a similar system (Lichvar et al. 2014) to help identify wetlands and impacts under Federal jurisdiction (U.S. Army Corps of Engineers 1987). The classification of species was arbitrary at the time and the information utilized has still not been fully validated. The lack of information concerning herbaceous species is highlighted by disagreement in classifications of some species between the two systems, resulting in a critical need to refine these two classification systems with data specific to the hydrologic requirements of each species.

Historic datasets are useful to fill data gaps in a cost and time effective manner provided the data can be validated. The Southwest Florida Water Management District (District) initiated an annual monitoring program over more than two decades to document observed changes in
ground cover vegetation and hydrology of isolated cypress swamps north of Tampa Bay, Florida and forms the basis for the current study. The current study addressed two questions regarding ground cover vegetation of geographically isolated cypress swamps north of Tampa Bay, Florida: 1) What are the hydrologic conditions (hydroperiod, average depth, and maximum depth) of the herbaceous species most widely occurring in isolated cypress domes and 2) What changes in the state system of species classification are required in order to make the system more accurate.

**Material and methods**

In response to observed changes in ground cover vegetation and hydrology in cypress domes north of Tampa Bay, the District began monitoring ground cover vegetation in wetlands from three areas: Cypress Creek Preserve (Cypress Creek, 2,072 hectares), Starkey Wilderness Park (Starkey, 3,367 hectares), and Green Swamp Wildlife Management Area (Green Swamp, 20,514 hectares). All three locations are managed as native habitats for low impact public recreational activities. Cypress Creek and Starkey also contain numerous ground-water pumping wells as part of the domestic water supply for Hillsborough, Pasco, and Pinellas counties, Florida.

The District monitored 19 wetlands, ranging in size from 0.17 (Cypress Creek 2) to 25.89 hectares (Starkey 6) (Table 2.1). Monitoring was initiated between 1975 and 1983, depending on the wetland, and continued annually through 2002. All samples were collected during the beginning of the growing season (May-July) prior to the summer, wet season. Percent coverage of herbaceous and tree/shrub species (<1 m in height) were visually estimated using a one square meter (1 m2) sample plot, permanently established in the deepest portion of each wetland. All
species were identified to species, with questionable samples sent to the University of South Florida herbarium for identification. Species names and classifications utilized in this study follow Wunderlin (1983). All ground cover data was transformed to a presence/absence matrix before subsequent analysis. Relative and absolute abundance (percent cover) estimates for each species were not utilized on account of small sample quadrat size and variability in environmental conditions prior to sampling, which could affect relative species cover estimates. For the current study, herbaceous species not found in at least 10 samples and young specimens not identified to species were omitted from analysis. In addition, moss, algae, and non-rooted species were not excluded.

The District installed piezometers and/or continuous recording surficial wells immediately adjacent to the sample plots of each wetland to monitor hydrology. Water level data were collected at each wetland both at the time of monitoring and at least monthly for the duration of the study. Hydroperiod (HP, percent of time standing water of any depth was present at the piezometer/well) and average water depth (AD, m) for each sampling plot were determined by averaging all water level recordings during the calendar year prior to each monitoring event for each wetland. The maximum water depth (MD, m) observed in each wetland one year prior to sampling was determined. Ground water levels and soil moisture were not available. Statistical differences among the wetland hydrologic conditions inhabited by each species were determined using an analysis of variance (ANOVA) using IBM SPSS Statistics Version 22.

To evaluate the degree of similarity among individual species’ observed hydrologic tolerance, each of the 29 species assessed was assigned a numerical value between 1 and 29 based on its position in the rank order of each hydrologic parameters, i.e. the species with the
shortest mean hydroperiod was assigned a value of 1, the next shortest hydroperiod a value of 2, etc. Comparisons were made among the hydrologic values using a Pearson’s Correlation Coefficient, and parameters with a PCC greater than |0.5| were considered significantly correlated.

A distance based redundancy analysis (dbRDA) was used both to define species associations and the hydrologic parameter (HP, AD, or MD) most correlated with species’ distributions. A presence absence transformation was used to reduce the effects of small plot size, number of plot replicates per wetland, and variations in plant percent cover associated with annual climatic variations in winter precipitation and temperature.

Each species was displayed on the dbRDA along with its classification according to the current state system, which assigns individual species into one of 5 groups based on its reported location along a wetland slope. Aquatic species (AQU) are free floating or submerged aquatic species, Obligate (OBL) species are found in submerged or saturated soils, Facultative Wet (FACW) species in submerged or saturated soils but are occasionally found in uplands, Facultative Species (FAC) in uplands or shallow/transitional wetlands, and Upland species (UPL) are characteristic of uplands.

The state system was compared with the observed mean hydroperiod, average water depth, maximum water depth, and hydrologic average using concordance diagrams. The hydrologic average is the average of the HP, AD, and MD rank order value for each species. Species were subsequently reassigned into similar classification based solely on the observed average annual water depth of the wetlands where observed, with FAC species being present in wetlands with AD depths ranging from 0.0-0.1m, FACW from 0.1-0.2 m, and OBL from 0.2-0.3 m. Similarity between the old and new classifications were tested using a Pearson’s Correlation
Coefficient with UPL, FAC, FACW, OBL, and AQU were assigned values of 1, 2, 3, 4, and 5 respectively.

**Results**

A total of 103 vascular plant taxa were recorded among the three sample locations, with 46 taxa found at Cypress Creek, 54 at Green Swamp, and 68 at Starkey. Sixty-four taxa (64) were unique to a single sample location, while 20 were found at all three locations. Overall, tree/shrub species communities in the study wetlands had fewer species (19) than ground cover communities (84).

A total of 29 species were found in 10 or more samples and were included in the final database analyzed (Table 2.2). *Juncus repens* was the most consistently observed species being found in 36% of all samples and in wetlands located at Cypress Creek, Starkey, and Green Swamp. *Pluchea rosea, Panicum hemitomon, Carex joorii, Woodwardia virginica*, and *Rhynchospora corniculata* were the major subdominant species, being found in 17%, 14%, 12%, 12%, and 12% of all samples, respectively, as well as being present at all three sample locations.

In general, species more characteristic of deeper locations were also found in wetlands with longer hydroperiods. The rank order of species on the x-axis (Figure 2.1) was significantly correlated for all hydrologic combinations. HP and AD species were the most closely correlated (Pearson’s Correlation Coefficient, PCC=0.94), followed by MD and AD species (PCC=0.72), and HP and MD species (PCC=0.52). Averaging the three rank order placement values for each species showed that *Pontederia cordata* and *Ludwigia repens* were present in wetlands with the deepest water (AD=0.3 m each and MD=0.56 m and 0.55 m, respectively) and longest hydroperiods (89% and 87%, respectively) (Figure 2.1). *Amphicarpum muhlenbergianum* was
found at both the shortest hydroperiod (5%) and shallowest water depths (AD=0.01 m, MD=0.05 m). In addition, *Andropogon virginicus*, *Paspalum praecox*, and *Lachnanthes caroliniana* were also consistently found in wetlands with both reduced hydroperiod (<30%) and water depths (AD<0.055 m and MD<0.26 m).

*Proserpinaca palustris*, in addition to all tree/shrub species (*Taxodium distichum*, *Salix caroliniana*, and *Lyonia lucida*) sampled in the ground cover stratum (<1 m height), were found in samples with long hydroperiods (HP>62%), but shallow maximum depths (MD<0.41 m) (Figure 1). In contrast, *Erechtites hieraciifolius*, *P. hemitomon*, and *Blechnum serrulatum* were found in locations with short hydroperiods (HP<50%) that displayed relatively deep maximum depths (MD>0.45m).

A distance based redundancy analysis (dbRDA) conducted on species co-associations revealed that hydroperiod accounted for most of the observed variation (Figure 2.2). This was the only variable significantly correlated (|0.917|) with dbRDA axis 1 (43.8% of fitted variation, 9.3% of total variation). Average depth (|0.706|) was significantly correlated with dbRDA axis 2 (31.3% of fitted variation, 6.6% of total variation). Maximum depth was most closely correlated with dbRDA axis 3 (not pictured, 25% of fitted variation, 5.3% of total variation, (|0.776|), but was also significantly correlated with dbRDA axis 2 (|0.586|).

Of the 29 species included in the dbRDA analysis, 48% (n=14) were designated as obligate species (OBL), 28% (n=8) as facultative wet (FACW), 17% (n=5) as facultative and 7% (n=2) were unclassified (Figure 2.1a, 2.1b, 2.1c, and 2.2) by the state system. Obligate species contained the deepest water (mean AD=0.18 m and mean MD=0.46 m) and hydroperiods (mean=63%), followed by facultative wet species (FACW) (mean HP=42.6%, mean AD=0.11 m, and mean MD=0.39 m), and facultative species (FAC) (mean AD=0.07m, mean MD=0.35m,
and mean HP=23.2%). *Paspalum praecox* and *Lycopus rubella* were the notable exceptions and were associated with shorter hydroperiods. The two non-classified species, *Erianthus giganteus* and *Lindernia anagallidea* were located among the FACW and OBL species on the dbRDA (Figure 2.2).

When mean HP, AD, and MD values where each species was observed were plotted against a rank order x-axis, a linear relationship emerged ($R^2=0.98$, $R^2=0.97$, and $R^2=0.85$, respectively) in addition to considerable overlap in the 95% confidence interval around each hydrologic (Figure 2.1). Despite this overlap; however, significant differences among the mean wetland hydrologic conditions for each species were detected (Table 2.3). The characteristics of wetland species distributions are inconsistent with the current classifications used by the state of Florida, which uses sharply defined boundaries.

Concordance diagrams show that for the current classification system, average annual water depth and the average hydrologic placement values depicted the best-fit diagrams ($R^2=0.38$ and $R^2=0.36$, respectively) (Figure 2.3). Reclassification of the species based solely upon their observed hydrologic means, resulted in a large increase in the best-fit line ($R^2=0.83$) (Figure 2.4). Despite the large increase in $R^2$ values associated with reclassification and the fact that over half (n=15) of the species were reassigned, the two classification systems were significantly correlated (Pearson’s $= 0.59$).

**Discussion**

Cypress swamps are abundant in Florida and provide numerous benefits to society including ecotourism, storm-water control, and nutrient uptake (U.S.E.P.A. 2001). However, despite their importance and semi-protected status, the number and quality of cypress domes in
many areas continue to decline as urbanization expands (McCaulley et al. 2013). In Florida, hydrologic alterations are a major challenge in managing wetland ecosystems, as these parameters are changing as a result of both urbanization and climatic conditions (Abtew and Trimble 2010; Hwang et al. 2011; Jimenez Cisneros et al. 2014; Lee and Heaney 2003; Rose and Peters 2001; Teegavarapu et al. 2013). To help offset the future loss of cypress domes, a detailed understanding of the ecology of wetland plant species, as well as how they respond to biotic and abiotic changes, are needed. However, the extent of this information consists primarily of a limited amount of information concerning a small number of species such as *Blechnum serrulatum, Eupatorium capilli folium, Panicum hemitomon, Bacopa caroliniana* and *P. cordata* (MacDonal et al. 1992; Mayence and Hester 2010; Tobe et al. 1998; Visser and Sasser 2009; Wright and Wright 1932).

The species specific data presented in this study is unique in that to our knowledge no such vegetative database has been assembled with such detail or inclusiveness. The current study greatly expands upon the body of knowledge by describing the hydrological requirements of 29 species. This information is based on 20+ years of presence absence data and includes multiple climatic cycles, which includes the hydrologic extremes encountered during periods of excessive rainfall or drought. This information allows researchers to begin to add detail into the answer to the question of how exactly should herbaceous species communities shift in response to hydrologic changes.

The rapid growth and perennial nature of many herbaceous species (Bierzychudek 1982; Whigham 2004) combined with the relatively narrow range of water depths and hydroperiods they inhabited as described in the current study make them ideal candidates as indicators of short term hydrology patterns. *Panicum hemitomon, Blechnum serrulatum, Erechtites hieraciifolius, Eupatorium capilli folium*.
and *Eupatorium capillifolium* were characteristic of short hydroperiod and relatively deep-water conditions. *Bacopa caroliniana* and *P. cordata* were characteristic of communities with long hydroperiod in the current study and have been reported as having much greater germination rates in inundated wetlands compared to moist or saturated soils (Wetzel et al. 2001). While the focus of this study is on herbaceous species, information on young woody species recruits present in the ground cover strata was also available. Young cypress (<1m) and the other tree/shrub species were all observed in wetlands with relatively long hydroperiod paired with shallow water depths.

The current state system currently used by Florida was developed as a standardized way for state and local governments to assess impacts to wetland systems and any required remediation. While novel at the time, this system and the subsequent wetland restoration efforts often conducted have not evolved as rapidly as the baseline information about wetland ecology. In spite of regulations in place and a no net loss policy, Florida has experienced a continued loss of wetland habitats (McCauley et al. 2013; Rains et al. 2013).

The large degree of overlap observed in the mean hydrologic parameters for the wetlands each species was observed in suggests that the original state system of species classification does not reflect the species biology as described in this study. Furthermore, the hydrologic means of the species investigated were distributed along a continuum and not in discrete groups as they are assembled in the current state system. As a result, all species should be allowed to contribute to the community assessment based upon their ecology and not arbitrarily classified. This would allow for a continuous or sliding scale to be developed to assess wetland conditions and could result in drastic changes in how wetland communities are assessed for impact and/or restoration.
purposes. Such a system would require a tremendous amount of data to fully implement and would likely take years to implement.

If a method such as the state system must be used, significant changes may be required including the reclassification of some species and the addition of other species not currently listed by the state of Florida. Species reclassified based solely upon their observed hydrologic means, resulting in reclassification of nearly half of the species studied using hydroperiod data alone. In doing so, the example of species reclassification provided greatly increases the best-fit line (R2) from 0.37 to 0.83 in AD. For this method to work; however, specific hydrologic ranges must be specified for each group (UPL, FAC, FACW, OBL, AQU), in contrast to the general descriptions currently used. Combining multiple historic databases may be a time and cost effective way to obtain hydrologic information for these and other less common species not included in the state system. In addition, other factors known to influence the growth of vegetation must be accounted for such as soil condition, competition, predation, and fire frequency.

Detailed understanding of how ground cover species are governed by hydrology can provide an early warning of changing environmental conditions. Climate change is predicted to have dramatic changes in precipitation and evapotranspiration rates globally (Kirtman et al. 2013), with associated profound effects on wetland hydrology and vegetation. Urbanization will also place additional stress on water supply as the demand for fresh water and the percentage of impervious surfaces continues to increase (Faulkner 2004).

Based on the results of this study, a proposed replacement series of herbaceous species can begin to be assembled giving managers more accuracy in predicting how ground cover communities of cypress domes will respond to both short-term (inter-annual climatic) and long-
term (watershed changes, climate change) alterations of hydrology. Altering a wetland’s hydrology should exclude certain species as hydrology extends beyond their range and favor other species as the hydrology approaches a new mean. Such changes have been documented in the Florida Everglades, where communities regularly fluctuate depending on managed water levels (Armentano et al. 2006; Busch et al. 1998; David 1996; Nott et al. 1998; Ross et al. 2003). Tree mortality and fall, coupled with changes in ground cover communities, have been documented in several of the sample wetlands at Cypress Creek and Starkey and attributed to reduced hydrology associated with excessive groundwater extraction (Rochow 1994). Had data for herbaceous species been available and utilized, it is possible that short-term changes in groundwater extraction timing and volume could have prevented the significant tree mortality observed.

Understanding the ecology of specific species and ecosystems can also provide insight into the long-term-viability of certain ecosystems. When mature, *Taxodium* sp. are the most flood tolerant wetland tree species in Florida; however, soil dehydration, relatively shallow water depths, and frequent inundation are required for cypress seed germination (Casey and Ewel 2006; Demaree 1932; Dickson and Broyer 1972; Ewel 1990; Harms et al. 1980). Many tree and shrub species have seeds that are viable for less than one year (Middleton 1993) and as a result, these species are less likely to persist in seed banks following drainage than herbaceous species. Therefore, *Taxodium* communities may not be capable of re-establishing themselves following disturbances lasting longer than one year if water depth and hydroperiod patterns are not sufficient.

The current study demonstrated the potential value of long-term archived databases, as the extended period of record and number of wetlands sampled in this study provided a unique
opportunity not present with most short duration research projects. Monitoring was conducted over more than 20 years in many wetlands, which allowed species with vastly different hydrologic requirements to respond to multiple climatic cycles and events (i.e. periods of drought and flood) (SWFWMD unpublished data). In contrast, data collection periods of most studies are a few years at best, providing only a short term perspective for each species that lacks long term responses to the entire hydrologic range that species can exist. Such studies may not be long enough for even the herbaceous species to respond to hydrologic changes. The extensive sampling in this study also allowed for detailed information on subdominant species (29 species were found in 10 or more samples), species overlooked from most investigations.

While historic databases contain vast amounts of ecological data, careful validation is required before use. Variations in intraspecific ecology, sampling error, and microtopography are all potential sources of error (Hester et al. 1998; Vivian Smith 1997), which must be considered. Monitoring in the current study was conducted by three individuals utilizing the same sample locations and methodologies throughout the duration of the study, with questionable specimens identified by the herbarium at the University of South Florida. The relatively small sample plots (1m²) and extensive period of monitoring should have reduced any large sources of topographic variation and error.

While the details of the species hydrologic tolerances described here are relevant to herbaceous communities located north of Tampa Bay, Florida, the implications of this study are applicable anywhere wetlands are being assessed for condition, restoration, or impacts. In many cases the accuracy of these systems is suspect and validation is urgent in order to maximize wetland resource protection to prevent a further degradation aquatic habitats.
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Table 2.1. Wetland Sample Locations at Cypress Creek Preserve (Cypress Creek), Green Swamp Wildlife Management Area (Green Swamp), and Starkey Wilderness Park (Starkey).

<table>
<thead>
<tr>
<th>Wetland Number</th>
<th>Cypress Creek</th>
<th>Green Swamp</th>
<th>Starkey</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28° 18 18.01</td>
<td>28° 21 43.01</td>
<td>28° 15 27.02</td>
</tr>
<tr>
<td>2</td>
<td>28° 17 25.41</td>
<td>28° 23 28.56</td>
<td>28° 15 19.67</td>
</tr>
<tr>
<td>3</td>
<td>28° 17 46.28</td>
<td>28° 22 35.01</td>
<td>28° 15 06.10</td>
</tr>
<tr>
<td>4</td>
<td>28° 16 21.46</td>
<td>28° 23 32.01</td>
<td>28° 14 28.64</td>
</tr>
<tr>
<td>5</td>
<td>28° 24 47.00</td>
<td>28° 15 22.35</td>
<td>82° 35 22.31</td>
</tr>
<tr>
<td>6</td>
<td>28° 23 40.19</td>
<td>28° 14 55.66</td>
<td>82° 33 22.54</td>
</tr>
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<td>7</td>
<td></td>
<td>28° 14 27.33</td>
<td>82° 34 49.43</td>
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<td>8</td>
<td></td>
<td>28° 14 44.45</td>
<td>82° 34 57.84</td>
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<tr>
<td>9</td>
<td></td>
<td>28° 14 10.72</td>
<td>82° 35 08.06</td>
</tr>
</tbody>
</table>
Table 2.2. Distribution of the 29 most widely observed species among sample locations (C=Cypress Creek, GS=Green Swamp, and S=Starkey) and each species numeric code used for species abbreviation on Figure 2. Abbreviations for species names are as follows: Polygonum hyd. = Polygonum hydropiperoides and Amphicarpa muh. = Amphicarpa muhlenbergianum

<table>
<thead>
<tr>
<th>Code</th>
<th>Species</th>
<th>Site</th>
<th>Code</th>
<th>Species</th>
<th>Site</th>
<th>Code</th>
<th>Species</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Proserpinaca palustris</td>
<td>C</td>
<td>11</td>
<td>Lynonia lucida</td>
<td>GS</td>
<td>21</td>
<td>Diodia virginiana</td>
<td>C,GS, S</td>
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<td>2</td>
<td>Ludwigia repens</td>
<td>C,GS, S</td>
<td>12</td>
<td>Bacopa caroliniana</td>
<td>C,GS, S</td>
<td>22</td>
<td>Carex joorii</td>
<td>C,GS, S</td>
</tr>
<tr>
<td>3</td>
<td>Pontederia cordata</td>
<td></td>
<td>13</td>
<td>Polygonum hyd.</td>
<td>C,GS</td>
<td>23</td>
<td>Erechtiites hieracifolia</td>
<td>C,S</td>
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<tr>
<td>4</td>
<td>Rhynchospora corymbosa</td>
<td>C,GS, S</td>
<td>14</td>
<td>Taxodium distichum</td>
<td>GS,S</td>
<td>24</td>
<td>Woodwardia virginiana</td>
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</tr>
<tr>
<td>5</td>
<td>Salix caroliniana</td>
<td>C</td>
<td>15</td>
<td>Myrica cerifera</td>
<td>GS,S</td>
<td>25</td>
<td>Eupatorium capillifolium</td>
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</tr>
<tr>
<td>6</td>
<td>Stillina aquatica</td>
<td>S</td>
<td>16</td>
<td>Panicum hemitomon</td>
<td>C,GS, S</td>
<td>26</td>
<td>Lachnanthes caroliniana</td>
<td>C,GS, S</td>
</tr>
<tr>
<td>7</td>
<td>Panicum rigidulum</td>
<td>C,GS, S</td>
<td>17</td>
<td>Erianthus giganteus</td>
<td>GS,S</td>
<td>27</td>
<td>Paspalum praecox</td>
<td>C,GS, S</td>
</tr>
<tr>
<td>8</td>
<td>Sagitaria graminea</td>
<td>C,GS</td>
<td>18</td>
<td>Blechnum serrulatum</td>
<td>GS,S</td>
<td>28</td>
<td>Andropogon virginicus</td>
<td>C,GS, S</td>
</tr>
<tr>
<td>9</td>
<td>Lindernia anagallida</td>
<td>GS,S</td>
<td>19</td>
<td>Lycopus rubellus</td>
<td>C,GS, S</td>
<td>29</td>
<td>Amphicarpa muh.</td>
<td>C,S</td>
</tr>
<tr>
<td>10</td>
<td>Juncus repens</td>
<td>C,GS, S</td>
<td>20</td>
<td>Pluchea rosea</td>
<td>C,GS, S</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.3. ANOVA results for significant differences in (a) hydroperiod, (b) average water depth, and (C) maximum water depth among species.

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<thead>
<tr>
<th></th>
<th>Sum of Square</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
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<td>11169.7</td>
<td>16.634</td>
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</tr>
<tr>
<td><strong>Within Groups</strong></td>
<td>515042</td>
<td>767</td>
<td>671.502</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>827794</td>
<td>795</td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th></th>
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<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Groups</strong></td>
<td>3.692</td>
<td>28</td>
<td>0.132</td>
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<tr>
<td><strong>Within Groups</strong></td>
<td>6.393</td>
<td>767</td>
<td>0.008</td>
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<td></td>
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<tr>
<td><strong>Total</strong></td>
<td>10.085</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Sum of Square</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
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<tbody>
<tr>
<td><strong>Between Groups</strong></td>
<td>7.535</td>
<td>28</td>
<td>0.269</td>
<td>10.549</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Within Groups</strong></td>
<td>19.566</td>
<td>767</td>
<td>0.026</td>
<td></td>
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<tr>
<td><strong>Total</strong></td>
<td>27.102</td>
<td>795</td>
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Figure 2.1. Mean (a) hydroperiod, (b) average water depth, and (c) maximum water depth in wetlands where each species was observed. Solid bars represent the range of values within 95% confidence intervals and line bars depict the full range of hydrologic means encountered for each species. Complete species names are listed in Table 2. *A. muhlen* is abbreviated for *Amphicarpum muhlenbergianum* and *P. hydro* is abbreviated for *Polygonum hydropiperoides.*
Figure 2.2. Distance Based Redundancy Analysis based on species presence/absence. Numbers for each point on the diagram correspond to species listed in Table 1.
Figure 2.3. Concordance diagrams for state system and observed (a) hydroperiod, (b) average water depth, (c) maximum water depth, and (d) the average of the 3 other hydrologic parameters.
Figure 2.4. Improved Concordance Diagrams of species reclassifications based upon observed average water depth of (Figure 5b) wetlands where each species was detected. Reclassifications to the state system groupings assume that FAC species were detected in average water depths ranging between 0.0 m and 0.1 m, FACW species between 0.101 m and 0.2 m, and OBL species > 0.201 m.
CHAPTER THREE

RESPONSE OF GROUND COVER VEGETATION OF CYPRESS DOMES TO REDUCED GROUND WATER EXTRACTION NORTH OF TAMPA BAY, FLORIDA

Abstract

Ground water is an extremely important source of fresh water for human consumption; however, its extraction is now known to result in several adverse impacts on surface ecosystems including the alteration of wetland hydrology, which can then alter vegetation structure. Despite the severe impacts associated with ground water extraction and the continued loss of wetlands globally, virtually no information exists on the potential recovery of wetland vegetation communities when extraction rates are reduced. Historical ground cover and water level data (1985-2002) were combined with recent monitoring (2011-2013) to examine the response of ground cover communities of cypress domes in Tampa Bay, Florida to reductions in ground water extraction. A Before After Control Impact (BACI) design Permanova was used to determine the response of two (2) well fields (Cypress Creek and Starkey) to reductions in ground water extraction compared with a control location (Green Swamp) experiencing zero ground water withdrawals within the location boundaries.

Mean hydroperiod and annual water depth at Cypress Creek, where ground water extraction was greatest, were much lower than at Starkey or Green Swamp. Reductions in ground
water extraction did not result in increased mean hydroperiod and annual water depth at all impacted wetlands with some locations becoming drier. Ground cover communities in contrast all shifted towards increased water depth and hydroperiod following GWE reductions, while control wetlands all became more indicative of drier conditions. The predicted response of vegetation to increased water levels associated with GWE reductions was not detected in several wetlands. Instead, ground cover communities provided a more uniform response to GWE reductions than hydrology and provide critical information detailing wetland restoration success, which may be easily dismissed with the lack of hydrologic response.

**Introduction**

Human populations have relied on groundwater as a stable source of clean water for thousands of years, and in some cases, civilizations have collapsed when available ground water resources were exhausted (Binford et al. 1997, Schwarz and Ibaraki 2011). It was not until modern ground water extraction (GWE) technology, which greatly increased both accessibility and volume of ground water extracted, that the severe impacts now associated with over-extraction became evident. Sustained GWE has increased sinkhole formation and salt-water intrusion in coastal aquifers and altered hydrology of regional lakes, streams, and wetlands, which has impacted vegetation communities (Barlow and Leake 2012, Cooper et al. 2015, Rochow 1994, Stewart 1968, Stewart and Hughes 1974, USGS unpublished data).

Understanding the impacts of GWE on ecosystems and the effectiveness of potential restoration activities to areas adversely impacted by extraction is of vital interest to human populations globally, which are projected to continue to increase into the future (United States Census Bureau 2016) and continue to rely heavily on groundwater. In more developed,
relatively water rich areas, many communities are demanding environmental restoration as populations expand into areas previously reserved for ground-water extraction (Rand 2003). Cypress (*Taxodium* sp.) swamps are one of the most abundant and widespread types of wetlands in the Florida and have shown a continued decline in number and quality in recent years despite government regulations designed for prevention (McCauley et al. 2013, Rains et al. 2013). Currently, little information is available to predict the recovery of cypress swamps following reductions in long term GWE.

One of the most widespread methods of preventing loss of wetland vegetation involves artificially enhancing surface hydrology with other water sources, often the same groundwater being extracted which initially caused the impacts (Jones and Clarke 1990, Tampa Bay Water 2014a). Surface augmentation with groundwater ultimately increases the overall amount of water withdrawn, which could result in more severe impacts to wetlands not being augmented; in addition to the additional time, effort and cost associated with installing the infrastructure required.

Reducing GWE and allowing wetlands to recover naturally is a potential alternative to augmentation. The effects of GWE reductions on wetland hydrology should be quick and inexpensive as no infrastructure is required. In Plant City, Hillsborough County, Florida, groundwater levels recovered in less than a week following a temporary extraction to insulate strawberry crops from freezing temperatures (Aurit et al. 2013). This event was limited in its duration; however, the effect of extraction reductions following chronic pumping remains poorly understood.

Wetland plant communities regularly fluctuate between flood and drought tolerant species during wet and dry periods, respectively. In many cases, this response can be relatively
quick with ground cover communities often responding within several years of hydrologic manipulation (Armentano et al. 2006, Busch et al., 1998, David 1996, Murray-Hudson 2014, Nott et al., 1998, Ross et al., 2003, Todd et al. 2010). This rapid response should provide an early warning for adverse changes to hydrology; however, the response of ground cover communities in swamps to hydrology remains relatively unstudied. Extensive and chronic pumping has the potential of affecting many other parameters that can affect ground cover communities, such as the amount of organic material in soil and the viability of seeds for some wetland species (Laanbroeck 1990, Weinhold and van der Valk 1989, Wetzel et al. 2001).

The Tampa Bay area (TB) of Florida is ideally suited to study the response of cypress wetland plant communities to reductions in GWE. Large scale pumping began in 1931 in Pasco County (Tampa Bay Water 2015 a) and additional well fields have been established as the metropolitan area has progressively expanded. As of June 2015, groundwater accounted for 68% of the domestic needs of the 2.3 million residents of Hillsborough, Pinellas, and Pasco Counties (Tampa Bay Water 2015 b). Beginning in the 1970s, the Southwest Florida Water Management District (SWFWMD) initiated ground cover vegetation monitoring in response to observed changes in wetlands of the well fields, which were assumed to be from adverse effects of ground water extraction (Rand 2003). Conflict over impacts associated with GWE and public demand for restoration resulted in an agreement to reduce GWE between 2003 and 2008 and to find additional sources of fresh water.

The current study examines the response of ground cover communities to reductions in ground water extraction following decades of steady extraction. A long-term, historical database (pre-reduction) was compared with post-reduction data to test the following hypotheses: 1) Herbaceous plant communities in locations where GWE was reduced will become more
indicative of wetter conditions, while non-pumped communities and communities where GWE was not reduced should remain stable, and 2) the mean hydrologic (hydroperiod and water depth) characteristics of pumped locations will increase following GWE reductions, while non-pumped locations will remain stable.

Material and methods

Sample Locations - Isolated cypress dome communities were studied from three locations north of Tampa Bay, Florida: Cypress Creek Preserve, Starkey Wilderness Park, and Green Swamp Wildlife Management Area. All areas are managed for nature conservation and low impact public use, such as hiking and biking (Florida Fish and Wildlife Conservation Commission 2015, SWFWMD 2015 (1), SWFWMD 2015 (2)).

Cypress Creek Preserve (2,072 hectares) and Starkey Wilderness Park (3,367 hectares) are located in Pasco County and contain numerous groundwater production wells to meet residential demands of the Tampa Bay area (SWFWMD 2015 a, b). Two wetlands were sampled within Cypress Creek and six within Starkey (Table 3.1) which represent Impact (pumped) sites. Green Swamp Wildlife Management Area (20,514 hectares) is located at the intersection of Pasco, Lake, and Sumter Counties (FWC 2015). Three wetlands were sampled within Green Swamp, where no groundwater extraction occurred within the area during the study (i.e. Ground Water Extraction, GWE = 0 mgd). Hence, cypress domes in Green Swamp represent Control (non-pumped) sites.

All wells in Cypress Creek and Starkey actively produced ground water throughout the study period. Ground water extraction began at Cypress Creek and Starkey well fields during 1974 and 1976, respectively. Ground water production at Cypress Creek increased through 1979
and at Starkey through 1985, because of the addition of eleven and twelve wells, respectively. After this time, production remained relatively stable until mandated GWE reductions were implemented between 2002 and 2003 at Cypress Creek and 2007 and 2008 at Starkey (Tampa Bay Water 2014 a, b). Despite its smaller area, Cypress Creek has historically produced nearly twice the volume of ground water than Starkey.

A ground water extraction impact factor (IF) was calculated to account for distance related effects of GWE (Bays and Winchester 1986, Kendy, and Bredehoeft. 2006), which takes into account the volume of ground water extracted (mld), number of wetlands in the well field, and distance between wetland and each production well. It was calculated for each sample (wetland x year) as follows:

\[ IF_i = \sum_j \frac{V_j}{D_j} \]

Where, IF = Groundwater Extraction Impact Factor, i = wetland, V=volume of ground water extracted from well j, and D = the distance between the sample wetland and well j. Annual groundwater extraction volumes (million liters per day, mld) were collected and provided by Tampa Bay Water in tabular form from annual monitoring reports (Tampa Bay Water 2014 a,b). The distance from well to wetland was determined using aerial photography using ImageJ software.

Vegetation Monitoring – The effect of reduced GWE on herbaceous communities of isolated cypress domes was assessed by combining annual historical data collected by SWFWMD and recent vegetation monitoring. Historical (pre-reduction) community monitoring began in 1985 and was conducted annually through 2002. Post-reduction herbaceous communities were assessed between 2011 and 2013 for Cypress Creek and Starkey. Green Swamp wetlands were monitored during 2013 only.
Annual vegetation monitoring was conducted almost exclusively during May, although occasional samples were collected during June. A permanent one-meter square (1m²) sample plot was established in the deepest portion of each wetland immediately adjacent to a staff gauge/piezometer/well. All plants less than 1 m tall and rooted within the quadrat were identified to species and assigned a percent cover value ranging between 0% (species absent from sample) to 100% (complete coverage, monoculture). Questionable samples were sent to the University of South Florida Herbarium for identification/confirmation.

Hydrology was monitored by SWFWMD using staff gauges/piezometers and/or continuous recording wells installed adjacent to each sampling plot. Water levels (NGVD) were monitored at least monthly (staff gauges/piezometers) and in some cases daily (wells). An additional reading was taken at the time of vegetation sampling.

Water level data were used to determine significant responses of hydrology to GWE reductions and were used as a covariate for ordination analyses. Hydrologic parameters calculated included annual hydroperiod, average water depth (meters, m), and maximum water depth (m) for each wetland twelve months prior to vegetation monitoring. Hydroperiod was defined as the percent of time a wetland quadrat experienced water levels >0.0 m for the calendar year prior to the monitoring event. Average water depth was the mean of all water level measurements and maximum water depth was the single maximum water level recording during the calendar year prior to vegetation monitoring.

Monthly precipitation volumes and minimum air temperatures were not available for each wetland. As a result, levels for each county were used and provided by SWFWMD. Pasco County (SWFWMD 2015) values were used for Cypress Creek and Starkey. Because Green
Swamp was at the intersection of three counties, precipitation values for Pasco, Lake, and Sumter counties were averaged.

Differences in the mean IF at CC, S, and were determined using an independent t-test (2 tailed, 95%) in IBM SPSS version 22.0. A permanova in an asymmetrical, hierarchical Before After Control Impact (BACI) design was used to assess differences in hydrology (hydropериод, average depth, maximum depth) and herbaceous communities using Primer/Permanova+. Samples taken between 1985 and 2002 were designated as pre-GWE reduction conditions (Before) and 2011-2013 for post-GWE reduction years (After). Control wetlands were located in Green Swamp and Impact wetlands were located in Cypress Creek or Starkey. The 29 most commonly observed species, as described by Thurman et al. (2016), were included in vegetation analyses. Annual precipitation volumes, minimum temperature (C), and IF were used as a hydrologic covariate parameters for the hydrologic Permanova, while HP, AD, MD, Precipitation, and IF were covariates for ground cover communities. Significance levels for all analyses were set at P<0.05. Changes in the importance of individual ground cover species following GWE reductions were quantified using the Indicator Value (IndVal) method, as described by Dufrene and Legendre (1997).

Similarities between vegetation communities among sample locations and between hydrology were visualized using a Principal Components Analysis (PCO, Hydrology) or distance based redundancy analysis (dbRDA, vegetation) in Primer/Permanova+. Hydrology data was normalized and assembled into a Bray-Curtis similarity matrix. The IF and precipitation were used as covariate data for the hydrologic dbRDA. Ground cover data (species abundance) was presence-absence transformed prior to determining distance using Euclidian Distance. Precipitation, the IF, and temperature were utilized as vegetative covariates.
Results

Green Swamp (GS) and Starkey (S) displayed the longest mean hydroperiods (58% and 52%, respectively) and deepest average water depths (0.14 m and 0.18 m, respectively) during the study period (pre- and post- reduction years combined), compared to Cypress Creek, which displayed the shortest annual hydroperiod (18%) and shallowest mean annual water depth (0.048 m).

Mean ground water extraction volumes were reduced from 106.4 million liters per day (mld) to 58.3 mld at Cypress Creek and from 48.1 mld to 16.7 mld at Starkey after cutbacks were initiated during 2003 and 2008, respectively. The mean well field Impact Factor (IF) declined from 0.094 to 0.051 at Cypress Creek (t=2.970, 36.5 df, Sign.=0.005) and from 0.027 to 0.01 at Starkey (t=11.933, 28 df, Sign.=0.000) (Fig. 3.1). Once production peaked at a well, both the mean IF and volume extracted remained relatively steady annually. No wells were located within Green Swamp and the wetlands of this study and all extraction volumes and wetland IF were 0.0.

Reductions in GWE did not produce significant differences in wetland hydrology (Control Impact x Pre Post, P(perm)=0.898) (Table 3.2). Wetland hydrology differed significantly with the annual climatic variables Year and Precipitation (P(perm) = 0.006 and 0.001, respectively) and wetland number (Wetland (Location (Control Impact))) (p(MC)=0.001). No differences were detected in hydrology among sample locations (Well field, P(perm)=0.21) or its interaction with GWE reductions (Wellfield (Control Impact) x Pre Post Reduction, P(perm)=0.063) and Year (Wellfield (Control Impact) x Year, P((perm)=0.14). When samples
were analyzed at the Control Impact Level (pumped vs. non-pumped) no differences in hydrology were detected (P(perm)=0.751).

After GWE reductions were implemented, 55% (n=6) of the sample wetlands became slightly wetter, while the remaining wetlands became slightly drier (Figure 3.2). Most well field wetlands (63%, CC1, CC2, S4, S5, and S6) and a single control wetland (GS3) all displayed increases in hydrology (hydroperiod, average water depth, and maximum water depth). Most (2) of the control wetlands and half the S wetlands became drier during the post-reduction period. The hydrologic base variables (HP, AD, and/or MD) were correlated with dbRDA Axis 1 (93% Fitted, 9.2% of Total Variation), while GWE reductions (IF) and minimum temperature (T) were most closely associated with dbRDA axis 2 (6.9% Fitted, 0.7% of Total Variation). The IF was inversely related to water depth. Precipitation increased slightly, but not significantly, from 1271 mm – 1343 mm at CC and S from 1296 – 1347 mm at GS between pre- and post-reduction periods (Data not shown).

Thirteen (44%) of the 29 dominant species found in the Before samples were observed during post-reduction years, with CC, S, and GS all displaying differences in the species response (Table 3.3). Carex joorii was the sole species with increased abundance following GWE reductions at Cypress Creek, while Amphicapa muhlenbergia, C. joorii, Eupatorium capillifolium, Rhyncospora corymbosa, and Taxodium sp. all became more abundant during post-reduction periods at Starkey. Taxodium sp. seedlings displayed the largest increase in IndVal following reductions in ground water extraction volumes at the well fields (1.4% - 64%). Juncus repens was the most widely reported species present before GWE reductions were enacted; however, this species displayed a declining trend during the Before period and was absent from all samples by 2002. Although not observed within the After sample quadrats, J. repens was
observed outside the sample plots in two sample wetlands during monitoring. *Woodwardia virginiana* was the only species with increased dominance during post-reduction periods at control (Green Swamp) wetlands (Table 3.3).

GWE reductions had a significant effect on ground cover communities at both the pumped vs not pumped (Control Impact x Pre Post Reduction, P(perm)=0.017) and wetland level (Wetland (Wellfield (Control Impact)) x Pre Post Reduction, P(perm)=0.007), as was indicated by the PERMANOVA Analysis (Table 3.4). In addition, differences in ground cover vegetation were significant among years (P(perm)=0.041) and wetland (P(perm)=0.001). Changes in vegetation were not detected with any differences in sample location (Well field), precipitation, pumped vs not pumped locations (Control Impact), and all wetlands combined in pre post reduction periods (Pre Post).

All wetlands shifted along dbRDA axis 1 (46.3% fitted variation, 16% total variation), which was most closely correlated with hydroperiod and precipitation (Figure 3.3). After reductions in GWE, Impact wetlands all shifted in the direction associated with increased hydroperiod and average water depth, while control wetlands shifted towards drier hydrologic conditions. All well field wetlands also shifted towards reduced IF and maximum water depth. One wetland (Cypress Creek 1) displayed a large response to extraction cutbacks, while the remaining well field wetlands responded to a much lesser degree. This wetland was characterized by reduced occurrence of *Andropogon virginicus*, *A. muhlenbergia*, and *Lachnolaimus caroliniana*. Control wetlands (GS) all shifted in similar direction and degree, showing virtually no change along dbRDA axis 2.
Discussion

Following ground water extraction reductions, wetland hydrology and ground cover slightly different responses. Wetland hydrology (HP, AD and MD) was most associated with annual climatic variables (like precipitation and year and less) with most (60%) wetlands displaying increases in water levels and duration. Ground cover communities at well fields all responded with communities shifting towards extended HP and depth, while non-pumped wetlands at GS all became drier.

Ground water extraction (GWE) is widely known to depress hydropenia and water depth (Stewart 1968, Stewart and Hughes 1974, Parker 1975, Watson et. al. 1990); however, as this study details, the relationship may not be as straightforward as assumed. The reduced overall mean hydropenia and average water depth observed at Cypress Creek compared to Starkey (S) and Green Swamp (GS) was most likely influenced by the different levels of GWE experienced at the different locations. The Cypress Creek wellfield historically produced nearly twice the volume of groundwater as Starkey, despite being considerably smaller in area and containing nearly as many wells (12 Starkey vs. 11 Cypress Creek, respectively). Not all well field wetlands responded by becoming wetter however.

All wetlands located in well fields experienced a reduction of at least 50% in their mean impact factor, yet half (S1, S2, and S3) of the wetlands located in S responded with reduced hydropenia and/or water depth like 2/3 of the control wetlands at GS. The hydrology of these wetlands was more impacted by the natural variations in climate, which occur annually in south Florida (Hwang et al. 2011), than by GWE. The IF of these wetlands declined less than the remaining S wetlands (which became wetter) and these wetlands also were located towards the periphery of the well field and closer to major roads and development. Differences in
surrounding land use may be affecting this trend, with residential areas requiring lower water levels and duration than natural areas. Differences in subsurface geology can also alter the connection between ground and surface water (Stewart 1968, Stewart and Hughes 1974, Parker 1975, Watson et al. 1990), effectively helping to insulate them from some impacts from ground water reductions and allowing any potential changes in local precipitation to become evident. While precipitation did not change between GWE reduction periods, county-wide precipitation volumes were used and other researchers have shown the large differences in precipitation across small distances (Abtew and Trimble, 2010; Hwang et al., 2011; Teegavarapu et al., 2013). Two of the Control wetlands also became drier following reductions providing further evidence that GWE reductions did have an impact on hydrology at more than half of the well field wetlands.

While the lack of a clear response in wetland hydrology to GWE reductions was unexpected; ground cover vegetation in CC and S wetlands all responded as predicted and became more indicative of wetter conditions. Control wetlands at GS; however, all shifted towards drier conditions. Vegetation communities should shift between more flood or drought tolerant species as water levels and duration increase and decrease, respectively.

While hydrology is a major factor influencing vegetation species survival, other factors can also influence plant communities. Light levels, soil characteristics, and water chemistry were not measured in this study and can all limit species distribution (Oldeman and van Dijk 1991, Sharpe and Shiels 2014) and some have even been shown to be more important than hydrology (Schulten et al. 2014). In addition, many wetland plant species promote each other’s persistence and prevent succession into a new community based upon environmental gradients alone (Bertness and Callaway 1994, He et al. 2013). Wetlands with ground cover communities responding opposite to hydrology are responding to a hydrologic factor not accounted for or
some other factor not included directly in the study, which caused wetlands getting drier to respond with ground cover species becoming more characteristic of wetter communities.

Juvenile *Taxodium* sp. were much more prevalent in post-reduction communities, particularly at Starkey. When mature, *Taxodium* can survive extended periods of flood and drought (Harms et al. 1980); however, soil exposure and fluctuating water levels are required for both seed germination and to inhibit the growth of faster growing recruits (Demaree 1932, Dickson and Boyer 1972, Ernst and Brooks 2003, Ewel 1990). The reestablishment of *Taxodium* communities capable of replacing adult trees lost through natural or human induced mortality is essential for the long term survival of cypress dome communities and all species utilizing these habitats and GWE reductions appear to have increased *Taxodium* sp. recruitment in some wetlands.

*Juncus repens* was the most dominant species observed during the early pumping years; however, it was absent by 2002. While restoration efforts were not sufficient to reestablish populations of *J. repens* in sample quadrats, this species was detected again in two sample wetlands during post-reduction years (more than 10 years after it was last recorded in pre-reduction years). It is anticipated that this species will continue to increase in cover providing ground water extraction and precipitation volumes do not change. The reestablishment of this species may be a key factor in restoring well field wetlands to historic conditions, although little is known about this and other herbaceous species inhabiting forested ecosystems.

The current study demonstrates the importance of long-term monitoring. The long-term monitoring data collected by the SWFWMD and used as pre-reduction conditions, allowed this project to be completed and shows that hydrologic and vegetative restoration through GWE reductions at well fields is possible although other factors such as local precipitation must be
included. Restoration success and timing can also be influenced by soils and nutrient availability, which can take decades or longer to regenerate following impact (Ballantine and Schneider 2009; Laanbroeck 1990). As a result, determining the success of any restoration project should take a multivariate approach and occur over an extended time frame, which will allow for more detailed responses to be detected and more successful restoration to be completed.

Cypress and other wetlands in Florida have diminished in number and quality (McCauley et al. 2013, Rains et al. 2013) despite current management and restoration regulations designed to prevent a net loss of wetland function (Florida Administrative Code 62-345). Best estimates predict that precipitation will continue to decline, while populations and fresh water consumption continue to increase (Kirtman et al. 2013, Tampa Bay Water 2013, United States Census Bureau 2016), which will likely lead to further GWE and associated hydrologic alterations.

Large and continued changes in the hydrology can potentially lead to a drastic change in plant communities, many of which can have feedback mechanisms preventing them from returning to original conditions (Heffernan 2008, Lowe et al. 2001, van de Koppel et al. 2001, Scheffer et al., 2001, Scheffer et al., 2003). Such an alternative stable state does not appear to have occurred at the well fields as all wetland vegetation communities responded to extraction reductions. To offset a future potential catastrophic loss of wetland structure and function, conservation and restoration efforts must consider restoration of existing habitats following long-term abuse such as those found in the area well fields.
References


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Southwest Florida Water Management District (SWFWMD). 2015 (1).

https://www.swfwmd.state.fl.us/recreation/areas/cypresscreek.html

Southwest Florida Water Management District (SWFWMD). 2015 (2).

https://www.swfwmd.state.fl.us/recreation/areas/starkey-park.html


Thurman, P.E. 2016. Utilizing a Historical Database to Improve Herbaceous Vegetation and Hydrologic Models in Cypress (Taxodium sp.) Swamps North of Tampa Bay, Florida.


Table 3.1. Location (Latitude and Longitude) of Geographically Isolated Cypress Domes Monitored During the Current Study. *Denotes Ground Water Producing Well Fields.

<table>
<thead>
<tr>
<th>Wetland Number</th>
<th>*Cypress Creek</th>
<th>Green Swamp</th>
<th>*Starkey</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28° 17 25.41</td>
<td>28° 21 43.01</td>
<td>28° 15 27.02</td>
</tr>
<tr>
<td></td>
<td>82° 23 27.02</td>
<td>81° 56 47.27</td>
<td>82° 36 11.34</td>
</tr>
<tr>
<td>2</td>
<td>28° 16 21.46</td>
<td>28° 22 35.01</td>
<td>28° 15 19.67</td>
</tr>
<tr>
<td></td>
<td>82° 24 18.34</td>
<td>81° 55 46.27</td>
<td>82° 38 09.12</td>
</tr>
<tr>
<td>3</td>
<td>28° 15 27.02</td>
<td>28° 14 40.19</td>
<td>28° 14 55.66</td>
</tr>
<tr>
<td></td>
<td>82° 36 11.34</td>
<td>81° 58 15.31</td>
<td>82° 33 22.54</td>
</tr>
<tr>
<td>4</td>
<td>28° 15 19.67</td>
<td>28° 14 27.33</td>
<td>28° 14 44.45</td>
</tr>
<tr>
<td></td>
<td>82° 38 09.12</td>
<td>82° 34 49.43</td>
<td>82° 34 57.84</td>
</tr>
<tr>
<td>5</td>
<td>28° 15 27.02</td>
<td>28° 14 44.45</td>
<td>82° 34 57.84</td>
</tr>
<tr>
<td></td>
<td>82° 36 11.34</td>
<td>82° 33 22.54</td>
<td>82° 33 22.54</td>
</tr>
<tr>
<td>6</td>
<td>28° 14 44.45</td>
<td>28° 14 10.72</td>
<td>28° 35 08.06</td>
</tr>
</tbody>
</table>

* Denotes Locations located within ground water producing well fields.
Table 3.2. Before After Control Impact (BACI) Analysis for the hydrologic parameters (Annual Hydroperiod, Average Water Depth, and Maximum Water Depth) of isolated cypress domes north of Tampa Bay, Florida. P values <0.05 were considered significant (*).

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>Pseudo-F</th>
<th>P</th>
<th>Unique (perms)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Water Extraction Impact Factor</td>
<td>1</td>
<td>97.861</td>
<td>97.861</td>
<td>2.807</td>
<td>0.143</td>
<td>999</td>
<td>0.189</td>
</tr>
<tr>
<td>Annual Precipitation</td>
<td>1</td>
<td>86.584</td>
<td>86.584</td>
<td>23.586</td>
<td>0.001*</td>
<td>999</td>
<td>0.001*</td>
</tr>
<tr>
<td>Control Impact</td>
<td>1</td>
<td>28.258</td>
<td>28.258</td>
<td>0.71138</td>
<td>0.751</td>
<td>997</td>
<td>0.696</td>
</tr>
<tr>
<td>Pre Post Reduction</td>
<td>1</td>
<td>6.6712</td>
<td>6.6712</td>
<td>0.81904</td>
<td>0.717</td>
<td>999</td>
<td>0.547</td>
</tr>
<tr>
<td>Wellfield (Control Impact)</td>
<td>1</td>
<td>36.83</td>
<td>36.83</td>
<td>1.4033</td>
<td>0.21</td>
<td>999</td>
<td>0.248</td>
</tr>
<tr>
<td>Year (Pre Post Reduction)</td>
<td>19</td>
<td>58.027</td>
<td>3.0541</td>
<td>2.3892</td>
<td>0.006*</td>
<td>995</td>
<td>0.003*</td>
</tr>
<tr>
<td>Control Impact x Pre Post Reduction</td>
<td>1</td>
<td>1.3171</td>
<td>1.3171</td>
<td>0.39437</td>
<td>0.933</td>
<td>999</td>
<td>0.898</td>
</tr>
<tr>
<td>Wetland (Location (Control Impact))</td>
<td>8</td>
<td>199.7</td>
<td>24.963</td>
<td>34.38</td>
<td>1</td>
<td>999</td>
<td>0.001*</td>
</tr>
<tr>
<td>Control Impact x Year (Pre Post Reduction)</td>
<td>19</td>
<td>30.731</td>
<td>1.6174</td>
<td>1.6111</td>
<td>0.09</td>
<td>999</td>
<td>0.057</td>
</tr>
<tr>
<td>Wellfield (Control Impact) x Pre Post Reduction</td>
<td>1</td>
<td>3.5171</td>
<td>3.5171</td>
<td>2.1332</td>
<td>0.063</td>
<td>999</td>
<td>0.133</td>
</tr>
<tr>
<td>Wellfield (Control Impact) x Year (Pre Post Reduction)</td>
<td>19</td>
<td>17.614</td>
<td>0.9271</td>
<td>1.2936</td>
<td>0.14</td>
<td>998</td>
<td>0.103</td>
</tr>
<tr>
<td>Residuals</td>
<td>147</td>
<td>104.76</td>
<td>0.7127</td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
<td>227</td>
<td>687</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Table 3.3.** List of species with increased Indicator Values (IndVal) following ground-water extraction volumes (2011-2013). IndVals for pre-reduction periods are provided in parenthesis ( ).

<table>
<thead>
<tr>
<th>Species</th>
<th>Cypress Creek</th>
<th>Starkey</th>
<th>Wellfield Average</th>
<th>Green Swamp</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Carex joorii</em></td>
<td>100 (0)</td>
<td>24 (8.4)</td>
<td>28.2 (6.6)</td>
<td></td>
</tr>
<tr>
<td><em>Eupatorium capillifolium</em></td>
<td>30 (7.7)</td>
<td>30 (7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Rhyncospora corymbosa</em></td>
<td>20.4 (10.9)</td>
<td></td>
<td>20.6 (10.0)</td>
<td></td>
</tr>
<tr>
<td><em>Taxodium distichum</em></td>
<td>64 (1.5)</td>
<td>64 (1.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Amphicarpa muhlenbergia</em></td>
<td>44 (6.2)</td>
<td></td>
<td></td>
<td>23 (5.8)</td>
</tr>
<tr>
<td><em>Woodwardia virginica</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.4. Results of Before After Control Impact (BACI) design Permanova for Herbaceous Vegetation Communities Before and After Reductions in Ground Water Extraction Volumes. *Denotes significant differences. P values <0.05 were considered significant.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>Pseudo-F</th>
<th>P (perm)</th>
<th>Unique (perms)</th>
<th>P (MC)</th>
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<tr>
<td>Annual Precipitation</td>
<td>1</td>
<td>1227.8</td>
<td>1227.8</td>
<td>1.227</td>
<td>0.349</td>
<td>999</td>
<td>0.353</td>
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<tr>
<td>Control Impact</td>
<td>1</td>
<td>8962.3</td>
<td>8962.3</td>
<td>0.77399</td>
<td>0.657</td>
<td>998</td>
<td>0.5141</td>
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<tr>
<td>Pre Post Reduction</td>
<td>1</td>
<td>419.98</td>
<td>419.98</td>
<td>1.1408</td>
<td>0.437</td>
<td>998</td>
<td>0.349</td>
</tr>
<tr>
<td>Wellfield (Control Impact)</td>
<td>1</td>
<td>11300</td>
<td>11300</td>
<td>1.5782</td>
<td>0.149</td>
<td>998</td>
<td>0.2465</td>
</tr>
<tr>
<td>Year (Pre Post Reduction)</td>
<td>19</td>
<td>17081</td>
<td>899.01</td>
<td>1.806</td>
<td>0.066</td>
<td>997</td>
<td>0.041*</td>
</tr>
<tr>
<td>Control Impact x Pre Post Reduction</td>
<td>1</td>
<td>2066.9</td>
<td>2066.9</td>
<td>3.6781</td>
<td>0.05*</td>
<td>999</td>
<td>0.017*</td>
</tr>
<tr>
<td>Wetland (Location (Control Impact))</td>
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<td>1.1938</td>
<td>0.357</td>
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<tr>
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<td>0.41232</td>
<td>0.917</td>
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<tr>
<td>Wetland (Wellfield (Control Impact)) x Pre Post Reduction</td>
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<td>419.86</td>
<td>0.91055</td>
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<td>Residuals</td>
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<td>2.202</td>
<td>0.011*</td>
<td>998</td>
<td>0.007*</td>
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<tr>
<td>Total</td>
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</tbody>
</table>
Figure 3.1. Change in average Ground Water Impact Factor (IF) at Cypress Creek and Starkey wetlands associated with reductions in ground water extraction volumes in XXX in response to the Tampa Bay Water Wars. No ground water extraction occurred within the boundaries of Green Swamp.
Figure 3.2. Principal components Analysis Ordination (PCO) of wetland hydrology (Hydroperiod, HP; Average Water Depth, AD; and Maximum Water Depth, MD) at Cypress Creek (CC), Starkey (S), and Green Swamp (GS). The GWE Impact Factor (IF), annual precipitation, and minimum temperature estimates were included as predictor variables. Resemblance was conducted using Euclidean distance.
Figure 3.3. Distance Based Redundancy Analysis (dbRDA) for herbaceous vegetation communities of cypress domes communities north of Tampa Bay, Florida: Cypress Creek (solid icons), Starkey (open icons), and Green Swamp (lined icons). Pre-reduction periods are indicated by the number 1, while post reduction wetlands averages are indicated by the number 2. CC indicates wetlands located within Cypress Creek, GS wetlands in Green Swamp, and S wetlands in Starkey. Species correlations are included on for those species with Pearson’s Correlation Coefficient Values >0.4.
CHAPTER FOUR

VARIATION IN WETLAND TREE CANOPY STRUCTURE ALONG A GRADIENT OF GROUND WATER EXTRACTION VOLUMES

Abstract

Wetland trees are extremely tolerant of flood and drought conditions when mature, yet changes in the canopy strata can and do occur in response to hydrologic alterations associated with ground water extraction. Changes in the structure of tree communities can also alter ground cover community structure through changes in hydrology (evapotranspiration rates) and light availability. In isolated cypress swamps substantial tree mortality and replacement by non wetland tree species has been reported, but a detailed, quantitative description of how tree communities have been impacted by ground water extraction has not been completed. This study describes the effects of ground water extraction on tree communities (species composition, density, recruitment, mortality, size, canopy cover) located in isolated cypress (Taxodium sp.) swamps north of Tampa Bay, Florida. Four sample locations were sampled which each experienced a different level of impact associated with ground water extraction (Cypress Creek, Starkey, Green Swamp, and pumped but Augmented). Cypress Creek experienced the largest impact associated with ground water extraction and the shortest hydroperiod and shallowest water depths, while Green Swamp and Starkey were similar. Augmented wetlands displayed the
longest hydroperiods. Tree species composition was significantly related to hydrology with wetlands with reduced hydroperiod/water depth and increased impact from ground water extraction displaying increased importance of non-wetland trees such as *Pinus elliottii* and *Quercus laurifolia*. Increased ground water extraction resulted in increased density of live non-*Taxodium* species, increased wetland tree mortality, and decreased ability to intercept light. Hydrologic augmentation resulted in an increased overall mean trunk diameter, presumably as a result of the exclusion of young trees. The changes in light levels available for ground cover vegetation associated with ground water extraction, resulted in changes in ground cover communities. Excessive ground water extraction can potentially result in a complete change in vegetation communities at all vegetation strata; however, these changes may take decades to become evident. Due to the potentially long time required for changes in tree species composition to become visible, long term research is required to ensure the persistence of cypress domes. Wetlands in all locations remained dominated by *Taxodium* sp., however, trends in succession indicate a larger shift away from cypress communities which must be monitored carefully.

**Introduction**

Ground water has been a resource critical to the survival of many human populations globally for millennia (Binford et al. 1997, Schwarz and Ibaraki 2011); however, the over-extraction of ground water has resulted in numerous adverse impacts to surface ecosystems, particularly wetlands. Ground water extraction (GWE) reduces surface hydrology through the alteration of infiltration rates (Stewart 1968, Stewart and Hughes 1974, Parker 1975, Watson et.
al. 1990), which can then alter the vegetation species composition by fluctuating between flood and drought tolerant species.

Changes in vegetation structure can result from variations in the flood-tolerance and effects on growth rates of species located within a community (Megonigal 1997; Wilcox 1995). As a result, as water levels recede, the species composition can shift towards species more capable of surviving and reproducing under particular environmental conditions (Makarewicz and Likens 1975). Ground cover vegetation is highly dynamic and can respond to changes in water level and duration of inundation relatively quickly (3-4 years) (Armentano et al. 2006, Murray-Hudson et al. 2014, Todd et al. 2010); however, the impacts to tree communities may not be as rapid or easily observed.

Wetland trees, such as cypress, *Taxodium* spp., and swamp tupelo, *Nyssa sylvatica*, are extremely tolerant of flood and drought conditions when mature (Harms et al. 1980) and are capable of surviving the highly variable water levels resulting from routine climatic variation (van der Valk 2005). However, tree fall and encroachment of non-wetland species have been attributed to the altered hydrology that can result from over extraction of ground water (Rochow 1994, Stewart 1968, Stewart and Hughes 1974, Parker 1975, Watson et al. 1990). Alternate pathways of succession have been described for cypress swamps including transitioning from cypress into Bay Swamps or oak/pine forests (Casey and Ewel 2006, Marios and Ewel 1983). These successional paths appear to be largely determined by the depth and amount of organic soils, which can be altered drastically reduced hydrology (Laanbroeck 1990), as is common with GWE (Stewart 1968, Stewart and Hughes 1974, Parker 1975, Watson et al. 1990). Many vegetation species are also thought to provide insulation from environmental stress to each other resulting in communities more stable than would be predicted based upon hydrology alone.
(Bertness and Callaway 1994. He et al. 2013). As a result, predicting the direction of tree community succession associated with GWE may not be as straightforward as assumed.

Changes in tree density and health can also indirectly impact ground cover communities through changes in light intensity. Light availability influences survival and growth of both tree and ground cover species (Oldeman and van Dijk 1991, Sharpe and Shiels 2014); and may be more important than hydrology in some cases (Schulten et al. 2014). In forested wetlands, increased light availability should favor a different set of species, such as those associated with marshes. These communities may be considerably different than those found in dense forests; however, information concerning the light requirements of ground cover species remains elusive. The composition, density and size of both live and standing dead trees can alter the amount of light reaching the wetland below; however, the interaction between GWE, hydrology, ground cover, and trees remains poorly understood. Understanding this interaction is vital to the utilization of ground cover vegetation as early indicators of un-wanted ecological change associated with GWE.

As human populations and GWE continue to increase (Kirtman et al. 2013, Tampa Bay Water 2013, United States Census Bureau 2016), so does the importance of understanding how GWE impacts all communities so that adverse impacts can be avoided. The Tampa Bay area (Bay Area) is ideally suited to investigate the relationship between GWE, swamp tree communities and ground cover vegetation. The region has a long history of GWE to supply potable water to more than 2 million people (Tampa Bay Water 2013). GWE has been distributed among several well fields in a landscape of isolated wetlands and lands with conservation protection and no development. Pumping at these well fields was initiated between the mid-1970s and mid-1980s with extraction continuing until present day.
The current study describes the impacts to canopy species associated with GWE north of the Tampa Bay area, Florida. Tree species composition, size, and the amount of light available for photosynthesis (% PAR), were sampled from four different pumping regimes and volumes to test the following hypotheses: Increased GWE has resulted in wetlands with 1) fewer living cypress trees, 2) increased occurrence of trees other than *Taxodium* sp., 3) trees with a reduced trunk diameter, and 4) increased light availability for photosynthesis at the wetland floor.

**Material and methods**

Wetlands were selected from three locations located north of Tampa Bay, Florida, each location experiencing a different mean amount of GWE. Cypress Creek, Starkey, and Green Swamp are located north of Tampa Bay, Florida, ranged in size from 0.17 to 25.9 hectares, and were all surrounded by native vegetation on public lands managed for low impact public use (FWC 2015, SWFWMD 2015 a, b). Cypress Creek (CC) experienced the highest amount of groundwater extraction, with Starkey (S) producing approximately half as much extraction. Green Swamp (GS) was selected as a control location as no groundwater extraction occurs within the vicinity of the sample wetlands. Surface hydrology in two wetlands in Cypress Creek was artificially augmented (AUG) with ground water to enhance water depths and hydroperiod, which had been reduced due to groundwater extraction.

Up to three circular 0.0134 hectare plots were sampled along a linear transect in each wetland depending on wetland size and shape. Transects were established using a GPS from the wetland edge to the center along a linear line when possible. Plots were placed where possible and so as not to overlap when wetland dimensions were too small for linear transects or multiple plots. The center of each tree plot was permanently marked using PVC pipe and plot edge was
marked using surveying pin flags 6.55 m (radius) away from the center plot in the four cardinal directions.

A total of 14 wetlands (4 CC, 8 S, two GS, and 2 AUG) were sampled (Table 4.1). Tree species composition was assessed by counting all trees located within each plot. All individuals were identified to species, measured for diameter at breast height (dbh, trunk diameter > 1.5 m high) and assigned into one of five height categories: <1m (new recruits), 1-2 m (recent recruits), 2-3 m (immature), 3-6 m (young adults), and >6m (mature). Standing dead trees were identified and measured, but not included in estimates of tree density or species composition.

The amount of photosynthetic active radiation, PAR, µmol m-2 s-1) at each wetland was monitored quarterly (January-March, April-June, July- Sept., and Oct.-Dec.) using an Apogee Instruments MQ-100 Quantum Integral Sensor. One measurement was taken at the center of the sample plot with an additional four recorded on the plot edge in the four cardinal directions from the plot center at the location of the pin flags. An additional set of PAR measurements was taken in the full, unobstructed sun located adjacent to each wetland immediately before and after PAR values were recorded in the wetland. Wetland and full sun PAR values were transformed into percent (%) available PAR at the wetland floor.

The potential impact of ground water extraction on vegetation communities was determined using a ground water extraction impact factor (IF) that combines the volume of ground water extracted, number of ground water producing wells, and distance between wells and sample wetlands. The amount of ground water extracted and number of wells located within Cypress Creek and Starkey wellfields were provided by Tampa Bay Water in annual monitoring reports (Tampa Bay Water 2014 a, b). The distance between wetland and well was determined
using aerial photography and known distances in Image J software. The IF was determined using the following equation:

\[ IF_i = \sum_j \frac{V_j}{D_j} \]

Where, IF = Groundwater Extraction Impact Factor, i = wetland, V = volume of ground water extracted from well j, and D = the distance between the sample wetland and well j.

Water level data (m) were provided by SWFWMD and collected at a minimum of monthly intervals at established piezometers/continuous recording wells. Piezometer/wells were located at the deepest portion of the wetland and used to determine mean annual hydroperiod, water depth, and maximum water depth for each wetland. Hydroperiod is defined as the percentage of time during the previous calendar year when standing water was present in the wetland core. Mean water depth is the average of all water level measurements occurring during the calendar year prior to vegetation monitoring. Groundwater levels were not available for this study and as a result, all samples <0.0 m were treated as a 0.0 m water depth. Maximum water depth was the single deepest water level recorded during the previous year.

Statistical differences in the IF before and after reductions in ground water extraction volumes were compared using an independent samples t-test in IMB SPSS version 23.0). Similarity between the hydrology (IF, hydroperiod, average water depth, maximum water depth, precipitation) of the sample treatments (Cypress Creek Augmented, Cypress Creek Natural, Starkey, and Green Swamp) was determined using an Analysis of Variance (ANOVA) in IBM SPSS Version 22.0. Differences in tree species composition among the four sample treatments were determined using a hierarchical designed Permanova in Primer/Permanova+. Wetland hydrology was included as covariate data. Similarity among tree communities was visualized and the relative importance of the hydrological factors was determined using a distance based
redundancy analysis (dbRDA) and post-hoc Pearson’s Correlation Coefficients with Primer/Permanova+. Similarity among the

differences in mean tree density (all trees, Taxodium sp. only, non Taxodium sp., standing dead) was assessed using a Generalized Linear Model (GLM) in IBM SPSS Version 23.0. Differences in mean diameter at breast height (dbh), and the percent of photosynthetic radiation reaching the wetland floor were assessed using an ANOVA in IBM SPSS Version 23.0. Pair-wise differences among treatments were determined from a post-hoc Scheffe’s test.

Results

Cypress Creek (CC) (22.9 million gallons/day, mgd) produced more than twice the volume of ground water between 1985 and 2013 as Starkey (S) (11.2 mgd). No groundwater extraction occurred within the vicinity of Green Swamp (GS) wetlands. When the volume of groundwater extracted was combined with the number wells and distance between wetland and well, the mean Ground Water Extraction Impact Factor (IF, million gallons/day/m) for these locations was significantly different between S (0.02) and CC locations (0.08)(F=144.505, Sign.=0.00)(Figure 4.1). CC and wetlands augmented with ground water (AUG) displayed slightly different but statistically similar impact factors (IF, 0.0753 ml/d/m and 0.0822 ml/d/m, respectively). All pumping volumes remained relatively steady during the study period, with the exception of a single reduction during 2003 and 2008 at CC and S, respectively. Extraction volumes were reduced from 106.4 mld to 58.3 mld at Cypress Creek and from 48.1 mld to 16.7 mld at Starkey; while the IF declined from 0.094 to 0.051 at Cypress Creek (t=2.970, 36.5 df, Sign.=0.005) and from 0.027 to 0.01 at Starkey (t=11.933, 28 df, Sign.=0.000). Following
reductions, the IF at each wetland remained stable with the most impacted wetlands remaining the most impacted and the least impacted wetlands remaining the least impacted.

Statistical differences were detected in mean annual hydroperiod ($F_{(df1=3, df2=385)}=61.645, p<0.000$), average water depth ($F_{(df1=3, df2=385)}=9.489, p<0.000$), and maximum water depth $F_{(df1=3, df2=385)}=9.864, p<0.000$) among pumping regimes. CC locations displayed the shortest mean hydroperiod (21%) and average water depth (0.05 m), which were statistically lower than all remaining locations ($p<0.004$ each). S and GS locations were similar in hydroperiod ($p=0.575$, 53% and 60%, respectively) and average water depth ($p=0.994$, 0.17 and 0.18 m, respectively). AUG wetlands displayed, by far, the longest hydroperiod ($p<0.000$, 95% inundation); however, average water depth (0.25 m) was not different from that at CC or S ($p=0.591$ and 0.264, respectively).

Twelve tree species comprising 1,310 live individuals were measured during the study. *Taxodium* sp. was the dominant species and comprised 65% of all trees counted, followed by *Myrica cerifera* (10%), *Nyssa sylvatica* (8%), and *Pinus elliottii* (6%) (Table 4.2). Each remaining species comprised less than 5% of the total species count. Numerous shrub species were also encountered but not included in the analysis.

Changes in tree species composition were significantly correlated with nearly all hydrologic covariates tested at the wetland level (IF, hydroperiod, and average water depth) (Table 4.3). When wetlands were averaged into larger groups at the well field or pumped vs. non-pumped (Control Impact) level, no significant effects were observed. The primary axis identified in the dbRDA (axis 1, 93.9% fitted, 57.9% total variation) was most closely correlated with hydrology, with increased IF resulting in reduced hydroperiod and average water depth (Figure 4.2). *Pinus elliottii* and *Quercus laurifolia* were positively correlated with increases in
the IF and were observed at both CC and S locations (Figure 4.2). Most wetlands sampled were indicative of reduced hydroperiod and water depth. No covariate was correlated with dbRDA axis 2 (11.8% fitted, 7.3% total).

The density (trees per hectare, tph) of all non *Taxodium* tree species ranged between CC (1015 tph) and GS (373 tpa) wetlands (Figure 4.3). The IF was shown to be a significant predictor of non-*Taxodium* tree density \[W(\chi^2)=17.274, 1 \text{ df, p}<0.000\]. (Both Cypress Creek locations (CC and AUG) were dominated by and showed elevated densities of newly recruited trees other than *Taxodium* sp. (Table 4.2). The CC wetlands also displayed elevated densities of newly recruited *Quercus laurifolia* (<1 m); while AUG wetlands contained elevated densities of *Myrica cerifera* (all size classes).

The mean trunk diameter for all measurable trees ranged from 14.5 cm (dbh) at GS wetlands to 22.7 cm (dbh) at AUG wetlands (Figure 4.4). The mean trunk diameter at GS wetlands was statistically similar to both CC (dbh=15.09) and S (17.81 cm) wetlands; AUG wetlands were statistically unique (ANOVA, \(F_{(df1=3, df2=984)} = 13.777, \text{Sign.}=0.000\).

*Taxodium* (all size classes combined) was the dominant tree observed at all sample locations (Table 4.2). The density of *Taxodium* was not significantly affected by GWE (IF) \[W(\chi^2)=0.015, 1 \text{ df, p}=0.904\]. CC wetlands contained no new *Taxodium* recruits and held the lowest percent of *Taxodium* (59%) in their canopy structure among the CC, S, and AUG wetlands (Figure 4.3). Mature *Taxodium* (>6 m height) was the dominant size class in all sample locations except S, which was dominated by new recruits ranging between (1-2 m height). Starkey contained mid level total percent composition of *Taxodium* (69%) and multiple newly recruited individuals (71 tph) of *Taxodium*. Not pumped (GS) wetlands held the highest percent composition (84%) and largest density of *Taxodium* (2075 tph). Augmented (AUG) contained
among the lowest densities (1479 tph) and percent composition (46%) of *Taxodium* sp. of all sample locations.

A total of 129 standing dead trees were counted among the CC, S, and GS sample locations. Cypress Creek contained the highest density of standing dead trees (1293 trees per hectare, tph), followed by Starkey (158 tph), and Green Swamp (15 tph) (Figure 4.5). Ground water extraction (IF) was shown to be a significant predictor of standing dead tree density \( [W(\chi^2)=30.3, 1 \text{ df}, p<0.000] \). *Taxodium* sp. and *Nyssa sylvatica* were the most abundant species of standing dead tree observed (n=66, 51% and n=56, 43%). *Acer rubrum*, *Pinus elliottii*, and *Quercus laurifolia* comprised less than 3% of the standing dead trees observed. Wetlands were most distributed along dbRDA axis 1 (89.6% fitted, 20.2% of total variation) which was most closely associated with reductions in AD and standing dead *Taxodium* (Figure 4.6). The IF was most correlated with dbRDA Axis 2 (6.6% fitted, 1.5% total variation). Most of the standing dead trees observed mature (81%) or sub-adult (19%) prior to death. AUG wetlands were not included in the analysis of dead trees.

More light was available for photosynthesis at the wetland floor at the two locations impacted by GWE than at GS or AUG sites \( (F_{(df1=3, df2=1449)}=51.414, p<0.000)\) (Figure 4.7). Wetlands located in CC and S received significantly higher amounts of photosynthetic available radiation (CC=37.3%, S=32.6%) than GS (13.4%) or AUG wetlands (12.8%). Ground cover vegetation structure was correlated with mean wetland PAR, hydroperiod, and IF (Figure 4.8). Each parameter was correlated along the primary dbRDA axis identified (26.7% fitted, 20.9% of total variation). IF was inversely related to PAR with wetlands containing more wells producing more water closer to them containing a much higher percentage of PAR than remaining wetlands. The maximum water depth, MD, achieved annually in each wetland was correlated
with dbRDA axis 2 (23% of fitted, 18% of total variation). Wetlands with increased IF were associated with increased occurrence of *Pluchea odorada, Ludwigia repens, Cladium jamaicense*, and *Lachnolaimus caroliniana*. Increased light levels were associated with *Bacopa monieri*, while *Amphicarpa mühlenbergianum, Rhyncospora inundata, Panicum hemitomon, Stillinga aquatica*, and newly recruited *Taxodium* sp. seedlings were associated with increased hydroperiod.

**Discussion**

The hydrology observed at the sample locations reflects the levels of GWE occurring, with the most pumped locations (CC) having the shortest hydroperiods and water depths and the AUG wetlands containing the longest hydroperiods. The hydroperiod and water depth at moderately pumped Starkey and the non-pumped Green Swamp were not significantly different from each other and both were similar to that reported in the literature for cypress swamps (Ewel 1990). The depressed hydroperiod and water depth observed at CC is likely a result of elevated GWE occurring at CC. The wetlands sampled at CC had mean IFs nearly 4x that of S wetlands and, although not tested in the current study, previous research has shown GWE to reduce hydroperiod and water level at both CC and S (Stewart 1968, Stewart and Hughes 1974, Parker 1975, Watson et. al. 1990). The slightly reduced hydroperiod and average water depth at S are indicative of a system much less impacted by GWE and is similar to control wetlands not impacted by GWE.

The observed variations in canopy species structure have certainly occurred in response to different hydrology at the study locations, which is heavily driven by GWE (Stewart 1968, Stewart and Hughes 1974, Parker 1975). Reductions in water levels can increase mortality in
adult cypress and promote the expansion of less hydrophilic species resulting in a community
shift (Armstrong and Beckett 1987; Rochow 1994; Sorrel et al. 2000; Wilcox 1995; van der Valk
2005). Such a shift appears to be occurring at CC as evidenced by the increased abundance of *Q.
laurifolia* and *P. elliottii*, increased numbers of dead adult *Taxodium*, reduced recruitment of
*Taxodium* sp., and increases in species other than *Taxodium* or *N. sylvatica*. *Pinus elliotti* and
*Q. laurifolia* are both common to Florida swamps, but are typically found in highest densities
locations with hydroperiods below that of typical cypress swamps (6 months, 50%)(Casey and
Ewel 2006; Ewel 1990; Wharton et al. 1982). Previous research has also demonstrated that
increases in water levels by 0.2 m were sufficient to reduce the survival of *Liquidambar
styraciflua* and *Q. laurifolia* (Ernst and Brooks 2003). Although water levels in our study did not
differ by this much, less hydrologic variation is likely required to exclude many species from
successfully recruiting.

GWE may be providing an altered path of succession for *Taxodium* swamps than
described under traditional succession models under more natural conditions. Reductions in
hydrology associated with organic matter accumulation and fire suppression can result in a
cypress swamp transitioning to a bay swamp system (Casey and Ewel 2006); however, other
researchers have shown encroachment by pines and other hardwoods in wetlands impacted by
humans (Marios and Ewel 1983). Wetlands with reduced hydrology in our study were
experiencing increases in *Q. laurifolia* and *P. elliottii*. The reduced hydrology in wetlands
experiencing encroachment can result in a loss of organic matter (Laanbroeck 1990), which may
preclude the establishment of a bay swamp. Bays of any species (*Magnolia virginicus, Gordonia
lasianthes*) were uncommon in the study and evidence of soil subsidence/oxidation was
widespread, although not quantified, in well field wetlands.
GWE not only has the ability to alter wetland hydrology and vegetation species composition, but the amount of light present for photosynthesis in the ground cover stratum. In both pumped locations (CC and S), more than 2x to 3x the amount of light (%PAR) was available, and ground cover communities were shown to be correlated with PAR levels. While changes in light availability can alter the survival of some flora, as individual species may be more restricted to high or low light habitats (Sharpe and Shiels 2014), the light requirements of most ground cover species inhabiting swamps remains unknown. Since differences in tree densities were not observed, among CC, S, GS, and AUG sites, it is likely that changes in tree morphology may be occurring. In well fields, considerable more dead limbs were observed on Taxodium trees, which may be resulting in fewer, shorter limbs with less dense foliage capable of filtering light. Estimates of limb length, canopy cover, and foliage density were not collected during this study.

Wetlands with augmented surface hydrology also displayed trunk diameters larger than all other groups tested. Augmented wetlands displayed exceptionally long hydroperiods (95%) and were comprised primarily of either mature trees or trees with stable dbh like Sabal palmetto. Augmentation in these wetlands was likely sufficient to increase hydrology enough to preclude the establishment of additional canopy species as soils were only exposed for approximately 2 weeks a year. Previous research has also documented that Nyssa sylvatica showed an increase in the basal area following increased water levels (Ernst and Brooks 2003). However, as flood duration and intensity is increased to multiple years and over one meter, species such as swamp tupelo and cypress, which are considered to be highly flood tolerant, can become susceptible to mass mortality (Harms et al., 1980).
Current GWE and hydroperiod/water level ranges at S and GS appear to be suitable for the long-term survival of a *Taxodium* swamp; however, CC is likely too low and AUG wetlands too high. At CC and AUG; little evidence of cypress recruitment was observed, in addition to increased numbers of dead cypress and recruitment of other tree species. As a result, these wetlands are at more risk of change in canopy structure, because current hydroperiod and water depths appear to preclude seed establishment. At CC, further reductions in GWE and increases in water depth and duration would likely help protect cypress domes from future loss.

Augmentation of surface hydrology with ground water was effective at mitigating a loss of hydroperiod and water depth because of GWE, but these wetlands would actually benefit from reduced hydroperiods that could easily be achieved through alterations in augmentation timing to mimic natural hydrologic cycles. Both of these actions should be sufficient to help restore cypress regeneration and reduce mortality.

The changes described in the canopy species of pumped locations have severe long-term implications and highlight several gaps in information. Cypress remain the dominant species in each location and the restoration of self regenerating *Taxodium* appears possible despite the extended periods of GWE. Starkey wetlands showed a large pulse of recently recruited *Taxodium*, which occurred in recent years. During 2008, GWE at S was reduced and *Taxodium* recruitment appears to have occurred shortly afterwards. As a result, it is possible that *Taxodium* swamps currently not producing young, can be restored simply through hydrologic manipulation. Previous research has also documented that in many cases canopy cover and light levels can be restored relatively quickly following disturbance from natural disasters, such as hurricanes, providing soils are not severely impacted (Chazdon 2003); however the recovery of canopy cover loss as a result of chronic GWE remains less certain. Through sound management
decisions concerning withdrawal and timing, it appears that many adverse effects associated with GWE on surface ecosystems can be mediated. Alterations of GWE and augmentation levels at CC and AUG to produce wetland hydrologic characteristics more similar to S and GS would likely be sufficient to help promote the long-term viability of cypress swamps.
References

Armentano TV; Say JP; Ross MS; Jones DT; Cooley HC; Smith CS (2006) Rapid responses of vegetation to hydrological changes in Taylor Slough, Everglades National Park, Florida, USA. Hydrobiologia 569: 293-309.


Table 4.1. Location of Wetlands Highly Pumped (* Cypress Creek), Moderately Pumped (Starkey), Non-Pumped (Green Swamp), and pumped but Augmented (# Cypress Creek) by Ground Water Extraction. Cypress Creek and Starkey Wetlands are located in Pasco County, Florida and Green Swamp Wetlands are located at the intersection of Polk, Sumter, and Lake Counties, Florida.

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Table 4.2. Density (trees per hectare, tph) of tree and select shrub species in multiple size classes: new recruit (<1m), recent recruits (1-2m), immature (2-3m), young adult (3-6m), and mature (>6m) tree species counted in tree plots across all four GWE regimes. ±95% Confidence Intervals are provided in parenthesis ( ).

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<th>1-2m</th>
<th>2-3m</th>
<th>3-6m</th>
<th>&gt;6m</th>
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<td>135</td>
<td>165</td>
<td>406</td>
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<tr>
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<td>30</td>
<td>15</td>
<td>0</td>
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<td>15</td>
<td>135</td>
<td>421</td>
<td>1850</td>
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<td>15</td>
<td>19</td>
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</tr>
<tr>
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<td>53</td>
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<td>4</td>
<td>15</td>
<td>41 (5)</td>
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<tr>
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<td>4</td>
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<td>83</td>
<td>117</td>
<td>1222</td>
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<tr>
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<td>188</td>
<td>165</td>
<td>233</td>
<td>1429</td>
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Table 4.3. Permanova results for tree species communities sampled at highly impacted (Cypress Creek), moderately impacted (Starkey), non-impacted (Green Swamp) wetlands, and impacted but augmented wetlands (Cypress Creek).

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>Pseudo-F</th>
<th>P (perm)</th>
<th>Unique perms</th>
<th>P (MC)</th>
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<td>2.08E+05</td>
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<td>998</td>
<td>0.016</td>
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<tr>
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<td>1.25E+05</td>
<td>3.8736</td>
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<td>0.042</td>
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<tr>
<td>Mean Maximum Water Depth</td>
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<td>858.25</td>
<td>858.25</td>
<td>2.67E-02</td>
<td>0.867</td>
<td>997</td>
<td>0.877</td>
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<tr>
<td>Mean Ground Water Impact Factor</td>
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<td>1.34E+05</td>
<td>4.1773</td>
<td>0.038</td>
<td>999</td>
<td>0.037</td>
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<tr>
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<td>32380</td>
<td>32380</td>
<td>1.007</td>
<td>0.455</td>
<td>999</td>
<td>0.3974</td>
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<tr>
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<td>2.57E+05</td>
<td>32154</td>
<td>1.007</td>
<td>0.455</td>
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<td></td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
<td>7.57E+05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.1. Mean Ground Water Impact Factor of Wetlands highly impacted (Cypress Creek), moderately impacted (Starkey), non-impacted (Green Swamp) wetlands, and impacted but augmented wetlands (Cypress Creek). Error bars represent 95% Confidence Intervals.
**Figure. 4.2.** Distance Based Redundancy Analysis (dbRDA) for highly impacted (Cypress Creek), moderately impacted (Starkey), non-impacted (Green Swamp) wetlands, and impacted but augmented wetlands (Cypress Creek).
**Figure 4.3.** Mean density of Taxodium sp. and non-Taxodium tree species at Cypress Creek (CC), Starkey (S), Green Swamp (GS), and Augmented (AUG) wetlands. Error bars represent 95% Confidence Intervals.
**Figure 4.4.** Mean diameter at breast height (DBH) at Cypress Creek (CC), Starkey (S), Green Swamp (GS) wetlands, and Augmented (AUG). Mean Impact Factor (IF) for each group is depicted in (parenthesis). Different shaded bars represent different homogenous groups as identified by Scheffe’s test. Error bars represent 95% Confidence Intervals.
Figure 4.5. Mean density of standing dead trees (all species combined) observed at Cypress Creek, Starkey, Green Swamp, and Augmented locations. Different shaded bars represent different homogenous groups as identified by Scheffe’s test. Error bars represent 95% Confidence Intervals.
Figure 4.6. Distance Based Redundancy Analysis (dbRDA) for standing dead trees in highly impacted (Cypress Creek), moderately impacted (Starkey), non-impacted (Green Swamp) wetlands, and impacted but augmented wetlands (Cypress Creek).
Figure 4.7. Mean percent (%) of photosynthetically active radiation (PAR) at Cypress Creek (CC), Starkey (S), Green Swamp (GS) wetlands, and Augmented (AUG). Mean Impact Factor (IF) for each group is depicted in (parenthesis). Different shaded bars represent different homogenous groups as identified by Scheffe’s test. Error bars represent 95% Confidence Intervals.
Figure 4.8. Distance Based Redundancy Analysis (dbRDA) for ground cover communities (2011 – 2013) as described by Thurman et al. 2016 (b) in highly impacted (Cypress Creek), moderately impacted (Starkey), non-impacted (Green Swamp) wetlands, and impacted but augmented wetlands (Cypress Creek). Impact factor (IF), hydroperiod (HP), average water depth (AD), maximum water depth (MD), and % photosynthetically active radiation available (PAR) are included as covariates.
CHAPTER FIVE

GENERAL CONCLUSIONS

Increasing human populations and the withdrawal of ground water for human consumption continue to adversely affect wetland number and quality, despite efforts by regulatory agencies to prevent wetland loss (McCauley 2013). Reductions in hydrology, such as those associated with ground water extraction, are a common occurrence and affect countless wetlands. Many times these wetlands provide visual indicators of hydrologic changes through vegetation as these communities will fluctuate between flood and drought tolerant species as water levels increase and decrease, respectively. Observing these changes can allow time for the rapid identification of adverse impacts and allow time for hydrologic restoration.

The narrow range of hydrology where species in the ground cover strata were observed makes them ideal candidates for use as indicator species. While vegetation has been used as a hydrologic indicator previously, the lack of knowledge of the ecology of the species precluded their effective use. Ground cover vegetation can be used an indicator of hydrology 3-4 years prior (Armentano et al. 2006; Busch et al. 1998; David 1996; Nott et al. 1998; Ross et al. 2003), while canopy vegetation may take decades to respond. Adjusting species classifications to reflect the information presented in the current study will make wetland assessments considerably more accurate and useful. Additional changes in regulatory wetland assessment
methodology, such as developing a continuous scale system over a categorical one and including additional species, would also improve its accuracy and effectiveness of. As the impacts of climate change and human action become more evident on the hydrology of wetlands (Faulkner 2004; Kirtman et al. 2013; Mitsch and Gosselink 2007), many wetlands are likely to continue to decline in quality and quantity. Knowing the hydrology of the individual species allows assists wetland scientist in detecting vegetative response to hydrologic manipulation.

Reductions in ground water extraction were successful in shifting vegetation communities towards wetter species. Many wetlands had displayed declines or losses of key species such as *Juncus repens* and juvenile *Taxodium* sp.; however, as extraction volumes were reduced both of these species returned. These species had been absent for more than a decade prior to monitoring. The clear response of vegetation compared to hydrology highlights the potential of vegetation to be restored passively with no other intervention required. Continued monitoring is required however to help detect the effects of climate change. Ground water extraction is likely to increase globally into the future and uncontrolled may result in catastrophic losses of wetland communities, unless changes are made. In some cases such as ground water extraction, simply reducing the impact on a wetland may be sufficient to restore ground cover communities.

Ground water extraction displayed significant effects on tree species; however, these effects have taken decades to develop. Ground water extraction reduces wetland water levels and duration and has resulted in a shift from dominance by *Taxodium* sp. to non-wetland tree species such as oaks and pines. In many cases the non wetland tree species observed encroaching into cypress swamps were relatively young, despite the fact that the well fields had been pumped for more than 30 years prior to monitoring. *Taxodium* sp. remained the dominant
tree species in all wetlands; however, and no wetland had shifted into a new tree community type. This shift demonstrates the extended time required for changes in tree species to develop and the value of long term monitoring.

Extraction resulted in increased light availability as the wetland floor and in some cases light has been shown to be more important than hydrology in determining vegetation communities (Oldeman and van Dijk 1991; Sharpe and Shiels 2014; Schulten et al. 2014). As a result, ground water extraction may be resulting in an altered path of succession than may be assumed for ground cover species based upon conventional models. Typically, vegetation communities will shift towards more flood tolerant species during times of extended flood and upland species during periods of drought (Malecki et al., 1983; King 1995, Young et al., 1995). The changes in light availability may be having a significant effect on ground cover communities; however, the light requirements of most ground cover species have not been described.
References

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Nott MP; Bass OL; Fleming DM; Killeffer SE; Fraley N; Manne L; Curnutt JL; Brooks TM; Powell R; Pimm SL (1998) Water levels, rapid vegetational changes, and the endangered Cape Sable seaside-sparrow. Animal Conservation 1: 23-32.


