Hydrologic processes on tree islands in the Everglades (Florida, USA): tracking the effects of tree establishment and growth

Pamela L. Sullivan · René M. Price · Michael S. Ross · Leonard J. Scinto · Susana L. Stoffella · Eric Cline · Thomas W. Dreschel · Fred H. Sklar

Abstract The hydrodynamics of tree islands during the growth of newly planted trees has been found to be influenced by both vegetation biomass and geologic conditions. From July 2007 through June 2009, groundwater and surface-water levels were monitored on eight recently planted tree islands at the Loxahatchee Impoundment Landscape Assessment (LILA) facility in Boynton Beach, Florida, USA. Over the 2-year study, stand development coincided with the development of a water-table depression in the center of each of the islands that was bounded by a hydraulic divide along the edges. The water-table depression was greater in islands composed of limestone as compared to those composed of peat. The findings of this study suggest that groundwater evapotranspiration by trees on tree islands creates complex hydrologic interactions between the shallow groundwater in tree islands and the surrounding surface water and groundwater bodies.

P. L. Sullivan (✉) · R. M. Price · M. S. Ross · L. J. Scinto
Department of Earth and the Environment,
Florida International University,
Miami, FL 33199, USA
e-mail: sullivap@fiu.edu
Tel.: +1-305-3480281
Fax: +1-305-3483877

R. M. Price · M. S. Ross · L. J. Scinto · S. L. Stoffella
Southeastern Environmental Research Center,
Florida International University,
Miami, FL 33199, USA

E. Cline · T. W. Dreschel · F. H. Sklar
South Florida Water Management District,
Everglades Division,
West Palm Beach, FL 33406, USA

Introduction

Variation in groundwater evapotranspiration (ET_G) rates may be one of the largest driving factors in groundwater/surface-water interactions and, thus, the formation of landscape patterning across ecosystems of low topographic relief (Eppinga et al. 2008; Wetzel et al. 2005; Rietkerk et al. 2004). Groundwater/surface-water interactions strongly influence the chemistry of shallow groundwater and the location and patterns of vegetation in wetlands (Ferone and Devito 2004; Glaser et al. 1981). The Great Vasyugan Bog, Siberia, and the Okavango Delta, Botswana, are examples of wetlands comprised of raised ridges or islands that coincide with the presence of elevated ion and nutrient concentrations in groundwater and higher-order vascular plants, compared to the surrounding hollows and sloughs (Eppinga et al. 2008; McCarthy et al. 1998). A combination of positive and negative feedback mechanisms has been proposed for the formation of self-organizing patterns found in many wetlands (Rietkerk et al. 2004; Rietkerk and van der Koppel 2008). The hypothesis behind these feedbacks is that areas with high ET_G rates would lower the water table, creating an inward convective transport of nutrients and ions, which could increase the growth rate of biomass, and lead to an accelerated rate of soil accretion. The elevated ion and nutrient concentrations have a positive feedback on local biomass while negatively impacting vegetation at a greater distance by inhibiting their access to resources (Rietkerk and van der Koppel 2008). This hypothesis is supported by Engel et al.'s (2005) findings in the Pampas of South America, where sap-flow measurements and diurnal water-table fluctuations suggested that the ratio of ET_G to precipitation was greater in the tree plantation than in the surrounding grasslands. Furthermore, the increased ET_G coincided with a lowering of the water table and the development of elevated ion concentrations under the plantation (Jobbágy and Jackson 2007).

Similar feedback patterns may have led to the ridge-slough-tree-island topography of the Florida Everglades, USA (Fig. 1), where some of the highest soil and groundwater nutrient concentrations have been detected in tree islands. Gann et al. (2005) detected total soil phosphorus concentrations that were six-fold higher in tree islands (446 g kg^{-1}) compared to the adjacent marsh (78 g kg^{-1}). In addition, Ross et al. (2006) detected pore-water concentrations of soluble reactive phosphorus (SRP) to be two to three orders of magnitude higher in the tree islands compared to the surrounding marsh. Potential sources suggested for the high phosphorus concentrations detected in tree islands are the capture of dust from the atmosphere by the tree canopy, inputs of bird guano and bones (Coultas et al. 2008), and high ET$_G$ rates that increased inputs of high nutrient groundwater (Wetzel et al. 2005). High rates of ET$_G$ relative to recharge were again suggested as a driving factor when a diurnal drawdown in the water table was observed between sunrise and sunset on tree islands in the Everglades during the December–May dry season (Ross et al. 2006). Furthermore, the use of oxygen and hydrogen-stable isotopes of stem water, soil water and groundwater in a hardwood hammock tree island indicated that trees on such islands relied on groundwater during the dry season (Ewe et al. 1999). Less than 1% of the water utilized by trees was groundwater during the wet season, but during the dry season, groundwater constituted 86% of the water utilized. While nutrient concentrations, diel groundwater fluctuations, and groundwater isotopic values suggest a link between overlying vegetation and tree-island hydrodynamics, the impact of the ET$_G$ on tree-island groundwater/surface-water interactions has yet to be clarified.

Over the last century, the construction of canals, dikes and levees across the Everglades has led to drastic hydrologic changes, which have been linked to a 60 and 90% reduction in tree-island cover in Water Conservation Areas (WCA) 3 and 2, respectively (Sklar and van der Valk 2002) (Fig. 1). While such losses are sometimes attributable to fire, in many cases they result from extended periods of high surface-water levels, which have drowned trees and caused the loss of peat from the islands and ridges, and resulted in the accumulation of peat in sloughs (Sklar and van der Valk 2002). The loss of tree islands is a major concern in efforts to restore the Everglades because they harbor the highest plant and animal species diversity of the region (Gawlik et al. 2002). In addition, tree islands provide a topographic refuge for plant species that are non-flood tolerant and have high nutrient requirements (Davis and Ogden 1994).

The majority of the remaining tree islands in the Everglades are located in and around Shark Slough in the southern Everglades, the western edge of Water Conservation Area 3, and in Loxahatchee National Wildlife Refuge (LNWR, WCA-1) in the northern Everglades (Wetzel et al. 2005; Brandt et al. 2002). Though tree islands located in the northern and southern portions of the Everglades contain many of the same tree species, their underlying geology differs. In the southern Everglades, the limestone bedrock is very close to the soil surface. Most of the tree islands are thought to originate from limestone outcrops or mineral sediment mounds (Ross and Jones 2004). These tree islands are generally teardrop in shape and form a raised head and elongated tail oriented in the direction of surface-water flow. In LNWR, a thick layer of peat, 1.5–3.5 m deep, overwhelms any sign of the minor topographic change in the limestone bedrock. Tree islands in LNWR are of two types; typically small and round, or large and elongated in the direction of flow but without distinct tails (Brandt et al. 2000). The former group is known as "battery" tree islands that develop when a large piece of peat detaches from the bottom of a slough during high water levels (Stone et al. 2002). Although extensive studies have been conducted to define tree-island vegetation, shape, morphology, and surface-water dynamics, the relationship between tree-island hydrodynamics and the underlying geologic composition has not been well established.

The main objective of this research was to investigate the hydrodynamics of tree islands in their early stages of development. The project was conducted on constructed tree islands that were planted with tree saplings. Groundwater and surface-water levels were monitored over 2 years. Two types of tree islands were investigated: those that were constructed of peat, and others that were
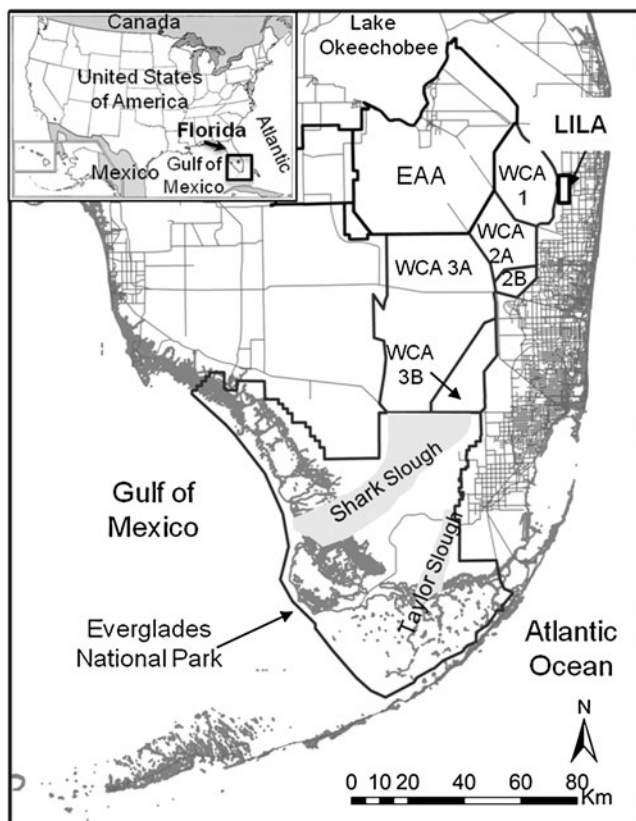

Fig. 1 Loxahatchee Impoundment Landscape Assessment (LILA) is located on the eastern edge of Water Conservation Area 1 (*WCA 1*), in Boynton Beach, Florida

constructed of limestone rubble with overlying peat. The effects of standing live biomass on ET_G rates and groundwater levels were also investigated.

Study site

Constructed in 2003, the Loxahatchee Impoundment Landscape Assessment (LILA) Facility represents a large physical model of the Everglades. LILA is located at the Arthur R. Marshall Loxahatchee National Wildlife Refuge, Boynton Beach, Florida (26º29.600′N, 80º13.000′W) and spans just over 34 ha (Fig. 1). LILA consists of four 8-ha macrocosms (M1 through M4), which mimic the Everglades ridge-and-slough and tree-island landscape features (Fig. 2). Each macrocosm contains two tree islands with different underlying geologic material, one consisting entirely of peat (peat islands) and one having a limestone rubble core overlaid by a thin layer of peat (limestone islands; van de Valk et al. 2008). The soil survey of the area classifies the peats in the LILA vicinity as 80% Okeelanta muck and 20% minor components (Natural Resources Conservation Service 2010). Each of the islands at LILA is approximately 43×71 m in size. The limestone tree islands were constructed of local limestone rubble extending approximately 7 m to the north and south and 24 m to the east and west of the center of the islands. The limestone rubble was buried about 31 cm beneath the peat and extended to a depth

about 91 cm (van der Valk et al. 2008). Over 700 saplings were planted on each tree island consisting of eight species common to the Everglades (Stoffella et al. 2010). Tree islands in M1 and M4 were planted in March 2006 (Planting-1), while the tree islands in M2 and M3 were planted in March 2007 (Planting-2).

The climate of the region is characterized by distinct wet (mid-May through October) and dry (November to mid-May) seasons with a 30-year annual average of 133 cm of precipitation (Ali et al. 2000). During the wet season, precipitation can be described as bimodal, with peaks in June and August. The surface-water levels in LILA are controlled to mimic those of the Everglades, with the highest surface-water levels occurring from September to January, flooding the tree islands, and the lowest surface-water levels occurring from April to June.

Materials and methods

Experimental design and water levels

Nine wells were drilled or augered into each of the eight tree islands; six wells were located on the edge of the islands while three were located in the center. The lithology of the sediments encountered during drilling was characterized. The wells had an average depth of 1.34±0.15 m and an average bottom elevation of 3.49±0.08 m (relative to the National Geodetic Vertical Datum of 1929, NGVD29). Each PVC-encased well had a diameter of 3.8 cm and a 0.6-m screen interval at the bottom. The two edge wells and one center well were equipped with In-Situ Level Troll 500 pressure transducers. Water levels in these wells were used to determine the effects of the proximity to the island's edge and the aboveground biomass on the water table and on ET_G rates.

A total of 28 wells were monitored from July 2007 to July 2009 (Fig. 2). Groundwater levels were recorded at 15-min intervals with the pressure transducers having an accuracy of 3.5 mm. Water pressure was corrected for water-specific gravity (0.99 as determined by a hydrometer) using the software provided by In-Situ. The elevation of the top of the PVC pipe was determined using a Wild Nak-2 level and stadia rod, which provided a 3-mm level of accuracy. The distance from the top of the PVC pipe to the bottom of the pressure transducer was measured to within 2 mm.

Surface-water stage was monitored at the eastern and western ends of each of the four 8-ha macrocosms, comprising a total of eight stations (Fig. 2). Surface-water stages were maintained according to an established hydrograph and surface-water levels were recorded every 15 min. Daily average surface-water levels were computed from the 15-min values. Surface-water levels at the center of the two tree island in each macrocosm were estimated from a linear interpolation between the surface-water stages on the eastern and western of the macrocosms. Hydraulic gradients were determined between the surface-water level and groundwater levels for the center of each
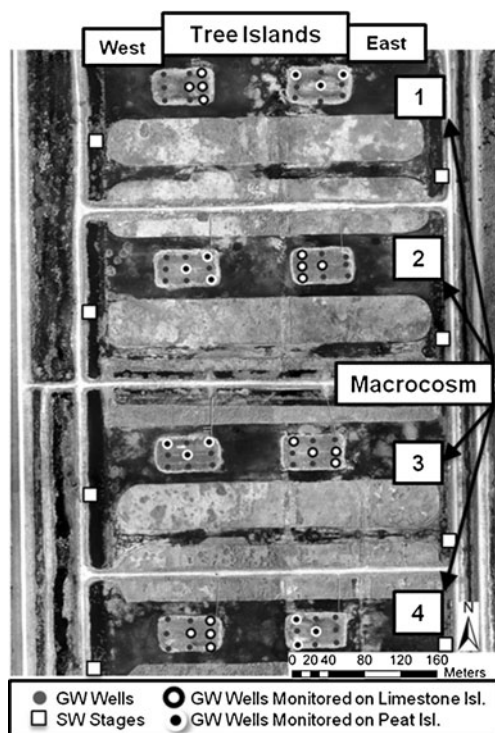

Fig. 2 LILA is comprised of four macrocosms that mimic the Everglades; each macrocosm has two tree islands with an underlying geology of either peat or limestone. Of the 72 wells at LILA, a total of 28 wells were monitored over the eight islands. *GW* groundwater; *SW* surface water

of the tree islands. Positive hydraulic gradients indicated groundwater discharging to the surface water while negative values indicated surface water recharging to the groundwater.

Daily rainfall values were collected from station LXWS (26°29′56.257″, 80°13′20.159″), located about 1 km from LILA, from July 2007 through June 2009. Daily values were summed to determine monthly totals. The monthly totals were compared to 30-year-average values obtained from rain gauge LWD.L28 (26°29′44.257″, 80°12′10.157″), located 1.8 km from LILA.

Groundwater evapotranspiration

White (1932) determined that a diurnal drawdown of the water table during daylight hours was a product of phreatophytic plants taking up groundwater and could be used to determine the average daily ET_G rate. The White method required that three assumptions be made: first, transpiration was negligible between midnight and 4:00 am; second, the diurnal water-table fluctuations were a result of groundwater uptake by plants and not a phenomena of pumping or recharge of the aquifer; and third, reasonable values of specific yield were obtained (Loheide et al. 2005; Healy and Cook 2002). The White method utilized the equation:

$$ET_G = S_y(\Delta s/t \pm r) \tag{1}$$

where the average daily loss of groundwater through evapotranspiration (ET_G) was the product of the specific yield (S_y), and the sum of the change in storage (Δs) per unit time (t) and the net recovery rate of the water table (r). The change in storage term was calculated by taking the difference between the water level at midnight on the day of interest and the water level at midnight 24 h later. Positive values indicated that there was a decline in the overall trend in the water table, while negative values indicated a rise in the water table. The net recovery rate of the water table was determined as the slope of the linear regression of the groundwater levels between midnight and 4:00 am (Fig. 3).

Specific yield

Laboratory and field methods were used to determine the readily available specific yield of the tree-island sediments. Polycarbonate tubes with a diameter of 5.08 cm were inserted in the center of the peat-based tree islands to collect soil cores. Three cores were obtained from a depth of 5–25 cm and two obtained from a depth 25–45 cm for a total five cores that had an average length of 15.06 cm. In the laboratory, each core was slowly submerged in water from the bottom to the top of the soil profile. Care was taken to ensure the entire column was saturated. Each core was oriented vertically and allowed to drain for 12 h. This time duration was chosen to attain the amount of water released over the diurnal fluctuation

time period (Meyboom 1967). The S_y was calculated based on the following expression (Meinzer 1923):

$$S_y = V_d/V_t \tag{2}$$

where the readily available specific yield (S_y) was the ratio of the volume of water that drained by weight (V_d), compared to the total volume of each core (V_t). Each core was tested twice ($n=10$) and the results were averaged to determine a mean S_y, and standard error.

Specific yield has been shown to increase with the depth of the water table in aquifers with a shallow water table, only reaching a stable value when the depth of the water table was approximately 2–3 m deep (Nachabe 2002; Loheide et al. 2005). To take this variability into account, the effective specific yield was also calculated using a modified version of the water table fluctuation method (Gerla 1992; Rosenberry and Winter 1997):

$$S_{ye} = P/\Delta h \tag{3}$$

where the effective specific yield (S_{ye}) was equal to the ratio of precipitation inputs (P) to the change in groundwater level (Δh). Precipitation data from rain gauge LXWS were used to determine P, while groundwater-level data from each of the wells were used to determine the Δh. Equation 3 required the assumptions that evapotranspiration, runoff, and subsurface flow were negligible over time and that the soil was above field capacity (Healy and Cook 2002). The effective specific yield was determined per rain event and averaged to obtain a monthly S_{ye} per well. The average monthly S_{ye} per well was then used in the White equation to calculate the average monthly ET_G per well.

Biomass

Allometric biomass equations were developed by collecting plant attributes (height, basal diameter and crown dimensions) and biomass data from individuals comprising the range of heights present in LILA tree islands (up to 5 m). The complete procedure and data analysis used to develop the equations is described in Stoffella et al. (2009). In the present work, a mixed-species regression model based solely on total height (measured on all individuals at 6-month intervals with a telescoping height pole) was used for biomass estimation. To compare biomass between the edges and centers of the islands, the biomass of each tree located within a 7-m radius around the monitoring wells was summed and divided by the area of the circle thereby circumscribed. On each island, two monitoring wells located on the edges of the islands were averaged to determined edge biomass while the biomass around the center monitoring well was used to represent the center biomass. The biomass at the center and the edges of islands were then averaged across all islands of similar geology and year of planting.
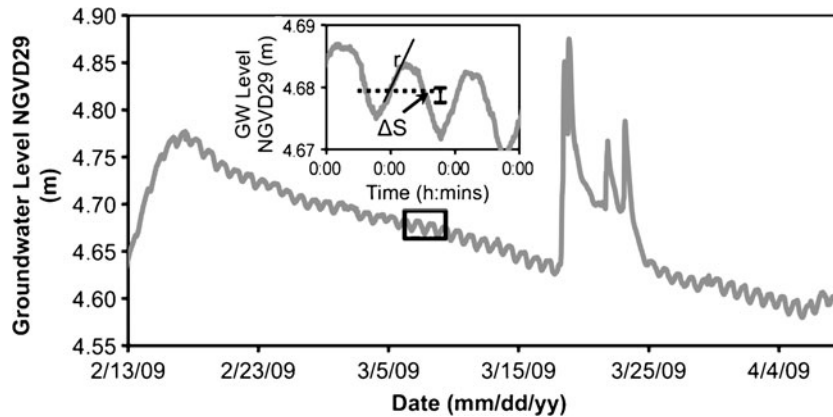
Fig. 3 Diurnal drawdown in groundwater levels from the center of a peat based island. Evapotranspiration from the groundwater (ET_G) was determined according to Eq. 1 using the slope between midnight and 4:00 am (r), the change in water level from midnight of the day of interest and the previous midnight (Δs) and the specific yield

Results

Lithology

The underlying substrate in the center of the peat and limestone-based tree islands substantially differed within the first meter of the ground surface (Fig. 4). At the center of the limestone islands, peat was detected to an average depth of 11 cm, and was underlain by limestone rubble that extended to an average depth of 59 cm (Stoffella et al. 2010). In all other areas on the limestone and peat islands the peat extended from the surface to a depth of at least 60 cm. Though most of the islands followed a similar lithologic pattern, clay was detected under the tree islands in M3. Over the entire expanse of the peat island in M3 (M3P), clay was detected at average depth of 67 cm and extended to 180 cm. On the limestone island (M3L), clay was only detected at the edges at an average depth of 171 cm, extended to 180 cm, and was overlain by 50 cm of sand. A combination sand and shell unit was detected under all of the islands at a starting depth of 60–80 cm (except M3P and M3L) and extended to a depth of at least 190 cm (Fig. 4). This unit consisted of coarse and fine sand with areas of compacted shell and is likely part of the Pamlico Sand Formation (Parker et al. 1955; Stone et al. 2002). Data from well logs in the surrounding area suggest that the depth to bedrock is approximately 3 m (Parker et al. 1955).

Precipitation and water levels

The total annual rainfall from July 2007 through June 2008 was 148.69 cm, slightly higher than annual rainfall from July 2008 through June 2009, which totaled 133.83 cm. The total annual rainfall in both years was below the 30-year annual average of 160.20 cm (see Fig. 1 in ESM). The largest amount of rainfall occurred between the end of May and October, typical of South Florida's wet season. In both years, the rainfall from November through January was substantially lower than the 30-year average.

Surface-water levels followed the seasonal rainfall patterns (see ESM Fig. 2). The highest surface-water levels occurred between September and December and the lowest levels typically occurred between March and June. From July 2007 through June 2009 surface-water levels ranged from 4.23 m to 5.15 m (see Fig. 2 in ESM). Surface-water levels in some of the macrocosms were occasionally lowered for short periods of time for experimental purposes. On average, the edges of the tree islands were inundated by surface water for 150 days from July 2007 to June 2008, and 186 days from July 2008 to June 2009.

The response of the water table to surface-water levels was similar on islands with similar geologic substrates (Table 1). Linear regressions between the surface-water levels and the groundwater levels on three of the peat-based islands (excluding M3P) indicated an almost one-to-one relationship between the two water bodies with an average slope of 1.03 (average $R^2=0.96$). For the limestone islands, the slope of a linear regression between groundwater levels (independent variable) and surface water averaged 0.86 (average $R^2=0.82$). The groundwater levels in peat tree island M3P, which contained some clay, responded to surface-water levels similarly to the limestone based islands, with a slope of 0.69 ($R^2=0.65$).
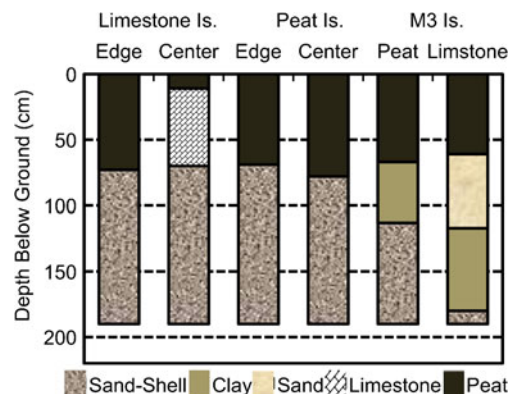

Fig. 4 The average sediment profile at the center and edges of the peat and limestone islands. In macrocosm 3 (*M3*) a thick layer of clay was observed across the peat island and at the edges of the limestone island

Table 1 Linear regression results between surface-water levels and groundwater in the center of the islands with differing geologic cores and locations (*E* East; *W* West). Regression results for the islands include: underlying geology, slope, standard error of the slope (*STE-slope*), intercept, standard error of the intercept (*STE-intercept*) and the square of the correlation coefficient (R^2)

Site	Island type	Slope	STE-slope	Intercept	STE-intercept	R^2
M3E	Peat	0.69	0.02	1.45	0.09	0.65
M1E	Limestone	0.82	0.02	0.80	0.09	0.72
M4E	Limestone	0.83	0.02	0.80	0.08	0.75
M2W	Limestone	0.86	0.01	0.48	0.07	0.93
M3W	Limestone	0.95	0.01	0.21	0.07	0.89
M4W	Peat	0.99	0.01	0.00	0.05	0.94
M2E	Peat	1.01	0.01	−0.16	0.03	0.97
M1W	Peat	1.10	0.01	−0.55	0.04	0.97

Throughout the 2-year study, the hydraulic gradient in the peat islands was always positive, ranged from 0.00 to 0.23, and averaged 0.05 (ESM Fig. 3). The average hydraulic gradient in the limestone islands (0.03) was similar to the peat islands but ranged from –0.24 to 0.47. The hydrologic responses of the peat tree islands were similar with the exception of M3P where the hydraulic gradient ranged from –0.11 to 0.27, and averaged 0.02. The hydrologic responses of all four limestone tree islands were similar. This report will focus on the groundwater/surface-water interactions on the peat and limestone tree islands in M1 (Fig. 5), with the understanding that similar responses were observed in the tree islands of the other three macrocosms.

From July 2007 through June 2009, the average daily groundwater level in the centers of the peat and limestone tree islands in M1 reached a maximum of 5.19 m (NGVD29). Minimum daily groundwater levels of 4.39 and 4.12 m were observed in the peat and limestone tree islands, respectively. During this same period the surface-water levels ranged from 4.26 to 5.15 m and averaged 4.60 for 2007–2008 and 4.70 m for 2008–2009. The highest water levels occurred between August and November, while lowest water levels typically occurred between March and May. Though groundwater levels in the center of the peat island were always elevated compared to surface water, groundwater level in the center of the limestone island was lower than the surface water when the surface-water level and precipitation inputs were low (Fig. 5).

Groundwater levels from three wells on each island were normalized to the surface-water levels and graphed to characterize the shape of the water table (Fig. 6). From July 2007 through June 2008, the water table was typically elevated in the center compared to the edges in both the peat and limestone tree islands (Fig. 6). From July 2007 through June 2009, the groundwater levels at the edges of the islands were always elevated compared to the surface water. However, from July 2008 through June 2009, the groundwater levels were lower in the center compared to the edges, which caused a hydraulic divide to be established along the edge of the tree islands (Fig. 6). The hydraulic divide first appeared on the limestone islands 1.3 years after the trees were planted, but was not sustained year round until 2.3 years after planting. On the peat islands, the hydraulic divide did not occur until 2.5 years after planting. The development of a water-table depression in the center on the islands led to a shift in the dominant direction of horizontal groundwater flow. During this period, groundwater flowed from the edges of the islands to the center of the islands as well as toward the surrounding surface water (Fig. 6). The greatest water-table drawdown occurred in the center of the limestone islands, averaging 6.33 cm lower than the edges and ranging from 0.16 to 18.05 cm. The center of the peat island had a much lower average drawdown of 1.21 cm compared to the edges and ranged from 0.12 to 2.01 cm.
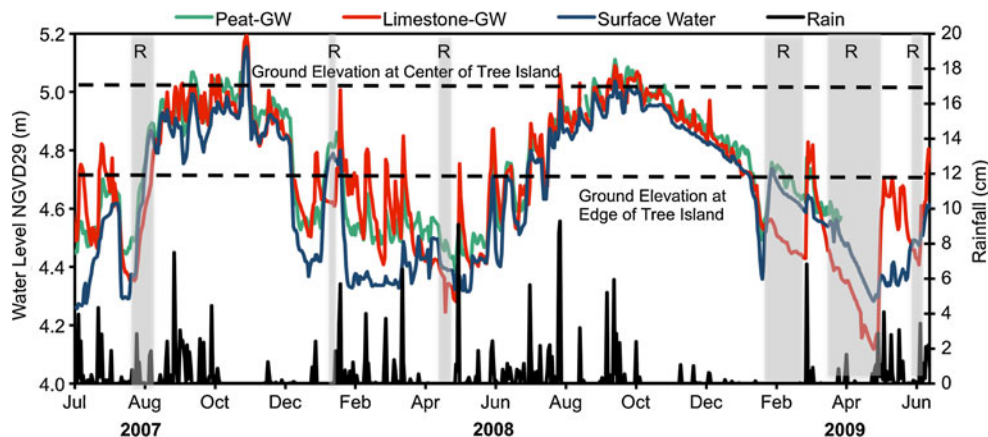

Fig. 5 Surface water (*black*) and groundwater levels from the center of the peat (*green*) and limestone (*red*) based tree islands in M1 from July 2007 through June 2009. The *gray boxes* indicate periods of groundwater recharge (*R*) by surface water on the limestone tree island
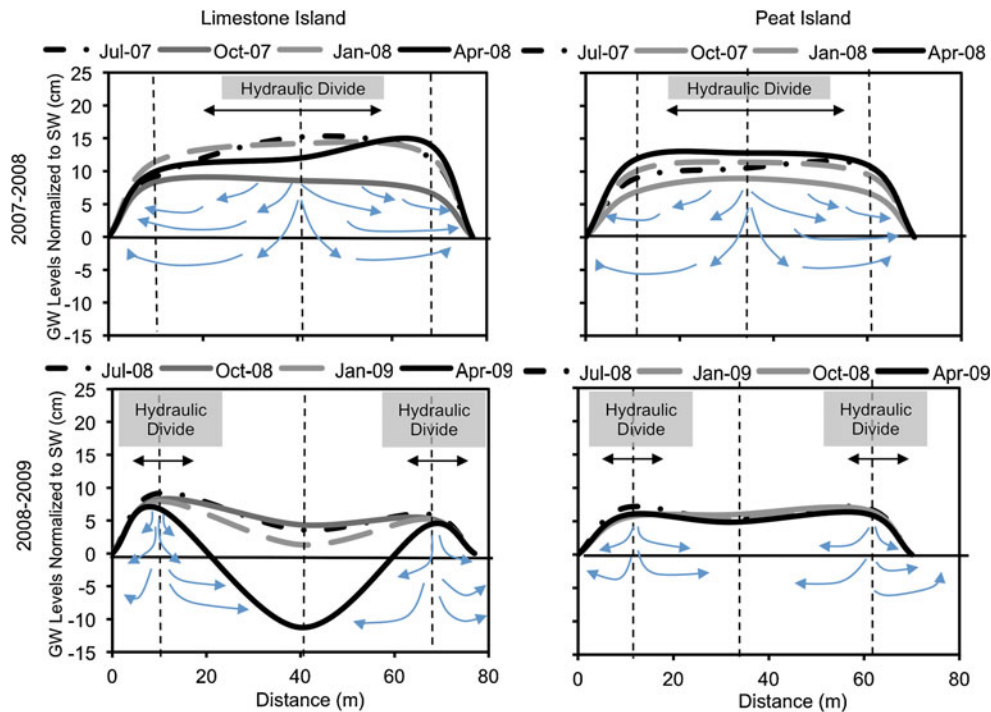
Fig. 6 Groundwater (*GW*) levels were normalized to surface water (*SW*) to depict the water table across the limestone (*left panel*) and peat (*right panel*) tree islands. The *horizontal solid line* at the value of zero represents the surface water, while the *vertical dashed lines* represent the well locations. For July 2007–April 2008 (*top row*) the dominant direction of groundwater flow was from the center of the islands toward the edges. A hydraulic divide developed on the edges of islands for July 2008–April 2009 (*bottom row*). *Blue arrows* indicate direction of groundwater flow

Specific yield

The average S_y obtained from the soil cores on the peat based tree islands was 0.15 ± 0.04 and ranged from 0.01 to 0.38. The S_{ye} values were similar to those obtained from the soil cores with an average of 0.15 and ranged from 0.01 to 0.40 (see Fig. 4 in ESM). The average S_{ye} for the center of the peat tree islands was elevated compared to the center of the limestone tree islands with values of 0.13 ± 0.01 and 0.10 ± 0.01, respectively. When the S_{ye} values were grouped according to location (edge or center), the S_{ye} in the center of the tree islands increased with depth to water for water-table depths greater than 20 cm below the ground surface (see Fig. 4 in ESM). Values of S_{ye} increased from 0.03 to 0.20 when the water table declined from 20 to 60 cm below the ground surface. When the depth to the water table was less than 20 cm below the ground surface, no relationship was detected between the depth to water and the S_{ye} at either the center or the edges of the islands.

Groundwater evapotranspiration

The average daily ET_G values per month for all wells averaged 3.69 mm d^{-1} and ranged from 0.27 to 14.23 mm d^{-1}. During the first year of this study, the average ET_G was 4.02 mm d^{-1} with the most elevated values detected in September, May and June with the lowest values detected in November and December. During the next year, the average ET_G was slightly lower

with an average ET_G of 3.47 mm d^{-1}. During this period, the highest values were detected in April, May, and August while the lowest values were detected in December, January and February. When the ET_G values were grouped according to both location (edge vs center) and underlying sediments, the average annual ET_G was similar on the edge of the peat and limestone tree islands, with values 3.84 and 3.87 mm d^{-1}, respectively.

Due to annual high water levels that inundated the edges of the islands from September through December, ET_G values could not be calculated using the White method for wells in those locations. Therefore, the ET_G of the center and edges of the islands could only be compared for months when data were available from all locations. The average annual ET_G for the center of the limestone islands, 4.02 mm d^{-1}, was elevated compared to the center of the peat islands, 3.06 mm d^{-1}. Typically, the center of the limestone islands had the elevated average daily ET_G value per month compared to the edges, which were elevated compared to the center of the peat islands (Fig. 7).

Biomass

The accrual of aboveground tree biomass on all islands showed a strong seasonal pattern with relatively little growth occurring between September and March, followed by higher growth from March to September. In addition, the rate of biomass accumulation increased on all islands during the last year. From March 2007 through
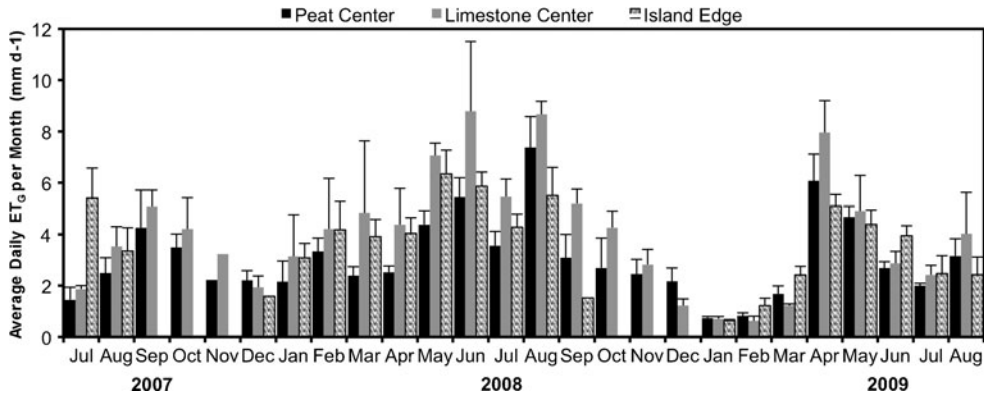
Fig. 7 Average daily evapotranspiration from groundwater (ET$_G$) per month for the center of the peat (*black*) and limestone (*gray*) islands compared to the edges (*striped*)

September of 2009 the aboveground biomass more than doubled on the edges of the islands while in the center of the islands the biomass increased by nearly six-fold. From March 2007 to March 2008, the average aboveground biomass on the edges of the limestone islands was similar to that of the center, with a difference of 0.01 tonnes per hectare (t ha^{-1}) on the Planting-1 islands and 0.12 t ha^{-1} on the Planting-2 islands (Fig. 8). During this same period the average aboveground biomass in the center of the Planting-1 peat islands was substantially elevated compared to the edge, with a difference of 0.77 t ha^{-1}, while little difference in the aboveground biomass was detected between the center and edge of the Planting-2 peat islands (Fig. 8). From September 2008 to September 2009, the biomass in the center of all of the islands was elevated compared to the edges by at least 0.60 t ha^{-1}, with the greatest difference detected between the center and edge of the peat islands (Fig. 8).

Discussion

Soil cores and depth to bedrock probes of the heads of tree islands indicate that 1.5–3.5 m of peat separate the top of
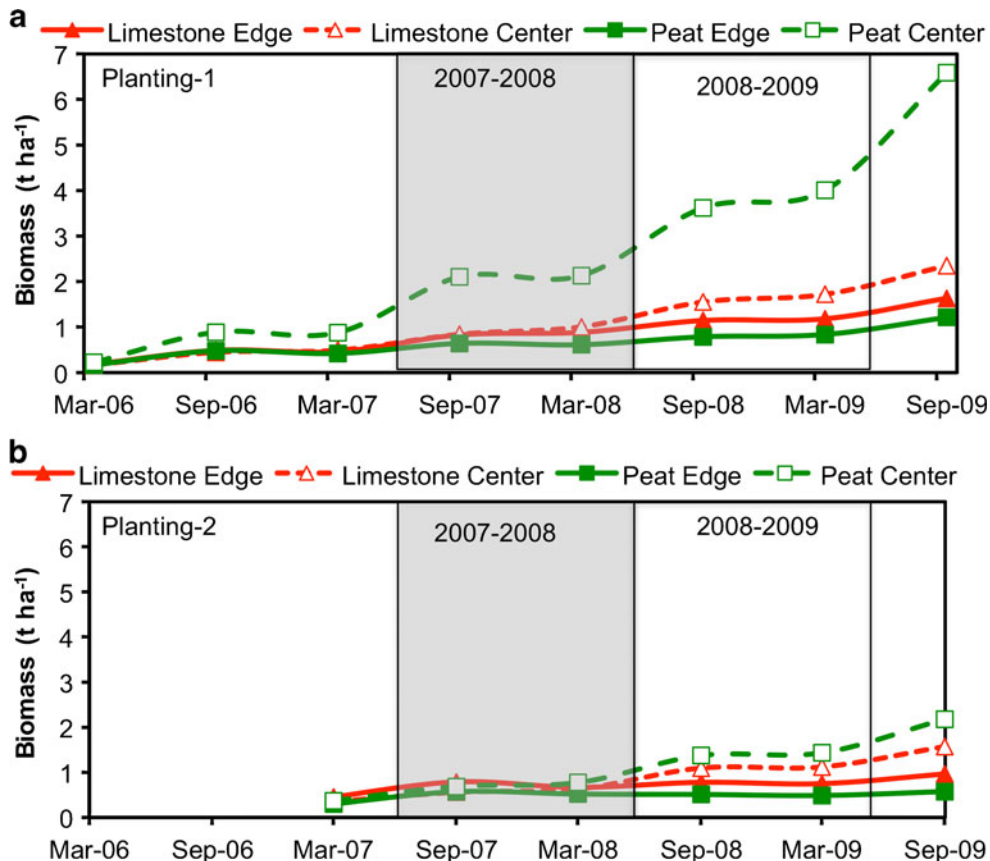

Fig. 8 Aboveground biomass (t ha^{-1}) predicted from mixed-species regression model based on height for four different combinations of substrate type and ground elevation in tree islands of macrocosms **a** M1, M4, **b** M2, M3

the tree islands from the underlying bedrock in the northern Everglades, while only 25–90 cm peat overlies the mineral substrate or bedrock in the central and southern Everglades (Brandt et al. 2002; Mason and van der Valk 2002; Stone et al. 2002; Schwadron 2006). With similar thickness in the overlying peat, the peat trees islands at LILA seem to mimic those of the Water Conservation Area 3, located in the central portion of the Everglades (Mason and van der Valk 2002). Furthermore, the limestone islands at LILA may be similar to a number of fixed islands in Everglades National Park such as Crandon and Sour Orange hammocks. On these islands, 25–50 cm of organic coarse loamy soil separated the top of the islands from a 40–75 cm thick mineralized or calcrete layer that was underlain by a 50-cm thick layer of dense-black-earth midden before reaching bedrock (Graf et al. 2008; Coultas et al. 2008). Although the thickness of overlying peat, presence of a calcrete layer, and depth to bedrock vary widely between tree islands of the Everglades, the variability in tree-island stratigraphy is captured in the constructed islands at LILA.

The range in the hydraulic gradients from the limestone tree islands at LILA (–0.24 to 0.47) was greater than values previously reported in the Everglades. The highest published hydraulic gradient was 0.10 measured adjacent to a levee road (Harvey et al. 2004). However, the average hydraulic gradients measured on the peat (0.05) and limestone (0.03) tree islands at LILA were similar to a value of 0.02 reported in the interior of the Water Conservation Area 2 (Harvey et al. 2000), but significantly greater than a hydraulic gradient of 0.005 reported for Taylor Slough (Harvey et al. 2004). The large variability in the hydraulic gradients observed in the tree islands at LILA were most likely due to the managed surface-water level, which was sometimes raised or lowered quickly to accommodate other studies or to stay on the operational hydrograph.

The S_{ye} values at LILA varied greatly (0.10–0.27) when the water table was within 20 cm of the ground surface, while the S_{ye} values increased from 0.03 to 0.20 with water-table depth deeper than 20 cm. Though slightly elevated, specific yield modeling results of Everglades peat showed similar patterns to those at LILA. When the water table was within 15–20 cm of the ground surface, the specific yield values were highly variable and ranged from 0.1–0.5, but when the depth of the water table was greater than 20–30 cm, the specific yield increased with depth to 0.2 (Sumner, 2007). The readily available specific yields of mineral soils were also found to increase with water-table depth when the water table was within 1 m of the ground surface (Loheide et al. 2005), though the reverse was observed in peat soils (Boelter 1965; Heloitis 1989). The increase in S_{ye} with water-table depth, at depths greater than 20 cm, on the islands at LILA may be attributed to the sand-shell layer that underlies the peat on all of the islands.

The ET_G rates at LILA followed a seasonal pattern and monthly mean akin to those of a forested area with a shallow water table examined in Hillsborough County, Florida (Nachabe et al. 2005); using the White method, these authors found that the average daily ET_G per month in the forest ranged from 0.1 to 7.8 mm d^{-1}, with the highest rates detected in May through July. Lysimeter data for the Everglades Nutrient Removal project, 25 km from LILA, showed seasonal evapotranspiration patterns analogous to the ET_G rates at LILA, with the highest rates detected between May and July, but with a much smaller range, exhibiting values of 1.9 to 5.8 mm d^{-1} (Abtew 1996). Using the energy budget method, German and Sumner (2002) calculated rates of evapotranspiration that ranged from 1.69 to 5.92 mm d^{-1} during a drought year in a sawgrass area of Blue Cypress Marsh, located north of Loxahatchee. The average daily ET_G per month detected in the summer of 2008 at LILA were elevated compared to data reported by Abtew (1996) and German and Sumner (2002). The large range in specific yield values that occurred when the water table was close to the ground surface may have led to an over estimation of ET_G during the wet season.

The greater ET_G rates in the center of the limestone tree islands compared to the peat islands may be attributed to variations in the overlying biomass. Stoffella et al. (2010) found that the height of the trees increased in the peat tree islands with increasing elevation. Furthermore, they noted from aerial photos that fewer ruderal herbs and shrubs persisted in the center of the peat tree islands compared to the limestone. The lower ET_G rates in the center of the peat-based islands may be attributed to increased shading, lower air and soil temperatures, development of a litter layer and the reduced air flow associated with the greater aboveground tree biomass (Le Maitre et al. 1999; Holmgren et al. 1997).

In addition to the amount of aboveground biomass more than doubling from 2007–2008 to 2008–2009, the distribution of the aboveground biomass also changed. In 2007–2008 the aboveground biomass was equally distributed between the edge and center for most of the islands while for 2008–2009, the center of the islands had at least 1.5 times more aboveground biomass compared to the edges. Over the same time period, a shift occurred in the groundwater flow direction in the islands. For 2007–2008 groundwater consistently flowed radially away from the center of the islands toward the edges where it discharged to the surface water. In 2008–2009, the water table in the center of the islands was depressed compared to the edges, which created a hydraulic divide along the edge of the islands. From this divide, groundwater flowed in two directions; one from the edges of the island toward its center, and the other from the edges of the island to the surface water (Fig. 6). Though the average monthly ET_G rates slightly decreased from 2007–2008 to 2008–2009 on both island types, the aboveground biomass increased. This increment was particularly high in the center of the peat tree islands where biomass increased 5.7 t ha^{-1} in Planting-1 islands and 1.8 t ha^{-1} in Planting-2 (Fig. 8). An increase in aboveground biomass would be expected to increase transpiration, but could have also increased shading, reduced soil temperatures and increased humidity, all of which would reduce evaporation. Lauenroth and

Bradford ([2006](#)) found that as the biomass in a short grass steppe in Colorado increased, the ratio of evaporation to evapotranspiration decreased significantly while the ratio of transpiration to evapotranspiration increased.

Though the average monthly ET_G rates on the islands at LILA were similar from the first to the second year of the study, there was a large increase in the biomass specifically in the center of the islands, which may suggest that the ratio of transpiration to evaporation increased. The likely increase in transpiration rates is further supported by the drawdown detected in the water table in the center of the tree islands. Given that the White method was used to calculate evapotranspiration from below the water table, an increase in ET_G in the center of the island would not be captured if the trees relied more on unsaturated zone groundwater. These results suggest that measuring ET_G by the White method may not be sufficient for comparing interactions within the ridge-slough-tree-island continuum. In the future, the estimation of ET_G in the tree islands could be improved by taking sap-flow measurements.

The larger drawdown in the water table in the limestone islands compared to the peat islands may be attributed to the hydraulic properties of the island sediments. Harvey et al. ([2004](#)) found that the hydraulic conductivity of peat in WCA 2, just southwest of LILA, was substantially lower than that of the underlying limestone bedrock with average values of 60 and 9,000 cm d^{-1}, respectively. The limestone rubble cores on the tree islands at LILA, likely do not reflect that of the underlying bedrock and may have a hydraulic conductivity lower than that of the peat due to the mixture of peat and limestone rubble. Kamann et al. ([2007](#)) found that the permeability of a pebble layer decreased with increased proportions of sand, with the pebbles reaching a permeability less than that of the sand when mixtures were comprised of less than 60% pebbles. A potentially lower hydraulic conductivity of the limestone islands compared to the peat islands may explain the larger drawdown observed in the center of the limestone islands.

Local, intermediate and regional groundwater flow paths have been attributed to topography, geology (i.e., hydraulic conductivity) and precipitation, where topographic highs tend to dominate local flow patterns (Tóth [1963](#); Sopocleous [2002](#)). Although the tree islands are only slightly raised above the surrounding landscape (≤1 m), the data from LILA suggest that complex and dynamic groundwater flow patterns can develop within them. The development of the hydraulic divide along the edges of the tree islands suggests reduced groundwater/surface-water interactions at a shallow (local) depth. The observed cone of depression in the center of the islands supports the possibility of a slightly deeper (intermediate) flow path of groundwater from beneath the slough into the tree island as induced by trees' transpiration, similar to what has been suggested by Ross et al. ([2006](#)). The results of this study also suggest that the hydrologic conditions in tree islands are dependent upon the inputs of precipitation and outputs of ET_G, and well as water levels and geologic conditions. Future modeling efforts would assist in providing a better understanding of these relationships.

The hydrodynamic conditions observed in the 2 years of this study lends support to the hypothesis that variations in ET_G across ecosystems can be a large driving factor in landscape patterning, especially in the Everglades (Eppinga et al. [2008](#); Rietkerk et al. [2004](#); Wetzel et al. [2005](#)). In addition to the change in groundwater-flow patterns, the variation in the underlying geologic conditions played a large role in the size of the water-table drawdown, particularly in the limestone islands. Similar to the islands at LILA, the underlying geology of the tree islands in the Everglades varies from the north and south and may in part explain the southerly increase in nutrient and ion concentrations detected in tree islands (Wetzel et al., Smith College, Biogeochemical processes on tree islands in the Greater Everglades: initiating a new paradigm, 2010). The observed water-table drawdown in the center of the tree islands at LILA indicates ET_G is a dominant process that creates a natural sink in the center of the islands where the exclusion of ions through transpiration and advective transport could lead to the concentration of ions and nutrients within the center of the tree islands.

Conclusions

In summary, the data from LILA suggest that overlying vegetation and underlying geologic conditions play a large role in the hydrologic conditions of tree islands. For 2007–2008, the groundwater levels indicate that the dominant direction of groundwater flow was from the center of the islands to the edges. Between the first and second year of the study, the amount of aboveground biomass nearly doubled. With this doubling of biomass, a water-table depression developed in the center of all of the islands and created a hydraulic divide along the edge of the island, which led to varying groundwater flow paths. The groundwater drawdown was larger in the limestone islands compared to the peat islands. The fast response in the water table with the growth of juvenile trees was unexpected, but provides insight into the formation and possible reconstruction of tree islands of the Everglades.

References

Abtew W (1996) Evapotranspiration measurements and modeling for three wetland systems in South Florida. Water Resour Bull 32(3):465–473

Ali A, Abtew W, Van Horn S, Khanal N (2000) Temporal and spatial characterization of rainfall over Central and South Florida. J Am Water Resour Assoc 36(4):833–848

Boelter HD (1965) Hydraulic conductivity of peats. Soil Sci 100(4):227–231

Brandt LA, Portier KM, Kitchens WM (2000) Patterns of change in tree islands in Arthur R. Marshall Loxahatchee national wildlife refuge from 1950–1991. Wetlands 20(1):1–14

Brandt LA, Siliveria JE, Kitchens WM (2002) Tree islands of Arthur R. Marshall Loxahatchee National Wildlife Refuge. In: Sklar FH, van der Valk AG (eds) Tree islands of the Everglades. Kluwers, Dordecht, The Netherlands

Coultas CL, Schawrdon M, Galbraith JM (2008) Petrocalcic horizon formation and prehistoric people's effect on Everglades tree island soils, Florida. Soil Surv Horiz 49(1):16–21

Daivs SM, Ogden JC (1994) Everglades: the ecosystem and it restoration. St. Lucie, Boca Raton, FL

Engel VC, Jobbágy EG, Stieglitz M, Williams M, Jackson RB (2005) Hydrological consequences of Eucalyptus afforestation in the Argentine Pampas. Water Resour Res 41, W10409, 14 pp

Eppinga MB, Rietkerk M, Borren W, Lapshina ED, Bleuten W, Wassen MJ (2008) Regular surface patterning of peatlands: confronting theory with field data. Ecosystems 11:520–536

Ewe SML, da Silveira Lobo Sternberg L, Busch DE (1999) Water-use patterns of woody species in pineland and hammock communities of South Florida. For Ecol Manage 118:139–148

Ferone JM, Devito KJ (2004) Shallow groundwater-surface water interactions in pond-peatland complexes along Boreal Plains topographic gradient. J Hydrol 292:75–95

Gann TGT, Childers DL, Randeaau DN (2005) Ecosystem structure, nutrient dynamics, and hydrologic relationships in tree islands of the southern Everglades, Florida, USA. For Ecol Manage 214:11–27

Gawlik DE, Gronemyer P, Powell RA (2002) Habitat-use patterns of avian seed dispersers in the central Everglades. In: Sklar FH, van der Valk AG (eds) Tree islands of the Everglades. Kluwer, Dordecht, The Netherlands

Gerla PJ (1992) The relationship of water table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands. Wetlands 12(2):91–98

German ER, Sumner DM (2002) Evapotranspiration rates from two different sawgrass communities in South Florida during drought conditions. Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, NV, 28 July–1 August 2002, 12 pp

Glaser PH, Wheeler GA, Gorham E, Wright HE Jr (1981) The patterned mires of the Red Lake peatland, northern Minnesota: vegetation, water chemistry, and landforms. J Ecol 69(2):575–599

Graf MT, Schwadron M, Stone PA, Ross M, Chmura GL (2008) An enigmatic carbonate layer in Everglades tree island peats. EOS Trans AGU 89(12):117–124

Harvey WJ, Jackson JM, Mooney RH, Choi J (2000) Interaction between ground water and surface water in Taylor Slough and Vicinity, Everglades National Park, South Florida. US Geol Surv Open-File Rep 00–483

Harvey WJ, Krupa SL, Krest JM (2004) Ground water recharge and discharge in the central Everglades. Ground Water 47(7):1090–1102

Healy WR, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeol J 10:91–109

Heliotis FD (1989) Water storage capacity of wetland used for wastewater treatment. J Environ Eng 115(4):822–834

Holmgren M, Scheffer M, Huston AM (1997) The interplay of facilitation and competition of plant communities. Ecology 78(7):1966–1975

Jobbágy EG, Jackson RB (2007) Groundwater and soil chemical changes under phyreatophytic tree plantations. J Geophys Res 112(G0213):1–15

Kamann PJ, Ritzi RW, Dominic DF, Conrad CM (2007) Porosity and permeability in sediment mixtures. Ground Water 45(4):429–438

Lauenroth WK, Bradford JB (2006) Ecohydrology and the partition AET between transpiration and evaporation in semiarid steppe. Ecosystems 9:756–767

Le Maitre DC, Scott DF, Colvin C (1999) A review of information on interactions between vegetation and groundwater. Water S A 25(2):137–152

Loheide SP II, Butler JJ Jr, Gorelick SM (2005) Estimating groundwater consumption by phreatophytes using diurnal water table fluctuations: a saturated-unsaturated flow assessment. Water Resour Res 40, W07030

Mason DH, van der Valk A (2002) Vegetation, peat elevation, and peat depth on two tree islands in Water Conservation Area-3A. In: Sklar FH, van der Valk AG (eds) Tree islands of the Everglades. Kluwer, Dordecht, The Netherlands

McCarthy TS, Ellery WN, Danergfield JM (1998) The role of biota in the initiation and growth of islands on the floodplain of the Okavanga Alluvial Fan, Bostwana. Earth Surf Process Land 23:281–316

Meinzer OE (1923) The occurrence of groundwater in the United States with a discussion of principles. US Geol Surv Water Suppl Pap 489

Meyboom P (1967) Groundwater studies in the Assiniboine River drainage basin: part II, hydrologic characteristics of phyreatophytic vegetation in south-central Saskatchewan. Geol Surv Canada Bull 139

Nachabe MH (2002) Analytical expressions for transient specific yield and shallow water table drainage. Water Resour Res 38(10):1193–1204

Nachabe M, Shah N, Ross M, Vomacka J (2005) Evapotranspiration of two vegetation covers in shallow water table environment. Soil Sci Soc Am J 69:429–499

National Resources Conservation Survey (2010) Web soil survey, national cooperative soil survey. National Resources Conservation Survey, Washington, DC. http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. Cited 21 March 2010

Parker GG, Ferguson GE, Love SK et al (1955) Water resources of southeastern Florida with special reference to the geology and ground water of the Miami area. US Geol Surv Water Suppl Pap 1255

Rietkerk M, van der Koppel J (2008) Regular pattern formation in real ecosystems. Trends Ecol Evol 23(3):169–176

Rietkerk M, Dekker SC, Wassen MJ, Verkroost AWM, Bierkens MFP (2004) A putative mechanism for bog patterning. Am Naturalist 163(5):699–708

Rosenberry DO, Winter TC (1997) Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. J Hydrol 191:266–289

Ross MS, Jones DT (2004) Tree islands in the Shark Slough landscape: interactions of vegetation, hydrology and soils. Final report, Submitted to the Everglades National Park, Homestead, FL, 196 pp

Ross MS, Mitchell-Brucker S, Sah JP, Stothoff S, Ruiz PL, Reed DL, Jayachandran K, Coultas CL (2006) Interaction of hydrology and nutrient limitation in ridge and slough landscape of southern Florida. Hydrobiology 569:37–59

Schwadron M (2006) Everglades tree islands prehistory: archeological evidence for regional Holocene variability and early human settlement. Antiquity 80(310)

Sklar FH, van der Valk A (2002) Tree islands of the Everglades: an overview. In: Sklar FH, van der Valk AG (eds) Tree islands of the Everglades. Kluwer, Dordecht, The Netherlands

Sophocleous M (2002) Interactions between groundwater and surface water: the state of science. Hydrogeol J 10:52–67

Stoffella SL, Ross MS, Sah J, Ruiz P, Lopez l, Colbert N, Dodge C, Heinrich J Trujillo D (2009) Estimating biomass production and nutrient concentrations of tree species growing along hydrologic gradient on LILA tree islands Biomass Estimation. Report to the South Florida Water Management District. SFWMD, West Palm Beach, FL, 12 pp

Stoffella SL, Ross MS, Sah JP, Price MP, Sullivan PL, Cline AE, Scinto LJ (2010) Survival and growth responses of eight Everglades tree species along an experimental hydrologic gradient on two tree island types. Appl Veg Sci. doi:10.1111/j.1654-109X.2010.01081.x

Stone PA, Gleason PJ, Chmura GL (2002) Bayhead Tree Islands on deep peats of the northeastern Everglades, chapter 3. In: Sklar FH, van der Valk AG (eds) Tree islands of the Everglades. Kluwer, Dordecht, The Netherlands

Sumner DM (2007) Effects of capillarity and microtopography on wetlands specific yield. Wetlands 27(3):693–701

Tóth J (1963) A theoretical analysis of groundwater flow in a small drainage basin. J Geophys Res 68(16):4795–4812

van der Valk AG, Wetzel P, Cline E, Sklar FH (2008) Restoring Tree Islands in the Everglades: experimental studies of tree seedling survival. Restor Ecol 16(2):281–289

Wetzel PR, van der Valk AG, Newman S, Gawlik DE, Gann TT, Coronado-Moliana CA, Childers DL, Sklar FH (2005) Maintaining tree islands in the Florida Everglades: nutrient redistribution is the key. Front Ecol Environ 3(7):370–376

White WN (1932) A method of estimating ground-water supplies based on discharge by plants and evaporations from soils: results of investigations in Escalante Valley, Utah. US Geol Surv Water Suppl Pap 659-A