

# The role of recharge and evapotranspiration as hydraulic drivers of ion concentrations in shallow groundwater on Everglades tree islands, Florida (USA)

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## Abstract:

Recently, evapotranspiration has been hypothesized to promote the secondary formation of calcium carbonate year-round on tree islands in the Everglades by influencing groundwater ions concentrations. However, the role of recharge and evapotranspiration as drivers of shallow groundwater ion accumulation has not been investigated. The goal of this study is to develop a hydrologic model that predicts the chloride concentrations of shallow tree island groundwater and to determine the influence of overlying biomass and underlying geologic material on these concentrations. Groundwater and surface water levels and chloride concentrations were monitored on eight constructed tree islands at the Loxahatchee Impoundment Landscape Assessment (LILA) from 2007 to 2010. The tree islands at LILA were constructed predominately of peat, or of peat and limestone, and were planted with saplings of native tree species in 2006 and 2007. The model predicted low shallow groundwater chloride concentrations when inputs of regional groundwater and evapotranspiration-to-recharge rates were elevated, while low evapotranspiration-to-recharge rates resulted in a substantial increase of the chloride concentrations of the shallow groundwater. Modeling results indicated that evapotranspiration typically exceeded recharge on the older tree islands and those with a limestone lithology, which resulted in greater inputs of regional groundwater. A sensitivity analysis indicated the shallow groundwater chloride concentrations were most sensitive to alterations in specific yield during the wet season and hydraulic conductivity in the dry season. In conclusion, the inputs of rainfall, underlying hydrologic properties of tree islands sediments and forest structure may explain the variation in ion concentration seen across Everglades tree islands. Copyright © 2012 John Wiley & Sons, Ltd.

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## INTRODUCTION

The availability, demand and flow of water across ecosystems are naturally governed by the interaction of climate, hydrogeology and vegetation (Rodríguez-Iturbe *et al.*, 2001; Jobbágy and Jackson, 2007; Muneerakul *et al.*, 2008; Noretto *et al.*, 2008). The unique patterns of vegetation occurring across savannas, tundras and wetlands have been attributed to the heterogeneity of soil type and topography, as well as plant morphology and vegetation structure. The hydrologic properties of geologic materials (porosity ( $n$ ), specific yield ( $S_y$ ), specific retention ( $S_r$ ) and hydraulic conductivity ( $K$ )) govern infiltration, moisture content, flow of water and water table position at both a local and regional scale (Nimmo, 2004); while vegetation structure and morphology (leaf area index, canopy roughness and rooting strategy and depth) govern evapotranspiration rates and influence soil properties and moisture on a local scale (Angers and Caron, 1998; Jobbágy and Jackson,

2007; Asbjornsen *et al.*, 2011). Across humid landscapes, patterns of vegetation have been attributed to feedback mechanisms affecting the interactions between water, soil and woody vegetation. In many of these landscapes, the transition between grasses and woody vegetation is often associated with an increase in evapotranspiration rates, shifting the overall demand of water on a local scale (Heuperman, 1999; Engel *et al.*, 2005; Jackson *et al.*, 2009). In humid lands, the presence of woody vegetation can promote oxic environments across predominately anoxic landscapes, as the greater demand for water by woody vegetation lowers flooding stress by reducing the water table position and increasing the vadose zone depth (Muneerakul *et al.*, 2008).

By lowering soil moisture and creating oxic conditions, woody vegetation in wetlands can positively influence the rates of evapotranspiration, mineralization, respiration and decomposition (Rodríguez-Iturbe *et al.*, 2007; Muneerakul *et al.*, 2008; Eppinga *et al.*, 2010). Jobbágy and Jackson (2007) hypothesized that phreatophytic vegetation has a large impact on the distribution and accumulation of nutrients and ions through two main interactions: (1) aquifer interactions, wherein trees relying on groundwater lower the water table, which leads to the advective movement of water and associated ions toward the center of a stand; (2) vadose zone

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interactions, wherein the uptake and exclusion of solutes by phreatophytes leads to a localized accumulation of nutrients and ions and regulates the interaction between the aquifer and ecosystem. In addition, phreatophytes have been hypothesized to negatively affect surrounding vegetation by limiting access to resources, as they accumulate nutrients and ions in their biomass, soil and groundwater (Rietkerk and van der Koppel, 2008). The balance between these positive and negative feedback mechanisms is thought to be partially responsible for the regular vegetation patterns seen across many wetlands (Rietkerk *et al.*, 2004; Eppinga *et al.*, 2009).

The accumulation of ions in the groundwater and vadose zone is regulated primarily by the local water budget (precipitation–evapotranspiration). In eucalyptus plantations located across southern Brazil and northern Argentina, Noretto *et al.* (2008) found that the accumulation of solutes occurred when the net water budget was lower than +10 cm per year. In a climatic gradient stretching from Scotland to Siberia, Eppinga *et al.* (2010) found that transpiration-driven nutrient accumulation supported landscape patterning in peatlands when the water budget was lower than +20 cm per year. Jackson *et al.* (2009) further suggested that shifts between grasses and woody vegetation could lead to the advective movement of water and solute toward the centers of treed areas across ecosystems where the precipitation to evapotranspiration ratio ranged between 0.85 and 1.15.

Like the tree islands and ridges of woody vegetation of the Okavango Delta in Botswana and the great Vasyugan bog in Siberia, hydrologic, foliar and soil data support the hypothesis that evapotranspiration-driven nutrient/ion accumulation plays a large role in the presence of tree islands in the Everglades of South Florida (Wetzel *et al.*, 2005; Ross *et al.*, 2006; Saha *et al.*, 2009; Wetzel *et al.*, 2009; Wang *et al.*, 2011; Sullivan *et al.*, 2011; Wetzel *et al.*, 2011). Across the freshwater portion of the oligotrophic Everglades, tree islands contain soil and pore water phosphorus and ion concentrations that are one to three orders of magnitude higher than the surrounding marsh (Gann *et al.*, 2005; Ross *et al.*, 2006; Wetzel *et al.*, 2011). The presence of diurnal water table fluctuations suggests that a proportion of groundwater is taken up during transpiration on tree islands (Ross *et al.*, 2006; Sullivan *et al.*, 2011). Groundwater levels across tree islands further indicate the seasonal presence of a water table depression within natural and constructed tree islands, which suggests the advective movement of regional water toward the center of the islands (Sullivan *et al.*, 2011; Sullivan, 2011).

Evapotranspiration-driven ion accumulation contributes to an explanation for the cause of recently discovered petrocalcic horizons found in the most elevated portion of some Everglades tree islands (Coultas *et al.*, 2008; Graf *et al.*, 2008). Groundwater chemistry data from two tree islands in the central portion of the Everglades suggest the precipitation of calcite and aragonite is an ongoing, year-round process in tree islands (Wetzel *et al.*, 2011; Sullivan, 2011). Furthermore, Sullivan (2011) suggested that the seasonal-driven ion accumulation promotes mineral

precipitation in the presence of elevated partial pressures of carbon dioxide ( $p\text{CO}_2$ ) in the groundwater.

Though data supports evapotranspiration-driven ion accumulation on tree islands, the combined effects of precipitation, evapotranspiration, underlying geology and inputs of regional groundwater on ion concentrations have not been explored in detail. Furthermore, the effect of mineral formation processes on soil physical properties such as  $K$ ,  $n$  and  $S_y$  has not been investigated. The main objective of the present paper is to develop a hydrologic model that predicts the relationship between precipitation, evapotranspiration, groundwater flow patterns and ion concentrations in tree island groundwater. Chloride transport was included in the model as a conservative constituent because chloride has little interaction with other ions in solution or the surrounding porous media. The model was calibrated using groundwater and surface water levels monitored on eight constructed tree islands from 2007 to 2010. Surface water levels, precipitation and hydraulic conductivity were used to determine evapotranspiration from the islands using a one-dimensional flow hydrologic model. Groundwater levels, precipitation and evapotranspiration were then used to determine the fluxes of water in and out of the trees and their effect on groundwater chloride concentrations. Once the best-fit chloride model was achieved, a sensitivity analysis was performed on the hydraulic parameters of  $S_y$ ,  $K$  and porosity. The results of the sensitivity analysis are discussed in the context of the potential effects of secondary calcium carbonate formation on the hydrologic properties of the sediments and the accumulation of ions in tree island groundwater.

## STUDY AREA

The Loxahatchee Impoundment Landscape Assessment (LILA) is a large physical model of the Everglades located at the Loxahatchee National Wildlife Refuge in Boynton Beach, Florida. The LILA consists of four macrocosms, each 8 ha in size, that mimic the tree island-ridge-slough landscape of the Everglades (Aich *et al.*, 2011). Within each macrocosm, two rectangular tree islands, each spanning 2800 m<sup>2</sup>, were constructed with different geologic materials. One island was constructed predominately of peat and the other contained a center of limestone rubble approximately 168 m<sup>2</sup> in area and 60 cm thick (van der Valk *et al.*, 2008; Stoffella *et al.*, 2010). All of the islands were overlain by a peat layer, which extended to a depth of 10 cm in the center of the limestone islands but was thicker, between 50 and 80 cm, along the edges of the islands (Sullivan *et al.*, 2011). Each of the tree islands was planted with over 700 saplings of eight tree species common to Everglades tree islands (Stoffella *et al.*, 2010). Four of the tree islands were planted in March 2006 (P1), while the other islands were planted one year later (P2).

Surface water levels in all macrocosms were managed in accordance with an operational hydrograph derived to mirror those in the Everglades, with elevated surface water levels between September and November and lower surface water levels between March and June (Sullivan *et al.*, 2011).

Within the macrocosms, surface water typically flows from west to east. The climatic conditions at LILA were similar to those across south Florida with distinct wet and dry seasons between June and November and December and May, respectively. The area received an average of 130–160 cm of rainfall per annum over the last 30 years (Ali *et al.*, 2000; Sullivan *et al.*, 2011).

## METHODS

### Groundwater and surface water monitoring

From July 2007 through June of 2010, groundwater levels were monitored in three wells on each tree island with an average depth of 1.34 m (Sullivan *et al.*, 2011) (Figure 1). The groundwater wells formed a transect across the tree islands, with two groundwater wells located on the edges of the islands and one located in the center (Figure 1). In-Situ Level Troll 500™ pressure transducers were used to record groundwater level in all 24 wells at a 15-min interval rate of collection, with an accuracy of 0.35 mm. All wells were surveyed using a Wild-Nak 2 level and stadia rod and referenced to NGVD29 with an accuracy of 3 mm.

Surface water levels were also monitored every 15 min by the South Florida Water Management District (SFWMD) via HANDAR/VAISALA 436 SDI stage recorders at the eastern and western boundaries of each macrocosm. The stage data was stored on a Campbell Scientific CR10X-TD 2M and relayed via radio modem to the SFWMD headquarters and placed in the publicly accessible DBHYDRO database ([http://my.sfwmd.gov/dbhydroplsql/show\\_dbkey\\_info.main\\_menu](http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu)). A linear interpolation between the two stages was used to determine the surface

water levels along the boundaries of each tree island. Groundwater and surface water levels were used as boundary conditions in the model; therefore the 15-min data were averaged for both the surface water and groundwater levels to determine the average daily surface and groundwater level. The groundwater fluxes, recharge, ET and chloride concentrations in the model were solved on a daily time step.

From October 2007 through May 2010, the chloride concentrations in 24 groundwater wells and eight surface water sites were measured biannually in October and April/May. Chloride was chosen for the model as a conservative tracer, and as an indicator of ionic strength as chloride was positively correlated with the other major ions (i.e. carbonate, calcium, magnesium and sodium) in the groundwater at LILA (Sullivan, 2011). For more detailed resolution in the temporal variability of chloride concentrations, groundwater was sampled monthly from four groundwater wells on one peat tree island and the adjacent surface water in 2009. These wells consisted of three with an average depth of 1.34 m, of which two were wells on the edge and one in the center of the island, plus one shallow well at a depth of 60 cm located in the center of the island (Figure 1). All groundwater and surface water sites were sampled using a peristaltic pump, and each well was purged of three well volumes prior to sampling. Samples were filtered through a 0.45- $\mu$ m filter, stored at 4 °C and analyzed for chloride concentration using a Dionex-120 Ion Chromatograph. Groundwater levels and chloride concentrations were grouped according to physical location (center *vs* edge), geologic material (peat *vs* limestone) and planting year (P1 *vs* P2).

### Slug tests

Slug tests were performed to determine the hydraulic conductivity of the geologic material surrounding 12 wells on the peat and limestone islands. Water levels in the wells were monitored at 0.5-s intervals with In-Situ Level Troll 500 pressure transducers for at least 3 min before the slug was introduced. Solid slugs measuring 15 and 30 cm in length were introduced to the wells, and water levels were measured until they were within less than 5% difference of the original water table position. The slug tests were repeated two to six times for each of the given slug lengths. The responses of the water levels were then analyzed using the Bouwer and Rice method (1976) for partially penetrating wells in an unconfined aquifer. The hydraulic conductivity (K) results were included in the hydrologic model to determine groundwater flux on the islands.

### Rainfall monitoring and estimating recharge

Daily rainfall values were obtained from the SFWMD DBHYDRO database ([http://my.sfwmd.gov/dbhydroplsql/show\\_dbkey\\_info.main\\_menu](http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu)) for LXWS station located approximately 1 km northwest of LILA from July 2007 through 2010. Total seasonal rainfall at the site was compared to the 30-year average (1980–2010) seasonal rainfall, with the wet season from July through December, and the dry season from January through June.

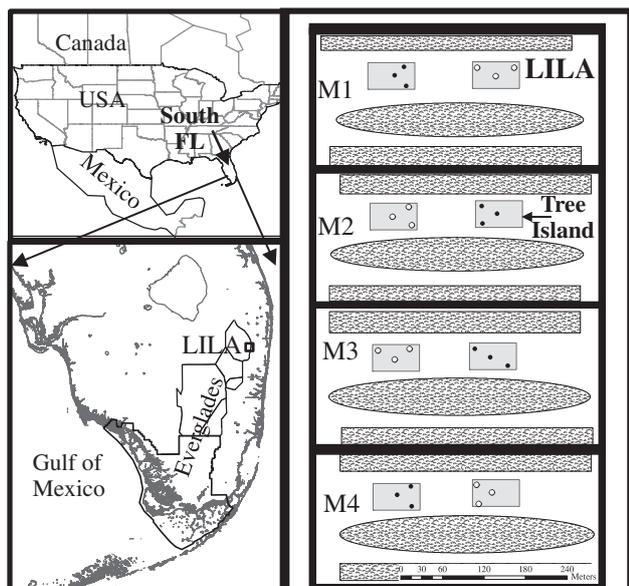


Figure 1. LILA is located in Boynton Beach, South FL, USA (top left), just on the outskirts of the current Everglades (middle left). Three wells were monitored on the Peat (black) and Limestone (white) tree islands at LILA (right). Of the four macrocosms (M), M1 and M4 contained islands planted in 2006 (P1 islands), while M2 and M3 contained islands planted in 2007 (P2 islands)

Recharge, or the amount of infiltrated rainwater ( $R$ ), around each well location was determined using a water table fluctuation method (Healy and Cook, 2002);

$$R = S_y \frac{\Delta h}{\Delta t} \quad (1)$$

where the change in the water table position ( $\Delta h$ ) over a given day ( $\Delta t$ ) was multiplied by the specific yield ( $S_y$ ) of the geologic material (Table I). Periods of recharge were limited to days in which rainfall was detected at the LXWS station. The  $S_y$  used to determine  $R$  was based on results by Sullivan et al. (2011), where  $S_y$  averaged  $0.15 \pm 0.04$  as determined from soil cores collected from the tree islands at LILA.

### HYDROLOGIC MODELS

#### Modeling evapotranspiration

To gain a better understanding of  $ET$ ,  $K$  and  $R$  as hydraulic drivers of tree island hydrodynamics, groundwater levels on the islands were used to determine  $ET$  given the following water balance and Darcy equations (Schwartz and Zhang, 2003);

$$(qh)_x = (qh)_{x+\Delta x} + (ET - R)\Delta x \quad (2)$$

$$q = -K \frac{\partial h}{\partial x} \quad (3)$$

where  $q$  was Darcy Flux and  $h$  represent the groundwater level at two locations ( $x, x+\Delta x$ ) on the island separated by a distance of  $\Delta x$  with a given hydraulic gradient of  $\partial h/\partial x$  (Table I).  $ET$  was solved using the following analytical solution derived from the above governing equations (2 and 3);

$$ET = K \left[ \frac{h_c^2 - h_1^2 - (h_2^2 - h_1^2) \frac{x_c}{L}}{(L - x_2)^2 \frac{-x_c}{L} - [(x_c - x_1)^2 - (L - x_1) \frac{x_c}{L}]} \right] + R \quad (4)$$

where  $h_c$ ,  $h_1$  and  $h_2$  represented the groundwater levels located at a distance of  $x_c$ ,  $x_1$  and  $x_2$  (Figure 2) from the boundary of the island,  $x_0$ , which had a length of  $L$ . A linear interpolation between the edge wells and center wells was established in order to estimate water level data on the islands for periods of missing data.

#### Modeling groundwater inputs and outputs

Once daily  $ET$  values were calculated, the daily discharge per unit width of the aquifer ( $m^3 m^{-1}$ ) was determined using the following analytical solution:

$$Q_x = -K \left[ \frac{(h_L^2 - h_0^2)}{L} \right] + a - b \quad (5)$$

where discharge ( $Q$ ) at any given distance  $x$  from the boundary of the island ( $x_0$ ) was the product of  $K$ , the difference of the surface water levels at the edges of the island ( $h_0$  and  $h_L$ ) and the difference of coefficients  $a$  and  $b$ :

$$a = ET \left[ 2(x - x_1)\mu(x - x_1) - \frac{(L - x_1)^2}{L} \right] - \frac{R}{2}(L - 2x) \quad (6)$$

$$b = ET \left[ 2(x - x_2)\mu(x - x_2) - \frac{(L - x_2)^2}{L} \right] - \frac{R}{2}(L - 2x) \quad (7)$$

A unit step function was utilized to solve for  $Q_x$  across the island as  $R$  occurred over the entire length of the island ( $L$ ), but  $ET$  was bounded by the location of the trees, which fell between the two edge well represented by  $x_1$  and  $x_2$  (Figure 2). The unit step function was defined by the following equations:

$$\mu(x - x_1) = \begin{cases} 1 & \text{for } x \geq x_1 \\ 0 & \text{for } x < x_1 \end{cases} \quad (8)$$

Table I. Description of variables used in the governing equations (Equations (2, 3)) and the one-dimensional hydrologic models (Equations (4, 12))

Variable	Description	Unit
$R$	Recharge of the groundwater from rainfall infiltration	cm day <sup>-1</sup>
$S_y$	Specific yield	unit less
$h$	Water level	m
$t$	Time	day
$ET$	Evapotranspiration	mm day <sup>-1</sup>
$K$	Hydraulic conductivity	m day <sup>-1</sup>
$x$	Distance too point of interest on the island from island boundary ( $x_0$ )	m
$Q$	Darcy flux	m day <sup>-1</sup>
$\partial h/\partial x$	Hydraulic gradient	unit less
$L$	Length of the island	m
$Q_o$	Groundwater discharge	m <sup>3</sup> day <sup>-1</sup>
$Q_{in}$	Groundwater flux into the island	m <sup>3</sup> day <sup>-1</sup>
$C$	Concentration of chloride in the center of the island at $t=0$	mg L <sup>-1</sup>
$C$	Concentration of chloride in the groundwater in the center of the islands	mg L <sup>-1</sup>
$C_{in}$	Concentration of chloride in the groundwater at the edges of the island	mg L <sup>-1</sup>
$C_r$	Concentration of chloride in the rainfall or in the shallow groundwater	mg L <sup>-1</sup>
$\partial c/\partial t$	Change in chloride concentrations over time	mg L <sup>-1</sup> day <sup>-1</sup>
$n$	Porosity	unit less
$A$	Area	m

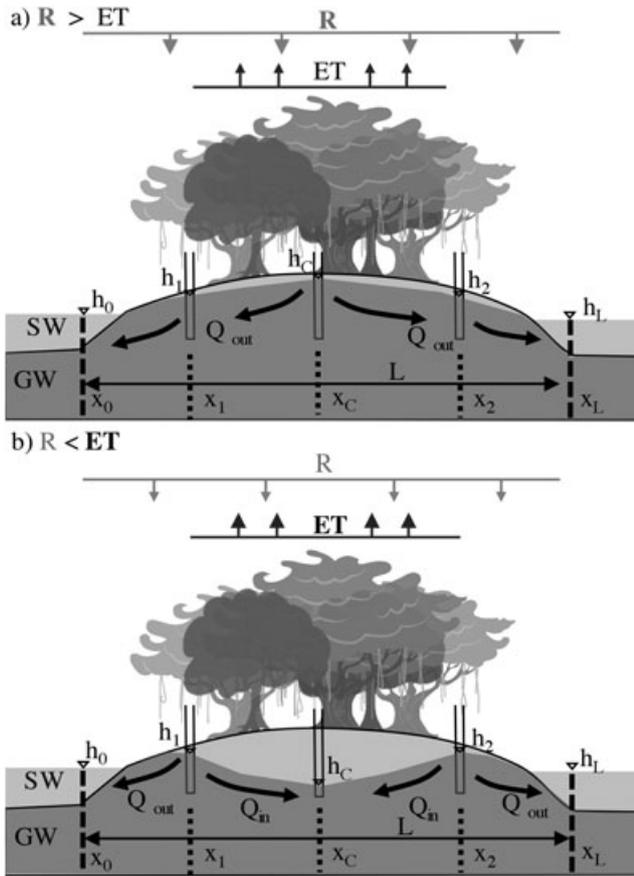


Figure 2. Conceptual diagram of the one-dimensional analytical models used to determine evapotranspiration (ET) and discharge (Q) on the tree islands. The height of the surface water ( $h_0$  and  $h_L$ ) and groundwater in the three wells ( $h_1$ ,  $h_c$  and  $h_2$ ) was denoted by the inverted triangle ( $\nabla$ ). Recharge (R) occurred between the boundaries of the island ( $x_0$  and  $x_L$ ), while ET was restricted between the edge wells ( $x_1$  and  $x_2$ ), which corresponded to the stand location. The direction of Q (i.e.  $Q_{in}$  or  $Q_{out}$ , indicated by flow arrows) changed depending on R:ET; (a) when  $R > ET$  the groundwater table was domed, which resulted in a  $Q_{in}$  equal to zero, while (b) when  $R < ET$  the groundwater table was depressed in the center of the islands and resulted in a positive  $Q_{in}$ .

$$\mu(x - x_2) = \begin{cases} 1 & \text{for } x \geq x_2 \\ 0 & \text{for } x < x_2 \end{cases} \quad (9)$$

*Modeling groundwater chloride concentrations*

The values of ET, R and Q were used to predict the chloride concentration  $[Cl^-]$ , in the center of the islands, C, using the following chloride balance equation (Bonte and Zwolsman, 2010);

$$\sum Q_{ad} C_{ad} = nAh \frac{\partial c}{\partial t} + \sum (Q_{ad} - ETA)C \quad (10)$$

$$\sum Q_{ad} C_{ad} = Q_{in} C_{in} + RAC_R \quad (11)$$

where  $Q_{ad}$  is the fluxes of water into the island (i.e. groundwater flow into the islands,  $Q_{in}$  ( $m^3$ ) and recharge R (m)), while  $C_{ad}$  denotes the respective  $[Cl^-]$  of the fluxes of water into the island (i.e.  $C_{in}$  and  $C_R$ ). Porosity is denoted by n, while A represents the area ( $m^2$ ) where ET and R (m)

occurred. The height of the water table (m) is represented by h, while  $\partial c/\partial t$  expresses the change in  $[Cl^-]$  over time (Table I). Earlier findings by Myers (1999) suggest that the porosity of South Florida peats could range from 0.58 to 0.97, while Schmoker and Halley (1982) found the porosity of near surface limestone averaged 0.50. Therefore, the porosity of the peat and limestone tree islands were set to equal 0.80 and 0.50, respectively. The C at any given point in time (t) was solved through the following analytical solution:

$$C = C_0 \exp \left\{ -t \frac{\sum Q_{ad} - ETA}{nAh} \right\} + \frac{\sum Q_{ad} C_{ad}}{\sum Q_{ad} - ETA} \left( 1 - \exp \left\{ -t \frac{\sum Q_{ad} - ETA}{nAh} \right\} \right), \quad (12a)$$

$$C = C_0 + \frac{\sum Q_{ad} C_{ad}}{nAh} t, \quad \sum Q_{ad} = ETA \quad (12b)$$

where  $C_0$  is the concentration at time zero ( $t_0$ ). The  $C_R$  varied between the  $[Cl^-]$  of rainfall and that of the shallow groundwater well. The  $[Cl^-]$  of rainfall was the mean of the three year precipitation-weighted average of chloride as reported by the National Atmospheric Deposition Program from 2007 through 2010 for sites FL11 and FL41, located in south and central Florida, respectively (<http://nadp.sws.uiuc.edu/>; Table II). Average weekly dry deposition  $[Cl^-]$  were obtained from the Environmental Protection Agencies' Clean Air Status and Trends Network (CASTNET; <http://epa.gov/castnet/javaweb/index.html>) for site EVE491 over the same period. As dry deposition only accounted for approximately 6% of the total annual atmospheric deposition (dry + wet) of  $Cl^-$  on the tree islands, dry deposition was excluded from the model. The  $[Cl^-]$  of the shallow groundwater,  $Q_{in}$ , and  $C_0$  used in the model was the mean  $[Cl^-]$  obtained from the shallow wells, edge wells and center wells, respectively (Table II). The K,  $S_y$  and n were varied by a magnitude of 25% to determine the sensitivity of the modeled groundwater  $[Cl^-]$  in the center of the tree islands to

Table II. The mean concentrations and range of all potential sources chloride to the LILA tree islands from 2007 to 2010. Rainfall and dry deposition data were obtained from National Atmospheric Deposition Program (NADP) and Clean Air Status and Trends Network (CASTNET), respectively

Sources	Mean (mg L <sup>-1</sup> )	Range (mg L <sup>-1</sup> )
Rainfall <sup>a</sup>	1.1	0.2–5.2
Dry deposition <sup>a</sup>	$1.8 \times 10^{-6}$	$5.8 \times 10^{-8}$ – $6.3 \times 10^{-6}$
Center		
Groundwater	58.5	21.5–115.8
Edge	40.5	16.5–63.6
Groundwater		
Shallow	72.9	46.4–126.0
Groundwater		
Surface water	32.8	16.7–55.5

<sup>a</sup> Data obtained from NADP or CASTNET.

the changes in the input parameters. To determine the effect of geologic material and stand age on the hydrodynamics and groundwater ion concentrations in the center of tree islands, groundwater and chloride modeling results were grouped and compared according to geologic material (Peat vs Limestone) and stand age (P1 vs P2).

### RESULTS

#### Precipitation and water levels

Over the 3-year period, inputs of rainfall during both the wet and dry seasons were typically lower than the 30-year average. Only during the dry season of 2010 were the inputs of rainfall equivalent to the 30-year average (Figure 3). Surface and groundwater levels followed a similar seasonal pattern, with elevated water levels between September and

November, and lower water levels between April and June (Figure 4). The groundwater levels in the center of the Peat and Limestone tree islands varied throughout the three year period, with a much larger amplitude in water levels detected in the center of the Limestone tree islands compared to the Peat islands (Figure 4a, b). During the dry season, when  $ET > R$ , groundwater levels in the center of both the Peat and Limestone tree islands were depressed compared to the groundwater on the edges (Figure 2b). Throughout this same period, groundwater levels in the center of the Limestone tree islands also dropped below that of the surface water, while groundwater levels in the center of the Peat islands remained elevated compared to the surface water year-round (Figure 4a, b)

#### Groundwater and surface water chloride concentrations

From 2007 to 2010, the groundwater  $[Cl^-]$  in the center of the islands were on average  $10 \text{ mg L}^{-1}$  higher than those observed on the edges (Table III). In addition, the center of

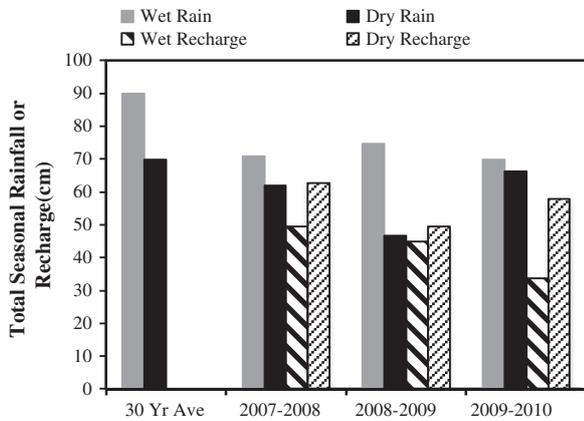


Figure 3. Rainfall (solid) and recharge (striped) for the wet (gray) and dry (black) seasons from 2007 to 2010, compared to the average seasonal 30-year rainfall

Table III. The overall average groundwater  $[Cl^-]$  on the tree islands at LILA based on tree island type (Peat vs Limestone), location (Edge vs Center) and sampling event timing (May vs October)

Macrocosm	Limestone		Peat		Sampling event	
	Edge	Center	Edge	Center	May	October
1	40.02	52.86	37.30	61.12	45.72	44.88
2	31.78	46.51	29.62	44.50	36.26	32.64
3	53.29	55.66	41.60	74.77	52.73	51.27
4	47.82	59.43	42.21	72.15	56.59	55.76
Average	43.23	53.61	37.68	63.14	47.83	46.14

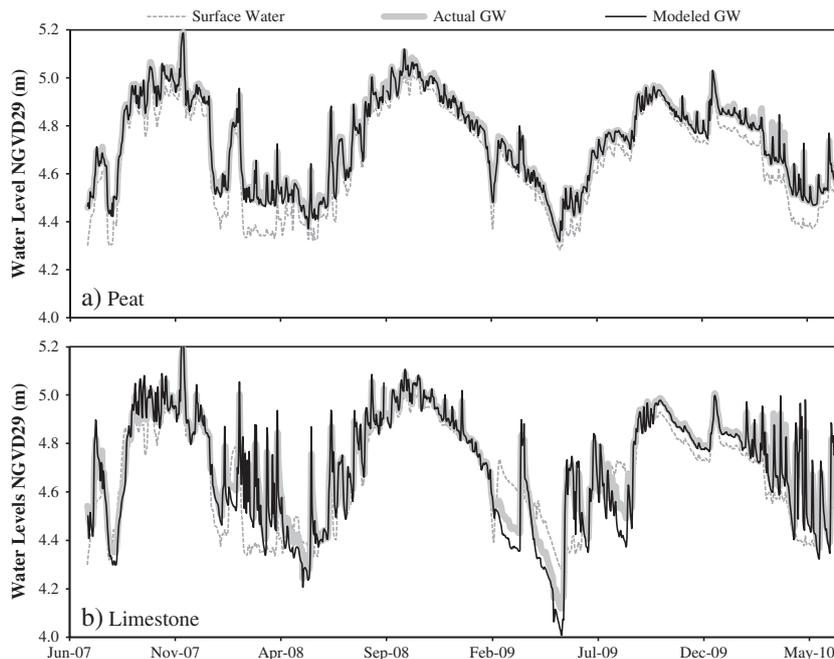


Figure 4. Groundwater levels (black) in the center of a Peat (a) and Limestone (b) tree island at LILA compared to the surface water levels (light gray) and the modeled groundwater water levels (gray dash) from July 2007 through June 2010

the Peat islands tended to have higher groundwater  $[Cl^-]$  compared to the center of the Limestone islands. The center of the P1 islands (M1 and M4; Table III) had an average  $[Cl^-]$  similar to the P2 islands (M2 and M3). Monthly sampling of groundwater from one Peat island revealed that the groundwater  $[Cl^-]$  in the center and shallow wells varied seasonally with elevated values observed in June, July and September (Figure 5), while the surface water  $[Cl^-]$  remained relatively stable. The groundwater  $[Cl^-]$  from the two edge wells on the island did not differ substantially

throughout the year so they were combined to form an average monthly value that ended up being similar to the surface water  $[Cl^-]$  year-round (Figure 5).

*Recharge and hydraulic conductivity*

The total annual R across all islands decreased throughout the study from 1.21 m in 2007–2008 to 1.09 m in 2009–2010. The total annual R values on the P1 islands were always lower than the P2 islands and averaged 0.99 m year<sup>-1</sup> and 1.23 m year<sup>-1</sup>, respectively. The total annual R values on the Limestone and Peat islands were similar, averaging 1.10 m year<sup>-1</sup> over the entire study. The total monthly R values were similar to precipitation amounts during the dry season but were substantially less than precipitation during the wet season (Figure 3).

The calculated hydraulic conductivity of all the wells at LILA averaged  $1.09 \pm 0.82$  m day<sup>-1</sup>. The P2 Limestone tree islands tended to have the highest hydraulic conductivity values, followed by the Peat islands, with the P1 Limestone islands tending to have the lowest values (Figure 6). The hydraulic conductivity value obtained per island was used to model ET and Q for that island.

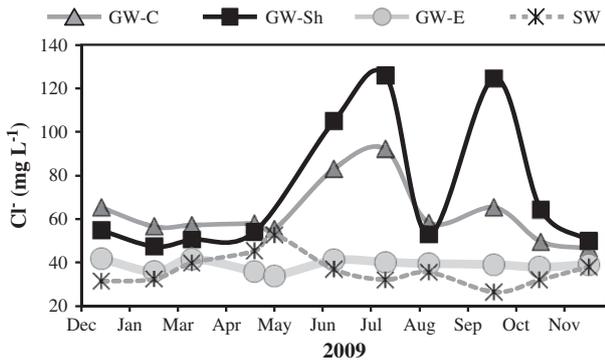


Figure 5. Monthly  $[Cl^-]$  in the surface water (SW) and groundwater (GW) in the center and shallow center wells and the edges of the tree islands

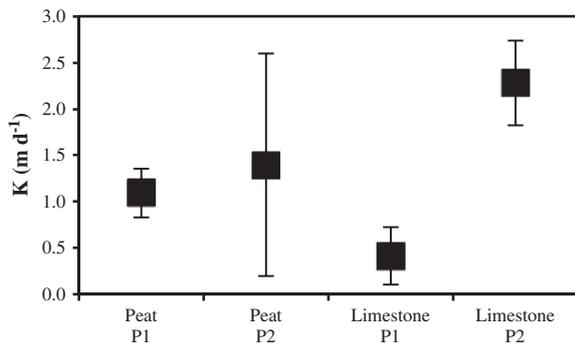


Figure 6. The average hydraulic conductivity (K) and standard deviation for the peat and limestone tree islands from Planting-1 (P1) and Planting-2 (P2)

*Evapotranspiration results*

From 2007 to 2010, the modeling results suggested an average daily ET per month of  $3.36 \pm 2.26$  mm day<sup>-1</sup>, with higher values occurring between April and July (Figure 7). Overall, monthly ET exceeded R on the P1 islands by an average of 12.31 mm, while monthly R was on average 0.73 mm greater than ET on the P2 tree islands (Figure 8a). The annual ET was greater on the Limestone islands compared to the Peat islands, which averaged 95 cm year<sup>-1</sup> and 78 cm year<sup>-1</sup>, respectively. Over the 3-year study, the annual ET exceeded R on both Peat and Limestone islands, but the ET:R ratio was greater on the Limestone islands compared to the Peat (b). The ET:R ratio was greatest between January 2009 and January 2010 (Figure 8a, b).

Daily values of ET and R were used to solve for water levels across the tree islands, to check that the modeled ET

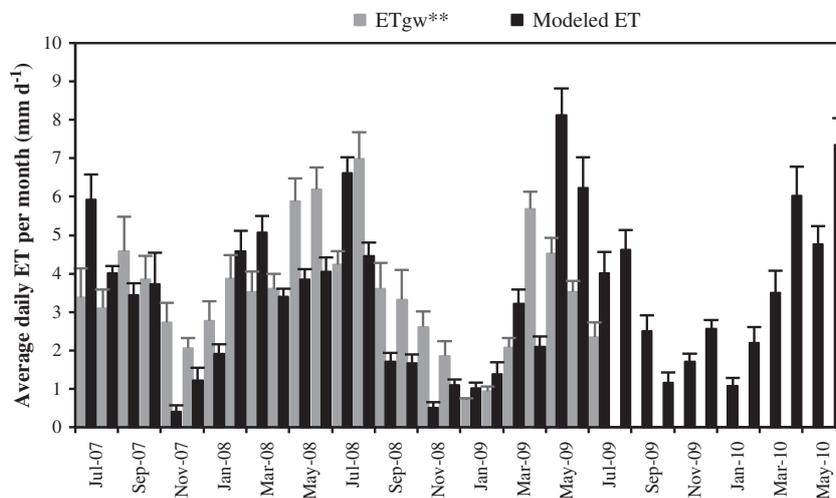


Figure 7. The average daily evapotranspiration (ET) per month as determined by the hydrologic model, compared to the average daily groundwater evapotranspiration (ET<sub>CW</sub>) determined using the White Method by Sullivan *et al.* (2011)

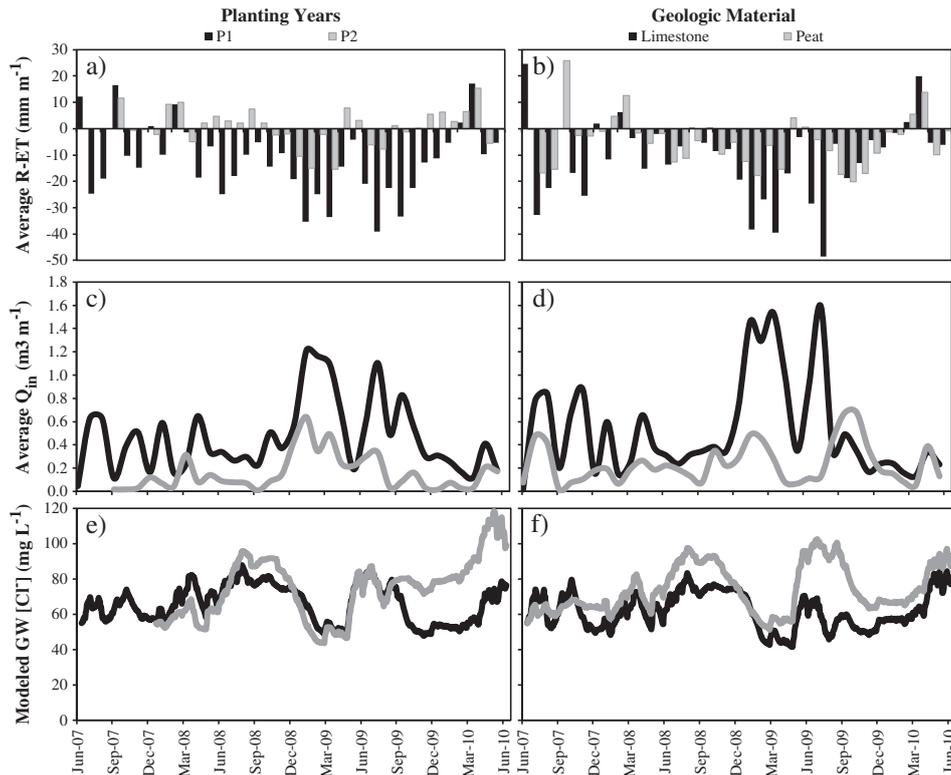


Figure 8. Modeling results from Planting-1 (P1, black) and Planting-2 (P2, gray) islands (Left) and the Limestone (black) and Peat (gray) islands (right). a and b) The average monthly difference in recharge (R) and evapotranspiration (ET, mm), c and d) monthly groundwater fluxes in ( $Q_{in}$ , gray,  $m^3$ ) and e and f) daily groundwater [ $Cl^-$ ] in the center of the islands

and R values predicted groundwater levels in the center of the tree islands. Modeled groundwater levels predicted actual groundwater levels with a good degree of accuracy, except during the dry season, when the modeled groundwater levels under-predicted the groundwater levels in the center of Limestone islands (Figure 4). The model also predicted that groundwater levels on the edges of the Peat and Limestone tree islands were on average 1–2 cm higher than the surface water level year-round, which was also observed in the field measurements.

*Groundwater flux results*

Modeling results indicated the largest  $Q_{in}$  values occurred in January 2009–2010 (Figure 8c, d). The total monthly modeled  $Q_{in}$  per unit aquifer ( $1 m^3 m^{-1}$ ) was three times higher on the P1 islands compared to the P2 islands, with a total of  $15.34 m^3$  over the 3-year study period (Figure 8c). The Limestone and Peat islands followed a similar pattern as the P1 and P2 islands but monthly modeled  $Q_{in}$  was typically greater on the Limestone islands compared to the Peat, especially at the end of 2007 and for all of 2009 (Figure 8d). The monthly modeled  $Q_{in}$  per island was predominantly dictated by the input of R, when R was high,  $Q_{in}$  did not differ from zero, while when inputs of R were low,  $Q_{in}$  was elevated.

*Chloride modeling results*

When  $C_R$  was set equal to that of rainfall, the groundwater [ $Cl^-$ ] in the center of the island steadily decreased from 55.00 to 44.91  $mg l^{-1}$  from 2007 to 2010. Conversely, when

$C_R$  was set equal to the average concentration of the shallow groundwater well, the modeled groundwater [ $Cl^-$ ] ranged from 40.91 to 150.87  $mg l^{-1}$  in the center of tree islands and better predicted the observed groundwater [ $Cl^-$ ] (Figure 9 and Figure 10). For the remainder of this paper, the modeled groundwater [ $Cl^-$ ] will only refer to the results acquired when  $C_R$  was set equal to the shallow groundwater [ $Cl^-$ ]. The predicted groundwater [ $Cl^-$ ] was elevated in all islands during the wet season and was substantially lower during the dry season. The modeled groundwater [ $Cl^-$ ] was lowest when  $Q_{in}$  from the tree islands was large, but when  $Q_{in}$  was low, modeled groundwater [ $Cl^-$ ] was elevated (Figure 8).

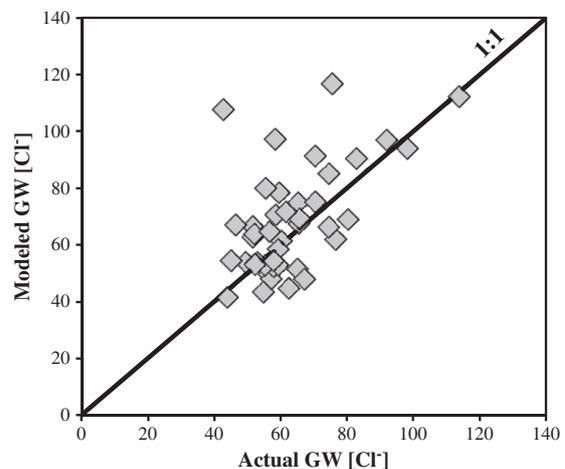


Figure 9. The modeled groundwater chloride concentration (GW [ $Cl^-$ ]) compared to the actual [ $Cl^-$ ] for all of the islands

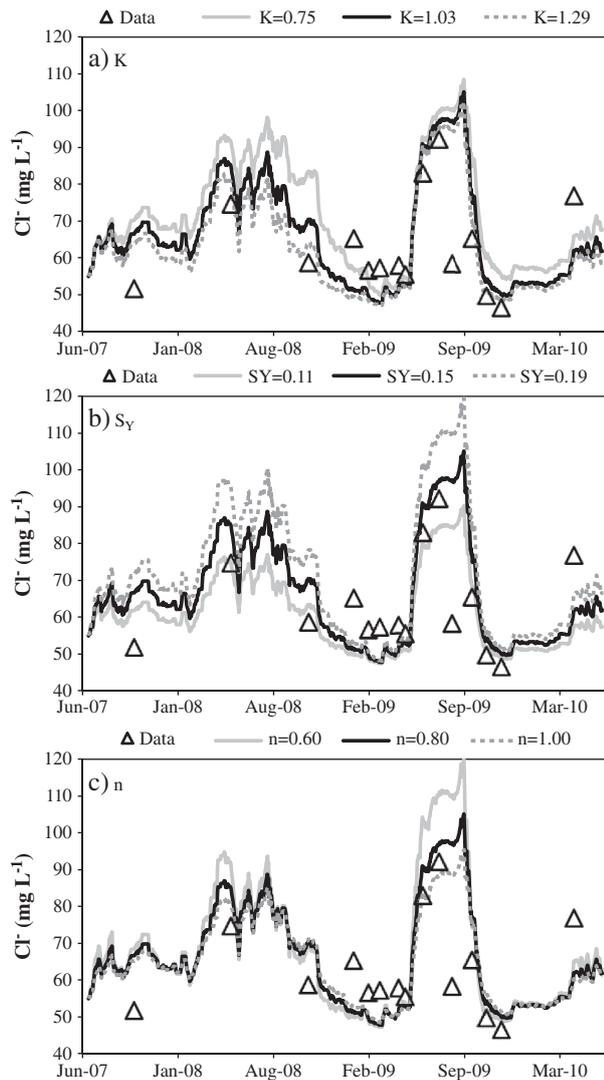


Figure 10. Sensitivity analysis for a) hydraulic conductivity (K), b) Specific yield ( $S_y$ ) and c) porosity ( $n$ ) for the groundwater chloride concentration ( $[Cl^-]$ ) predictions in the center of the tree islands, each parameter was altered positively (light gray dash) and negatively (dark gray) by 25%

Modeled groundwater  $[Cl^-]$  were on average slightly elevated compared to the observed values, which may be attributed to the fixed shallow groundwater  $[Cl^-]$  ( $C_R$ ). On three occasions, the model substantially over predicted the groundwater  $[Cl^-]$  when large and rapid changes in the surface water levels, required for other research projects, occurred at LILA (Figure 9).

Modeling results indicated that the average daily  $[Cl^-]$  in the P1 islands was similar to that of the P2 islands, except in the 2008 wet season and after September 2009, when substantially higher  $[Cl^-]$  were predicted in the P2 islands (Figure 8e). The modeled daily average  $[Cl^-]$  in the Peat islands was elevated 15–30  $mg L^{-1}$  during the wet season compared to the Limestone islands. In the dry season, the modeled average daily  $[Cl^-]$  was lowest in the Limestone islands (Figure 8f).

#### Sensitivity analysis

Overall, the groundwater  $[Cl^-]$  in the center of the island increased when K and porosity ( $n$ ) decreased but decreased

when specific yield ( $S_y$ ) decreased (Figure 10a, b, c). The model was most sensitive to specific yield (Figure 10b) during the wet season, when a 25% increase in specific yield led to a 12% increase in the groundwater  $[Cl^-]$ . During the dry season, the model was more sensitive to a 25% decrease in K, which led to a 14% increase in groundwater  $[Cl^-]$  (Figure 10a). The model was least sensitive to porosity, with the largest increase in groundwater  $[Cl^-]$  occurring during the wet season when porosity was reduced by 25% (Figure 10c).

## DISCUSSION

The results from LILA support the hypothesis that phreatophytic vegetation can affect ion accumulation and distribution through groundwater and vadose zone processes (Jobbágy and Jackson, 2007). The biannual groundwater sampling at LILA indicated little seasonal change in the ionic strength of the shallow groundwater (as approximated by  $[Cl^-]$ ). Similar to groundwater  $[Cl^-]$  observed on a limestone outcrop tree island in Everglades National Park (Sullivan, 2011), monthly sampling on one peat tree island and modeling results at LILA suggested that the ionic strength of the shallow groundwater was dynamic and driven by infiltrating rainwater and inputs of low ionic regional groundwater. Modeling results indicated that the ET:R was positively related to the flux of groundwater into the tree islands. Furthermore, the model predicted low groundwater  $[Cl^-]$  in the center of the tree islands as result of elevated ET:R and influxes of low  $[Cl^-]$  groundwater, which diluted the groundwater in the center of the island. The monthly groundwater  $[Cl^-]$  and modeled groundwater  $[Cl^-]$  in the center of the islands suggested that when the water table was low, ions likely accumulated in the vadose zone as a result of root water uptake and ion exclusion associated with ET. When recharge from infiltrating rain water occurred and the water table rose, the salts that had collected previously in the vadose zone became hydrolyzed, elevating the  $[Cl^-]$  in the groundwater.

#### Geologic material

The field data supported the modeling results that groundwater  $[Cl^-]$  in the center of the Peat islands was elevated compared to the Limestone islands. The modeling results indicated that the lower  $[Cl^-]$  observed in the Limestone tree islands was attributed to greater inputs of regional groundwater to the center of the tree island ( $Q_{in}$ ). The lower ET:R on the Peat islands indicates that recharge water had a greater influence on the groundwater  $[Cl^-]$  in those islands than on the Limestone islands. Though the modeling results indicate the shallow groundwater  $[Cl^-]$  in the Limestone islands remained lower year-round, the increased input of regional groundwater suggested that more ions would likely be stored in the vadose zone compared to that of the Peat based islands, as the ionic strength of regional groundwater is greater than that of rainfall. On the basis of field values, the K and specific yield ( $S_y$ ) used for modeling the Peat and Limestone islands were similar, which suggests that differences in the shallow groundwater  $[Cl^-]$  observed on the

islands at LILA may be explained by differences in other hydrologic properties, such as specific retention or porosity ( $n$ ).

The elevated porosity and low specific yield of Everglades peat compared to limestone (0.80 and 0.10–0.32, and 0.50 and 0.15, respectively; Schmoker and Halley, 1982; Myers, 1999; Bolster *et al.*, 2001) indicates that peat has a much higher ability to store water (specific retention) than does limestone. As soil moisture decreased in tree patches or islands, Engel *et al.* (2005) and Sullivan (2011) found that trees increasingly relied on groundwater as compared to soil water. The current modeling results indicate that the increased uptake of groundwater was concurrent with elevated inputs of regional groundwater and that regional groundwater inputs were more significant on the Limestone tree islands. The results of this study from LILA may provide insights into tree island dynamics across the greater Everglades. For instance, tree islands in the northern Everglades, which are underlain by a thick peat layer (Brandt *et al.*, 2002), most likely rely on soil water recharged from rainfall. Conversely, trees islands in the southern Everglades, which tend to be underlain by limestone, with little to no peat (Ross and Sah, 2011), most likely rely more on regional groundwater during the dry season. Over time, the difference in dry season inputs (soil water recharged by rain or regional water) could support the elevated ion concentrations found in the tree island groundwater in the southern Everglades (groundwater  $[\text{Cl}^-]$  of 90–210  $\text{mg L}^{-1}$  in WCA3 and 90–190  $\text{mg L}^{-1}$  in ENP, Wetzel *et al.*, 2011, Sullivan, 2011, respectively) compared to those in the northern Everglades (groundwater  $[\text{Cl}^-]$  of 20–90  $\text{mg L}^{-1}$ , Sullivan *et al.* unpublished data).

#### Biomass

The modeling results indicated that aboveground biomass influenced the shallow groundwater ion accumulation. The older tree islands (P1) had greater aboveground tree biomass compared to the younger islands (P2) (Stoffella *et al.*, 2010; Sullivan, 2011). The variation in the stand structure was concurrent with an elevated ET:R and  $Q_{\text{in}}$  on the older tree islands. These modeling results support the hypothesis that a positive relationship exists between elevated ET:R values and the advective movement of water toward the center of the island or stand as trees grow (Jobbágy and Jackson, 2007; Eppinga *et al.*, 2010). Similar to the Limestone islands, the lower groundwater  $[\text{Cl}^-]$  predicted in the P1 islands were concurrent with larger inputs of groundwater into the center of the tree island. The elevated groundwater  $[\text{Cl}^-]$  in the P2 islands during the 2010 dry season may be attributed to the above average monthly rainfall, which led to an elevated R to ET value for an extended period of time compared to the P1 islands. The modeling results further indicated that the elevated ET:R on the P1 islands was likely a result of increased interception, as recharge rates were lower on the P1 islands. These data suggest that variations in canopy cover and aboveground biomass caused by varying forest types (Bayhead, Bayhead Swamp, Hardwood Hammock) as well as disturbance from hurricanes and fire, may have long- and short-term effects on the accumulation and

distribution of ions in the shallow tree island groundwater. Islands with reduced canopy cover and aboveground biomass would likely mimic the conditions observed on the P2 islands.

#### Hydrologic properties: effects of mineral formation

Results from the sensitivity analysis suggested an alteration to the hydrologic properties of the underlying sediments on tree islands, such as the presence of pedogenic calcrete horizons (Coultas *et al.*, 2008; Graf *et al.*, 2008), and the year-round calcium carbonate mineral formation (Sullivan, 2011) may have long lasting effects on the accumulation of ions in shallow tree island groundwater. Because of the highly organic nature of wetland soils, the precipitation of calcite and aragonite would lower the porosity of the soils as a result of infilling (Angers and Caron, 1998; Nimmo, 2004). The results of the sensitivity analysis indicated that a decrease in the soil porosity would lead to an increase in the groundwater  $[\text{Cl}^-]$  by reducing the amount of water in storage (Figure 10b).

Calcrete pedogenesis could have a number of effects on the K of the underlying sediments on tree islands. As organic sediments shrink and swell depending on their water content, the timing of the calcium carbonate formation could affect the overall K of the material. If precipitation of calcium carbonates occurs in the dry season, the shrinkage, compression and elevated bulk density associated with unsaturated conditions (Schlotzhauer and Price, 1999) would lead to lower overall K of the sediments even during saturated conditions, as sediments would become rigid over time. The K would be expected to remain elevated year-round if precipitation of calcium carbonate occurred during saturated soil conditions that consequently would lead to increased interactions between the adjacent marsh and the tree islands during the dry season. Findings by Noretto *et al.* (2008) suggest that an increased K would lead to elevated concentration of ions in the vadose zone of afforested grasslands. The sensitivity analysis of the model suggested that increased K would lead to increased  $Q_{\text{in}}$  and lowered  $[\text{Cl}^-]$  the groundwater (Figure 10a).

The formation of calcium carbonate on tree islands may explain some of the difference in hydrologic properties recently discovered between tree islands and the adjacent marsh. Troxler and Childers (2010) and Sullivan (2011) found the K of two natural tree island sediments in the southern Everglades ranged from 1.01 to 43.20  $\text{m day}^{-1}$ , which were one to two orders of magnitude higher than the values that have been found in the Everglades peat marsh (0.54; Harvey *et al.*, 2004). Specific yield values on a natural island were also found to be slightly lower (0.08; Sullivan, 2011) on tree islands compared to marsh values (0.16–0.32; Myers, 1999). These differences in hydrologic properties between marsh and tree islands may help to reinforce positive feedback mechanisms that promote nutrient and ion accumulation within tree islands. Additional work is needed to understand the spatial variability in the hydrologic properties of tree islands and how they relate to the adjacent marsh at the landscape scale.

### Climate

Modeling results indicated that climate, specifically the amount and timing of rainfall, governed the inputs of regional groundwater into the tree islands. Over this 3-year study, below average seasonal rainfall was concurrent with the elevated fluxes of groundwater into the tree islands. Spatial variations of rainfall, hydrologic properties and stand structure may explain the north–south increase in ions and nutrient accumulation found in Everglades tree island soils and groundwater (Wetzel *et al.*, 2009; Sullivan *et al.*, unpublished data). Duever *et al.* (1994) found that average yearly and monthly rainfall amounts decreased from the northern to the southern Everglades, while recently Sklar *et al.* (2011) found that annual rainfall amounts decreased from the eastern coastal boundary of the Everglades westward. If ET rates, forest structure and underlying geology remained uniform across the Everglades, the change in R would create a gradient of ET:R values across the ecosystem that would affect tree island hydrodynamics, with islands that incur elevated ET:R having a greater dependence on inputs of regional groundwater during the dry season.

### Implications and limitations

This model describes how changes in K, porosity and specific yield influence shallow groundwater chemistry and tree island hydrodynamics for islands with different underlying matrices and aboveground biomass, but it does not elucidate how changes in hydrologic properties affect vadose zone dynamics, nor does it focus on the effects on vegetation. More work is needed to understand the effect of mineral formation and rooting strategy on the hydrologic properties of tree island sediments. The model indicated that changes in overlying forest structure (biomass) and underlying geologic material mediated the reliance of tree islands on regional groundwater. As tree islands increasingly rely on regional groundwater, the elevated uptake of groundwater may negatively affect the persistence of tree islands within their sphere of influence by increasing the competition for resources.

### CONCLUSION

Elevated inputs of regional groundwater into the tree islands were concurrent with elevated ET:R. During the dry season, the model predicted a decrease in the ionic strength of the groundwater as result of elevated ET:R that led to an increase in the  $Q_{in}$  of low ionic regional water. At the start of the wet season, the model predicted a substantial increase in the ionic strength of the tree island groundwater as a result of increased inputs of high ionic recharge water associated with infiltrating rainfall. The model indicated that  $Q_{in}$  was greatest on the Limestone and older tree islands and predicted they had lower groundwater ion concentrations compared to the Peat and younger islands. Sensitivity analysis of the hydrologic properties K, porosity and specific yield revealed the ionic strength of the groundwater was most sensitive to specific yield during the wet season and K

during the dry season. In conclusion, the modeling results indicated the ionic strength of the emerging LILA tree island groundwater was dynamic and governed by ET:R, hydrologic properties of the sediments and aboveground biomass.

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