Aridland constructed treatment wetlands II: Plant mediation of surface hydrology enhances nitrogen removal.

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ABSTRACT

Constructed treatment wetlands have been well established as effective and sustainable solutions to the problem of urban water treatment and reuse. However, treatment wetlands located in aridland cities may behave differently relative to their more mesic and humid counterparts, and this could potentially impact their ability to deliver the ecosystem services that are expected of them. Specifically, in hot, dry climates large water losses via evaporation and plant transpiration may comprise a major component of whole-system water budgets. Our primary goal was to develop a rigorous and informed model of how well these "working wetlands" function in hot, arid climates by developing and comparing robust water and nutrient budgets, as our process-based understanding of how mesic constructed wetlands function may not be readily transferred to arid climates where constructed wetlands are becoming increasingly widespread. At the Tres Rios constructed treatment wetland in Phoenix AZ USA, we quantified water losses via plant transpiration and open water evaporation as well as inorganic N loads into and from the whole wetland system and into the vegetated marsh. We found that water losses due to transpiration and evaporation were remarkably high when compared to most mesic constructed wetlands. Total water losses via evaporation and transpiration peaked at 300,000 m^3 mo^{-1} (714 L H_2O m^{-2} mo^{-1}) in the hot, dry summer months and averaged more than 70% of the whole-system water losses over a 27 month time period. At the same time, the vegetated marsh removed nearly all of the inorganic N that was supplied to it. Large transpirative water losses moved large volumes of replacement water into the marsh via a "biological tide" that provided more opportunities for vegetation and soil microbes to process N and other target solutes. This enhanced the N treatment efficacy of the Tres Rios constructed treatment wetland relative to humid, mesic systems. To our knowledge, this is the first time that biotically-mediated surface hydrology has been demonstrated in any wetland.

Keywords: Constructed treatment wetlands, water budgets, nutrient budgets, nitrogen removal, transpiration, urban wetlands

1. INTRODUCTION

The last two centuries have been characterized by a dramatic shift in human demographics and land use practices, with more people choosing cities and urban areas as their primary habitat. Specifically, since 1900 the human population living in urban areas has increased from 10% to over 50% globally, with that proportion projected to grow to 80% by 2050 (Grimm et al. 2008). As urban centers grow in size and number, so do their demands for resources and services. In particular, the last century has seen the transformation of many cities into “sanitary cities”, with highly centralized, capitalized, and expensive infrastructure designed to keep inhabitants healthy (Melosi 2000; per Grove 2009). This development of infrastructure has imparted considerable inertias on cities that make it more difficult for decision-makers to envision, let alone implement, novel or transformative new solutions to growing problems (Childers et al. 2014). Still, there are a number of ways in which urban infrastructure may make cities more resilient and sustainable by designing to optimize key ecosystem services (Pickett et al. 2013). One example of using infrastructure to optimize key ecosystem services is the increasing use of constructed treatment wetlands as part of wastewater treatment plants in place of expensive and energy-intensive treatment technologies.

Constructed treatment wetlands are a relatively low cost and low maintenance solution to the age-old problem of wastewater treatment and, more recently, water reclamation. They are especially attractive due to the fact that variable wastewater pathways and often relatively remote placement of wastewater treatment systems demand simple technologies that require little active management (Wallace and Knight 2006; Nivala et al. 2013). Most treatment wetlands are characterized by the presence of macrophytic vegetation, waterlogged or saturated soils, and municipal effluent that must be treated (Fonder and Headley 2013). While these wetlands share similar ecosystem service expectations, or “jobs”, of removing nutrients or other solutes (Tanner et al. 2012), they may be further differentiated with regards to the level of “hard” engineering components designed into them. These range from totally passive (horizontal flow) systems to intensely managed systems featuring pulse loading or active aeration (Fonder and Headley 2010). Design choices for treatment wetlands are often highly dependent on local or regional variables, including imposed statutory wastewater treatment regulations or site-specific conditions. Importantly, basic differences, such as climate, may limit general conclusions that might be drawn from comparative studies of treatment wetland efficacy (Nivala et al. 2013). While treatment wetlands are relatively similar in design and expectations, particular attention must be paid to the way these systems function in their respective climatic settings.

In arid environments, which occupy more than 30% of the earth's land surface, one of the biggest challenges facing cities is the scarcity of water. As a result, many of these cities are increasingly turning to the reuse of treated municipal effluent as a means of reclaiming and recycling water for various urban uses (Greenway 2005). Notably, in the aridland city of Phoenix AZ USA, virtually all municipal effluent is reused within the city (Metson et al. 2012), and the only significant export of water from the city is via evaporative losses to the atmosphere. The challenge facing water reuse is that using reclaimed water in densely populated areas requires that this water be clean. Increasingly, water service providers are turning to treatment wetlands that, in addition to cleaning effluent, can also provide auxiliary and serendipitous ecosystem services such as habitat for birds and other fauna and recreational spaces for urban dwellers. However, constructed treatment wetlands in hot, arid cities may face unique challenges relative to similar systems in more mesic and humid settings. In particular, treatment wetlands in hot, dry climates should lose large amounts of water to evaporation and plant transpiration. How aridland treatment wetlands perform under these conditions is not well quantified nor well understood, and our primary goal for this research was to better understand these dynamics. To address this goal, we quantified water and nutrient budgets for a constructed treatment wetland in Phoenix.

In Phoenix, annual precipitation averages 180 mm while potential wetland evapotranspiration is over 2100 mm (Kadlec 2008). Thus, the objectives driving our research in this wetland were: 1) to use a nutrient budget approach to determine net inorganic nitrogen (N) removal by the vegetated marsh and the whole system; 2) to measure transpirational water losses from the emergent macrophytes; 3) to calculate a dynamic water budget for the system based on surface water inflows and outflows, precipitation inputs, and estimates for open-water evaporation and plant transpiration, and; 4) to determine how well this aridland wetland removed N from municipal wastewater effluent.

Historically, phase-change atmospheric losses of water from wetlands have been presented as a single integrated process: evapotranspiration (E_t). Efforts to quantify and understand E_t in wetlands have been confounded by large differences in estimates across wetlands as well as divergences in the many ways that E_t may be calculated (Goulden et al. 2007). For the purposes of our study, we conceptually and empirically separated plant-mediated transpirational water losses from open-water evaporation. Transpirational water losses have been reported as both larger and smaller than water losses due to open-water evaporation, but it seems probable that transpiration dominates water loss in wetlands found in hot, arid climates (Pauliukonis and Schneider 2001). In fact, this has been documented for a wetland near our study system (Kadlec 2006). Open-water evaporation should also be high in these systems, and there are a variety of approaches to this calculation (Kumar et al. 2012). Many approaches to estimating E_t in wetlands have calculated it as a residual term in whole-system water and energy budgets that are based on meteorological data. However, a fundamental limitation with this approach for our study was that this “subtraction” approach did not articulate spatial heterogeneity and site-specific nuances that affect E_t, such as water level, plant community composition, and plant canopy structure (Lott and Hunt 2001).

The objectives we addressed in this study are clearly not new to the constructed treatment wetland literature. However, researchers have seldom rigorously studied wetlands that are specifically designed to perform particular ecosystem services but are located in hot, arid climates. Our research sought to tease apart the key components of the wetland water budget and combine them with a nutrient budget in order to understand how well the constructed treatment wetland we studied was performing. Our ultimate goal was to arrive at a more informed model of aridland wetland ecosystem service performance that can facilitate the best possible adaptive management of these systems.

2. METHODS

2.1. Site Description

Our study was conducted at the constructed treatment wetland associated with the 91st Avenue Wastewater Treatment Plant, which is the largest such facility in Phoenix. Construction of the 3-cell Tres Rios wetland system was completed in 2009-2010 and we began our work there in Summer 2011. We have focused our work on the largest of three wetland cells, which was planted first and came online in Summer 2010 (Figure 1). Each wetland cell is bounded by levee roads, and the cell we studied is 42 ha in size, half of which is fringing vegetated marsh and half of which is mostly open water with several small upland “islands”. Water depths in the marsh were consistently about 25 cm while open water depths were 1.5 to 2 m; because of the way water was managed in the system, these depths did not vary. Our study cell received from

95,000 to over 270,000 m^3 d^{-1} of effluent, depending on the time of year. The marsh areas were planted with seven emergent wetland species that are native to Arizona: *Typha latifolia, Typha domingensis, Schoenoplectus acutus, Schoenoplectus americanus, Schoenoplectus californicus, Schoenoplectus maritimus,* and *Schoenoplectus tabernaemontani. Schoenoplectus maritimus* was a minor component of the plant community and was out-competed within the first year of our research (Weller et al. this issue), so we focused our transpiration measurements only on the other six species.

INSERT FIGURE 1 HERE

2.2. Transpiration Measurements and Evaporation Calculations

We utilized a dual-gradient experimental design to study the two major hydrologic pathways of the wetland system: A whole-system gradient from the inflow to the outflow, and a within-marsh gradient that included 10 transects from the shore to the open water that were distributed evenly along the whole system gradient (Figure 1; for details, see Weller et al. this issue). All of our sampling followed a bimonthly schedule (January, March, May, July, September, and November), and we present data from July 2011 through September 2013 in this paper. We measured leaf-specific gas flux along marsh transects that included all species groups using a LICOR LI-6400 handheld infrared gas analyzer (IRGA). Measurements were made on individual *T. latifolia, T. domingensis, S. acutus, S. americanus, S. californicus,* and *S. tabernaemontani* plants at 50-cm intervals from near the water surface to the top of the canopy. We collected gas flux data continuously from early morning until as late in the day as was feasible. For logistical reasons, we sampled one transect at a time, with individual plants chosen haphazardly until all species present in that transect had been sampled a number of times. Due to site access restrictions, we were unable to collect nighttime transpiration data and thus assumed that nighttime transpirative water loss was negligible. Notably, this assumption is one reason that our transpiration estimates are conservative.

Several of the *Schoenoplectus* species have thick stems which required us to modify the stock LI-6400 IRGA sampling chamber in order to get a gas-tight seal without crushing the plant stems. To remedy this, we used custom-made foam pads that allowed us to seal the leaf chamber around these stems while minimizing damage to the plant material. Specifically, we were interested in IRGA measurements of leaf-specific transpiration rate (Tr; mmol H_2O m^{-2} sec^{-1}), photosynthetically active radiation (PAR, μmol photons), ambient air temperature (˚C), and relative humidity (%). All of these measurements were taken using the IRGA's default internal sensors. Daily transpiration data were expressed in units of leaf surface area, and we converted surface area to dry weight biomass by drying and weighing 8-10 samples of different surface areas and generating relationships between surface area and dry weight biomass for each species ($r^2>0.90$ and $p<0.01$ in all cases).

Half of the 42 ha wetland cell we sampled was open water, as determined by digitizing and measuring aerial imagery in ArcGIS (ver 10.0, ESRI, Redlands, CA). We calculated open-water evaporation (E, in mm hr^{-1}) using the Shuttleworth (1993) variation of the Penman (1948) equation:

$$\text{Open Water Evaporation} = ((S*PAR) + C*6.43*(1+0.536*V)*VPD)/(2.39*(S*C))$$

using hourly data for air temperature (T), relative humidity (RH), irradiance (PAR), barometric pressure (P), vapor pressure deficit (VPD), slope of the saturation vapor pressure curve (S), psychrometric constant (C), and wind speed (V) logged at an on-site meteorological station operated by the City of Phoenix (hereafter referred to as the "meteorological station"). If the hourly meteorological station data were missing or not reliable for any necessary variable (<5% of all hourly readings), we did not calculate transpiration or open-water evaporation. Because of these missing data, we are confident that our evaporation water loss values are underestimates and are further confident that our transpiration estimates are conservative. Finally, we calculated internal water loss using a dynamic monthly water budget for the whole system by summing the whole-system hourly water fluxes via open water evaporation (E) and plant transpiration (Tr) to monthly totals:

$$\text{Internal Water Loss} = E + Tr$$

and compared these data with the monthly whole-system water deficit, which we calculated by summing daily inflows (SW_i), rainfall (R), and outflows (SW_o) for the month and subtracting the latter from the former:

$$\text{Water Budget Deficit} = SW_i + R - SW_o$$

SW_i, SW_o, and R measurements were taken from whole-system data sets provided by the City of Phoenix (see Section 2.4 for details). After consultation with on-site engineers, we determined that vertical losses via percolation to groundwater were negligible so this parameter was not included in our water budget deficit calculations.

2.3. Water Quality Sampling

On the same bimonthly schedule described above, we collected water quality samples along both gradients. Triplicate water samples were collected by hand in acid-washed Nalgene bottles at the inflow and outflow points of the study cell, and at the shore and open-water ends of three marsh transects that represented the inflow-outflow whole system gradient (Figure 1). Nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+) samples were centrifuged to remove particulates and analyzed on a Lachat Quick Chem 8000 Flow Injection Analyzer (detection limit 0.85 µg NO_3-N/L and 3.01 µg NH_4-N/L). For simplicity, we will restrict our water quality analysis to dissolved inorganic nitrogen (NH_4^+, NO_3^-, and NO_2^-). Differences in water quality data were determined using a paired t-test for whole-system inflow versus outflow data, while an unequal variance t-test was used for shore versus open water marsh transect data.

2.4. Whole System Data

Our research at the Tres Rios constructed treatment wetland is in partnership with the City of Phoenix Water Services Department, and they provided us with key whole system datasets for our analyses. We used their daily inflow (SW_i) and outflow (SW_o) data (in mgd, converted to $m^3\ d^{-1}$), measured using standard acoustic Doppler flow meters, to calculate total monthly water flux into and out of our study cell from January 2012 through September 2013. For the months when we sampled the system, we combined total monthly water flux with inorganic N concentrations to calculate whole system monthly N loads. We used the previously discussed hourly meteorological station data to scale our transpiration estimates in time and to calculate evaporative water losses from the open-water component of our study cell (see Sections 2.2 and 2.5 for details). Because of inconsistencies in the rainfall data collected by the on-site meteorological station, we summed daily rainfall data from the nearby Goodyear airport to calculate monthly rainfall contributions (R) to the whole system water budget.

2.5. Data-Scaling and Water Budget Calculations

An important step in our whole-system water budget estimates was the scaling of leaf-specific measurements of transpiration water losses from individual plants to 21 ha of marsh, and from transpiration measurements made over the course of individual days to a 2+ year time-series. To scale transpiration water flux across space (Daily Tr_{System}; $m^3\ H_2O\ d^{-1}$ whole system^{-1}), we combined our IRGA measurements (Instantaneous $Tr_{IRGA;}$ mmol H_2O m^{-2} sec^{-1}), corrected for dry-weight plant biomass (Area/Bio; cm^2 gdw^{-1}), with the whole system live macrophyte biomass (Bio_{System}; Mg whole $system^{-1}$) calculated from the bimonthly data collected along our 10 marsh transects (see Weller et al. this issue):

$$\text{Daily } Tr_{System} = \text{Instantaneous } Tr_{IRGA} * \text{Area/Bio} * Bio_{System} * 74.06$$

where 74.06 was a dimensional analysis conversion for mmol H_2O to m^3 H_2O, seconds to days, and gdw biomass to Mg biomass for the 21 ha marsh. To estimate whole system biomass (Bio_{System}) we developed phenometric models that allowed us to non-destructively estimate live biomass for all plant species by making simple allometric measurements in the field (per Daoust and Childers 1998; Childers et al. 2006). Every two months, we measured all of the plants in five 0.25 m^2 quadrats that were randomly located along each of the 10 marsh transects shown in Figure 1, for a total of 50 0.25 m^2 quadrats sampled (for details Weller et al. this issue). We used simple linear interpolation to extrapolate plant biomass between bimonthly samplings, producing daily estimates of live macrophyte biomass from July 2011 through September 2013.

To scale our plant-specific transpirational water losses in time, we used the micrometeorological data generated by the IRGA at the time of sampling and the corresponding hourly data from the on-site meteorological station. Because plant transpiration flux is driven largely by T, PAR, and RH (Sánchez-Carrillo et al. 2001), we first regressed hourly meteorological station data for these three variables against the mean of all IRGA measurements for the same variables for that same hour for each transpiration sampling day. We then generated multiple regression models that related transpiration flux for each macrophyte species (per Mg dry weight of plant biomass) to PAR, T, and RH as measured by the IRGA. These models combined with the IRGA-meteorological station regressions allowed us to use continuous data from the meteorological station to interpolate our species-specific transpiration measurements through time, resulting in whole-system daily transpirative losses (in m^3 H_2O day^{-1} for the 21 ha of vegetated marsh) from July 2011 through September 2013. See Table 1 for a summary of all parameters, applications, methods, and sampling frequencies used to for these calculations.

INSERT TABLE 1 HERE

3. RESULTS AND DISCUSSION

3.1. Transpiration

The phenometric biomass models were the same for *T. latifolia* and *T. domingensis,* and for *S. acutus* and *S. tabernaemontani* (see Weller et al. this issue for details). For this reason we combined our leaf-specific transpiration measurements for both species of each genus in both cases. Transpiration rates for *S. californicus* and *S. americanus* were treated separately and discretely. On a typical hot, dry day in July, these rates were as high as 10, 14, 13, and 9 mmol H_2O m^{-2} leaf area s^{-1} for *Typha* spp., *S. acutus* + *S. tabernaemontani*, *S. californicus*, and *S. americanus*, respectively. In January, when air temperatures were low and plant biomass was at its annual minimum, the highest transpiration rates were only 2, 4, 4, and 6 mmol H_2O m^{-2} leaf area s^{-1} for *Typha* spp., *S. acutus* + *S. tabernaemontani*, *S. californicus,* and *S. americanus,* respectively. These rates equated to July 2011 averages of 30 ± 0.8, 16 ± 0.4, 0.6 ± 0.3, and 9.6 ± 0.02 mm day^{-1} and January 2014 averages of 1.7 ± 0.2, 1 ± 0.03, 0.4 ± 0.03, and 0.4 ± 0.03 mm day^{-1} for the entire standing stock of *Typha* spp.*,* *S. acutus* + *S. tabernaemontani, S. californicus,* and *S. americanus,* respectively. By comparison, Pedescoll et al. (2013) found that a *T. angustifolia*-dominated constructed wetland in a similarly arid climate transpired a maximum of 23 mm day^{-1}, which is similar to the maximum rates from our treatment wetland. In contrast, individual *T. domingensis* plants in the humid, mesic Florida Everglades transpired up to 11 mmol m^{-2} sec^{-1} (Koch and Rawlik 1993)—well below the maximum plant-specific rates we measured for this species. Reported transpiration rates for *Typha* spp. are even lower in cooler climates: 5.8 ± 0.9 mm day^{-1} in marshes along Oneida Lake NY USA (Pauliukonis and Schneider 2001) and 6.5 mm day^{-1} in marshes in Ohio, USA (Martin et al. 2003). These findings illustrate the dramatic differences in transpiration water loss between hot, arid and cooler, mesic wetlands.

We scaled these leaf-specific IRGA gas flux measurements in time to generate estimates of daily water loss by plant transpiration for the entire 21 ha vegetated marsh using hourly data from the on-site meteorological station. Regression relationships between meteorological station data and measurements within the canopy allowed us to extrapolate transpiration measurements between our bimonthly samplings. Multivariate regressions relating transpiration rate to T, RH, and PAR found that only T and PAR were significant predictors of transpiration by all four plant species groups, with relatively little interspecies variation in the strength of the relationships (r^2 =

0.57 to 0.67; all p-values <0.01). We scaled leaf-specific transpiration measurements in space using the live macrophyte biomass estimates for each species group from Weller et al. (this issue) after converting transpiration rates from mmol H_2O m^{-2} leaf area s^{-1} to ml H_2O gdw biomass^{-1} day^{-1} and ultimately to m^3 H_2O day^{-1} for the entire 21 ha marsh. We found considerable variation in transpirative water losses among the four species groups, with *Typha* spp. having the largest average transpiration rate (2614 ± 58 m^3 H_2O day^{-1} or 12.45 ± 0.28 L H_2O m^{-2} day^{-1}) and *S. californicus* the lowest average rate (221 ± 5 m^3 H_2O day^{-1} or 1.05 ± 0.02 L H_2O m^{-2} day^{-1}). Most, but not all, of this variation was driven by differences in the amount of live biomass (Weller et al. this issue). In fact, although *Typha* spp. has been steadily taking over the macrophyte community in our study wetland (Weller et al. this issue), *S. acutus* and *S. tabernaemontani* continued to make a contribution to overall daily transpirative water losses that was disproportionate to their contributions to total biomass (Figure 2). This disproportionate contribution to daily transpirative water loss was likely due to the fact that these large-stemmed bulrushes transpire considerably more water per unit biomass than do cattails.

INSERT FIGURE 2 HERE

As expected, all species groups showed strong seasonality, with the highest transpirational water losses in the hot, dry summer months and the lowest losses in the winter months (Figures 2 and 3). While close relationships between transpiration and seasonal variation in climate and biomass have been well documented in the literature (e.g. Moro et al. 2004; Pedescoll et al. 2013), the rates of water transpired from our Tres Rios system were considerably higher than even those from other arid wetlands. For example, Drexler et al. (2008) found that an arid wetland in California, USA transpired on average 6 mm day^{-1}, and Goulden et al. (2007) reported peak annual transpiration of less than 5 mm day^{-1} for another marsh in California. A study conducted by Bialowiec et al. (2014) in a cooler, more mesic wetland in Poland reported a maximum system-wide transpiration rate of 4.6 mm d^{-1}, and Abtew (1996) found that *Typha*-dominated marsh systems in the warm, humid Florida Everglades had maximum transpirational losses of only 3.6 mm day^{-1}. Overall, Tres Rios had transpirative water losses that were as much as an order of magnitude greater than has been reported for other wastewater treatment wetlands.

Whole-system macrophyte biomass exhibited regular seasonality, with peak biomass in July of approximately 400 to 600 Mg for the 21 ha marsh (Figure 3). As expected, whole-system transpiration losses closely mirrored plant biomass (Figure 3). The highest total monthly transpiration losses of approximately 200,000 to 300,000 m^3 for the 21 ha marsh were in June and July, when ambient air temperatures regularly exceeded 45°C and relative humidity was typically below 10%, and often below 5%. As we noted above, during this study, the plant community was tending towards a bi-specific stand of *T. domingensis* and *T. latifolia*, but the contribution of several *Schoenoplectus* species to transpiration flux remained strong (Figure 2).

INSERT FIGURE 3 HERE

3.2. Whole System Water Budget

Daily inflow and outflow data for our wetland study cell were used to calculate whole-system monthly water deficits. The inflow sensor was not fully operational until January 2012, and therefore whole-system water deficit was not calculated until January 2012 (Figure 4). The whole-system water budget was dominated by transpirational water losses and open water evaporation, the latter of which represented a lower fraction of our total water budget—on the order of a third or less—during the hotter months when plant biomass was higher and the plants were most productive (Figure 4). Notably, precipitation was only a small fraction of the water budget. During our study, Tres Rios received 105 mm (105 L H_2O m^{-2} yr^{-1} or 44,100 m^3 yr^{-1}), 122 mm (122 L H_2O m^{-2} yr^{-1} or 51,240 m^3 yr^{-1}), and 167 mm (167 L H_2O m^{-2} yr^{-1} or 70,140 m^3 yr^{-1}) of rainfall annually in 2011, 2012, and 2013 respectively. These inputs were very small when compared with transpiration and evaporation losses of 2.5 – 3.0 million m^3 y^{-1}. In 2012 and 2013, precipitation comprised on average 0.8% (with a maximum of 4.1% in January 2013) of the whole system monthly water deficit, while from 2011 to 2013 precipitation comprised on average only 1.9% (with a maximum of 16.2% in December 2012) of the total water losses via transpiration and open water evaporation.

INSERT FIGURE 4 HERE

In many months our transpiration + evaporation-based water budget was remarkably consistent with the inflow-outflow deficits, particularly in 2013 (Figure 4). We found that transpiration + evaporation represented an average of 70% of the whole-system water deficit throughout the study period (67% if March-May 2012 are included; see Figure 4 legend for explanation). This consistency lends confidence in our scaled-up transpiration measurements and calculations of open water evaporation. Notably, these contributions of evaporation and transpiration are much higher than those reported for constructed wetlands in mesic, humid climates. For example, Meuleman et al. (2003) reported that transpiration and evaporation comprised only 13% of the water budget for a constructed wetland in the Netherlands, where the climate is considerably cooler, more humid, and wetter than in Phoenix. Similarly, Kadlec et al. (2010) reported that transpiration and evaporation represented only 3% of total water outputs for a treatment wetland in Columbia, Missouri, USA and Favero et al. (2007) reported that these two water losses comprised only about 10% of the water budget for a constructed wetland near Venice, Italy.

3.3. Water Quality and Nitrogen Budget

We focused our analysis of nutrient sequestration on nitrogen (N), specifically dissolved inorganic nitrogen (NO_3^- and NH_4^+), because this was the focus of the City's Clean Water Act permit for the treatment wetland. At the whole-system scale, inflow loads of both NO_3^- and NH_4^+ were nearly always higher than outflow loads (Figure 6a and 6b), with inflow loads averaging 532 ± 84 (SE) kg d^{-1} and 169 ± 19 (SE) kg N d^{-1} and outflow loads averaging 417 ± 67 (SE) kg N d^{-1} and 87 ± 17 (SE) kg d^{-1} for NO_3^- and NH_4^+, respectively. The monthly whole-system N uptake rates averaged 3.51 ± 0.98 (SE) (16.71 ± 4.66 g N m^{-2} mo^{-1}) and 2.48 ± 0.61 (SE) (11.81 ± 2.90 g N m^{-2} mo^{-1}) Mg N mo^{-1} for NO_3^- and NH_4^+, respectively, from July 2011 through September 2013. On average, 22% of nitrate inputs and 48% of ammonium inputs were taken up between the whole-system inflow and outflow in spite of the short water residence time of the system and the likelihood that much of this water did not come into physical contact with the vegetated marsh that makes up 50% of the system by area.

INSERT FIGURE 5 HERE

Within the vegetated marsh, we were able to compare N concentrations along the three marsh transects but did not have water flux data to calculate actual nutrient removal rates. Still, we consistently found much lower concentrations of dissolved inorganic N in the near-shore water overlying the marsh, compared with concentrations at the marsh-open water interface. This pattern was most dramatic for NO_3^-, with near-shore concentrations that were often at or below the detection limit (Figure 6a). Marsh removal of NH_4^+ was also consistent through time and across seasons, but was less dramatic than with NO_3^- (Figure 6b). Weller et al. (this issue) estimated N uptake rates by the plants themselves based on productivity and tissue stoichiometry and found that 19% of the whole-system N removal could be directly accounted for by plant uptake. Even without actual nutrient flux estimates, it seems clear that the vegetated marsh was active and efficient in N removal, regardless of time of year.

INSERT FIGURE 6 HERE

3.4. A Plant-Mediated "Biological Tide"

The N concentration data from along our marsh transects (Figure 6) suggested that whole-system efficiency might easily be improved if more N-rich water could directly interact with the vegetated marsh. One possible mechanism for this is the lateral movement of water into the marsh to replace losses via plant transpiration, particularly in the summer when the plants are most productive, soil temperatures are highest, and transpiration is maximal. This lateral movement of water into the vegetated marsh is what we are calling a plant-mediated "biological tide." We refer to it as a "tide" because it is an active horizontal advection from open water areas into the vegetated marsh that is analogous to astronomical tides seen in coastal wetlands. To our knowledge, this is the first time that such control of surface hydrology by plants has been documented in a wetland.

We investigated this "biological tide" by calculating the volume of water overlying the marsh that was lost daily to transpiration. Water depth measurements at the 50 transect points where aboveground plant biomass was measured showed that water depth was consistent across space and time, with a mean of 24 cm. We subtracted the portion of this water volume that was occupied by plant stems by scaling up stem culm diameter measurements, and used this corrected volume to estimate transpirational losses. During the summer months, as much as 15 – 20% (approximately 8,000 to 11,000 m^3 H_2O day^{-1}) of the total volume of water overlying the marsh was transpired daily and must have been replaced by a lateral flow from the open-water areas to maintain the observed constant water depths (Figure 7). These values are conservative estimates because we were not able to account for the volume of water occupied by extensive thatched dead vegetation (i.e., wrack) on the marsh surface, thus suggesting that summertime water residence times in the marsh were likely less than 4-5 days.

INSERT FIGURE 7 HERE

These transpirative losses from the vegetated marsh, and lateral flow to replace them, were thus substantial. We argue that this plant-driven control of wetland hydrology, or "biological tide", may be an important mechanism in arid systems to move additional nutrients into the marsh for uptake and processing (Figure 8). This "biological tide" is pulling water and nutrients both laterally into the marsh and vertically down into the soils, creating more opportunities for plants to take up N and for soil microbes to process N and other bioactive solutes as Martin et al. (2003) and others have suggested. In fact, we argue that this “biological tide” phenomenon makes the Tres Rios treatment wetland more efficient at nutrient removal, and thus more effective at providing desired ecosystem services, than its counterparts in more mesic, humid climates. This phenomenon may actually be at work in many other treatment wetlands located in hot, dry climates. However, the high volume of water loss that drives the “biological tide” means that there is a trade-off between the provision of water-cleansing ecosystem services and the volume of water with improved water quality that can be exported from these systems for local reuse.

INSERT FIGURE 8 HERE

3.5. Summary

We found that water losses due to transpiration and evaporation were remarkably high compared with constructed wetlands in more humid, mesic climates. Total water losses via both processes peaked at over 300,000 m^3 $month^{-1}$ in the hot, dry summer months and averaged more than 70% of the whole-system water losses from June 2011 through September 2013. We found that large transpirative water losses actually appeared to enhance N removal efficacy relative to humid, mesic systems by drawing large volumes of replacement water and solutes into the marsh via a “biological tide”. This plant-mediated “tide” appears to be replacing more than 20% of the total volume of water overlying the marsh during hot, dry summer months. Transpiration-driven movement of shallow subsurface water has been documented in a number of wetlands, including into tree islands in the Okavango Delta in Botswana (Bauer-Gottwein et al. 2007, Ramberg and Wolski 2008) and in the Florida Everglades (Bazante et al. 2006, Troxler-Gann and Childers 2006, Sullivan et al. 2012). But, to our knowledge, this is the first time that biotically-mediated surface hydrology has been demonstrated in any wetland.

ACKNOWLEDGEMENTS

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FIGURE LEGENDS

Figure 1: The Tres Rios constructed treatment wetland cell used in this study. Blue arrows show the effluent inflow and outflow points and white lines are the approximate locations of the 10 marsh transects (each 50 – 60 m long). Water quality samples were collected at the inflow and outflow points and at 1) the northernmost transect closest to the inflow, 2) the southernmost transect nearest to the outflow, and the 3) eastern transect in between them. Total cell area = 42 ha; 21 ha of vegetated marsh and 21 ha of open water.

Figure 2: Total daily water loss via plant transpiration from the 21 ha of vegetated marsh. TYPHA=*Typha domingensis* and *T.latifolia*; SAC/STAB=*Schoenoplectus acutus* and *S. tabernaemontani*; SAM=*S. americanus*, and; SCAL=*S. californicus*.

Figure 3: Total live aboveground macrophyte biomass and total monthly transpiration water losses from the 21 ha marsh. Note that MT is equivalent to Mg.

Figure 4: Monthly total water losses due to open water evaporation and plant transpiration (stacked bars) compared with the inflow – outflow whole system water deficit. Note that the inflow sensor was not working properly prior to January 2012 or in March through May 2012.

Figure 5: Whole system nitrate (A) and ammonium (B) flux into the study cell (circles) and out of the study cell (squares).

Figure 6: Vegetated marsh concentrations of nitrate (A) and ammonium (B) flux near the shoreline (circles) and at the marsh-open water interface (squares) of the three water quality marsh transects.

Figure 7: Estimates of the volume of water overlying the 21 ha of vegetated marsh that was transpired daily by the plants and had to be replaced by the “biological tide”.

Figure 8: Conceptual schematic of our hypothesized “biological tide” in which high rates of plant transpiration, particularly during the hot, dry summer months, drive a lateral movement of water and solutes into the marsh and vertically down into marsh soils from the open-water areas. This biotically-mediated water flow may be replacing the entire volume of water overlying the marsh every 4 – 5 days at peak transpiration rates.

FIGURES

Figure 1:

Figure 2:

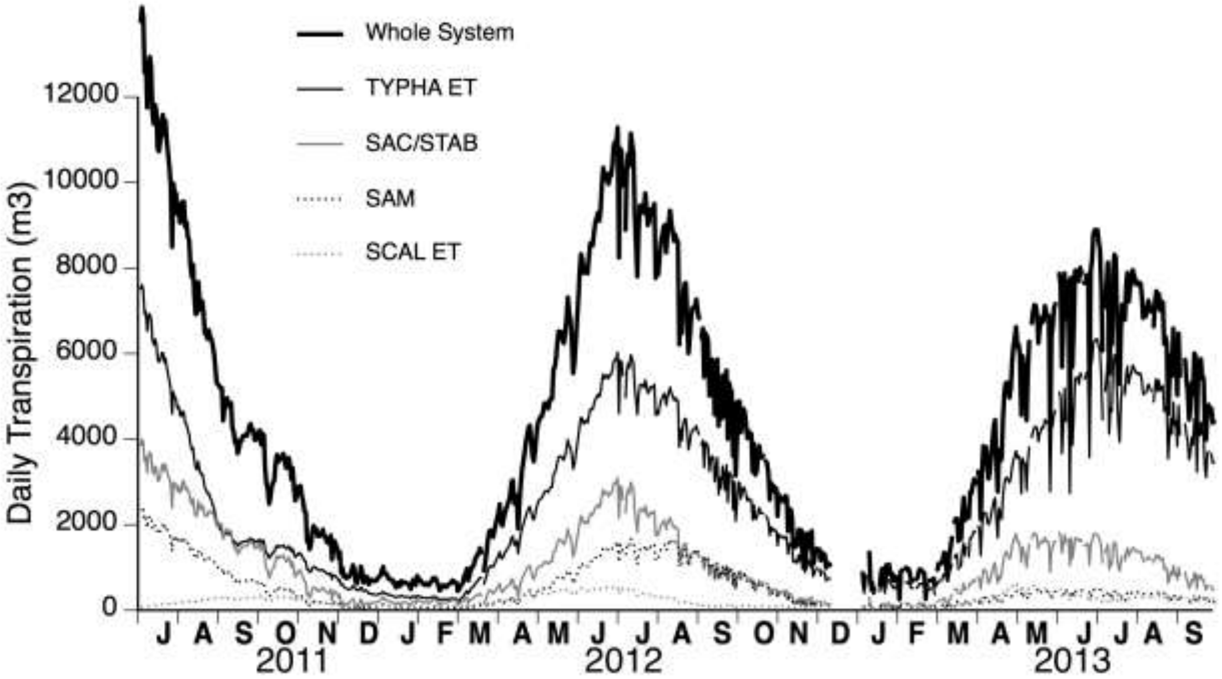
Whole System
TYPHA ET
SAC/STAB
SAM
SCAL ET
Daily Transpiration (m3)
12000
10000
8000
6000
4000
2000
0
J A S O N D J F M A M J J A S O N D J F M A M J J A S
2011
2012
2013

Figure 3:

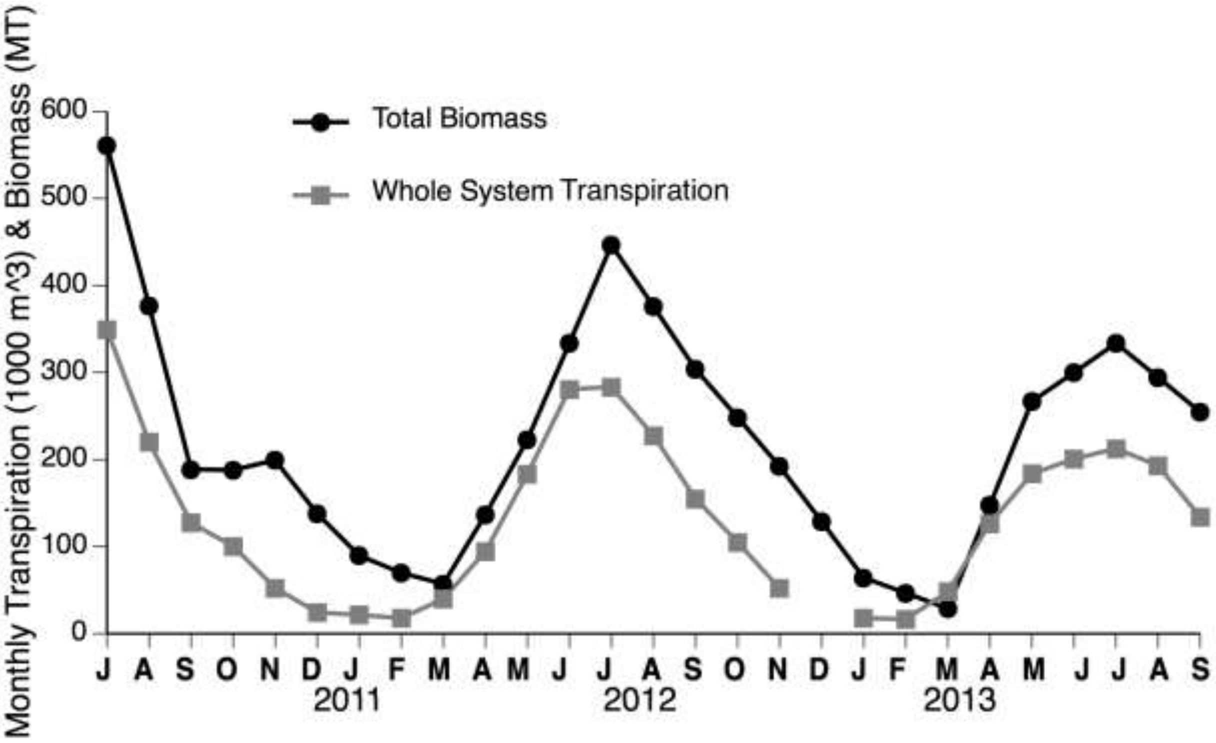
Monthly Transpiration (1000 m^3) & Biomass (MT)
600
500
400
300
200
100
0
Total Biomass
Whole System Transpiration
J A S O N D J F M A M J J A S O N D J F M A M J J A S
2011
2012
2013

Figure 4:

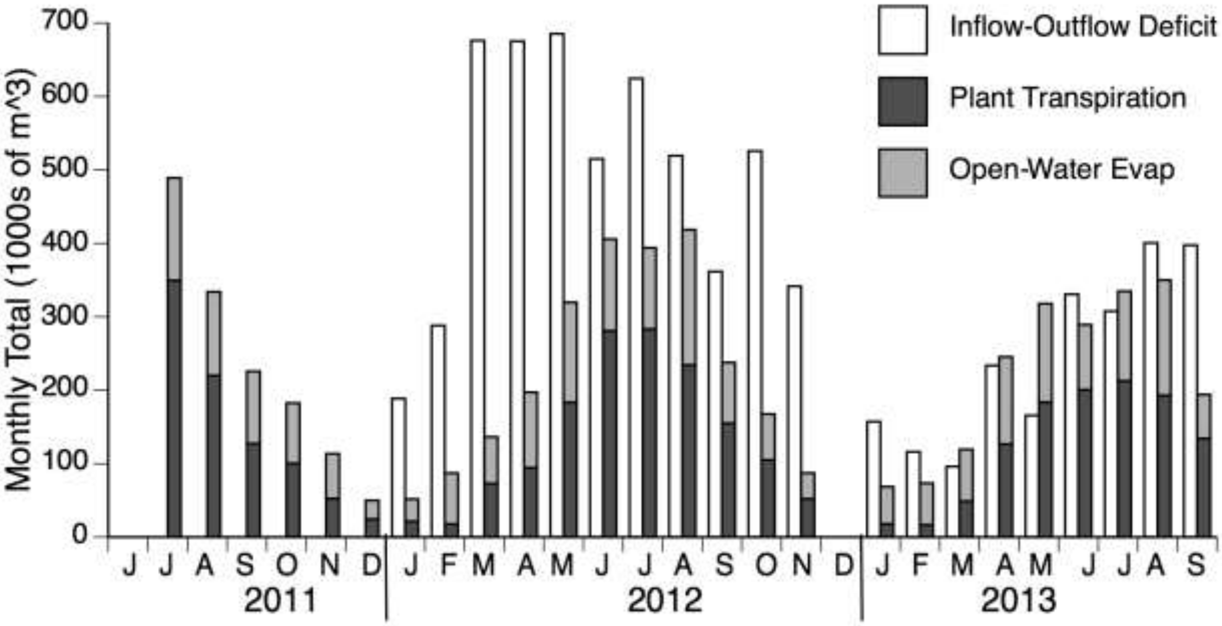
Inflow-Outflow Deficit
Plant Transpiration
Open-Water Evap
Monthly Total (1000s of m^3)
700
600
500
400
300
200
100
0
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
2011
2012
2013

Figure 5:

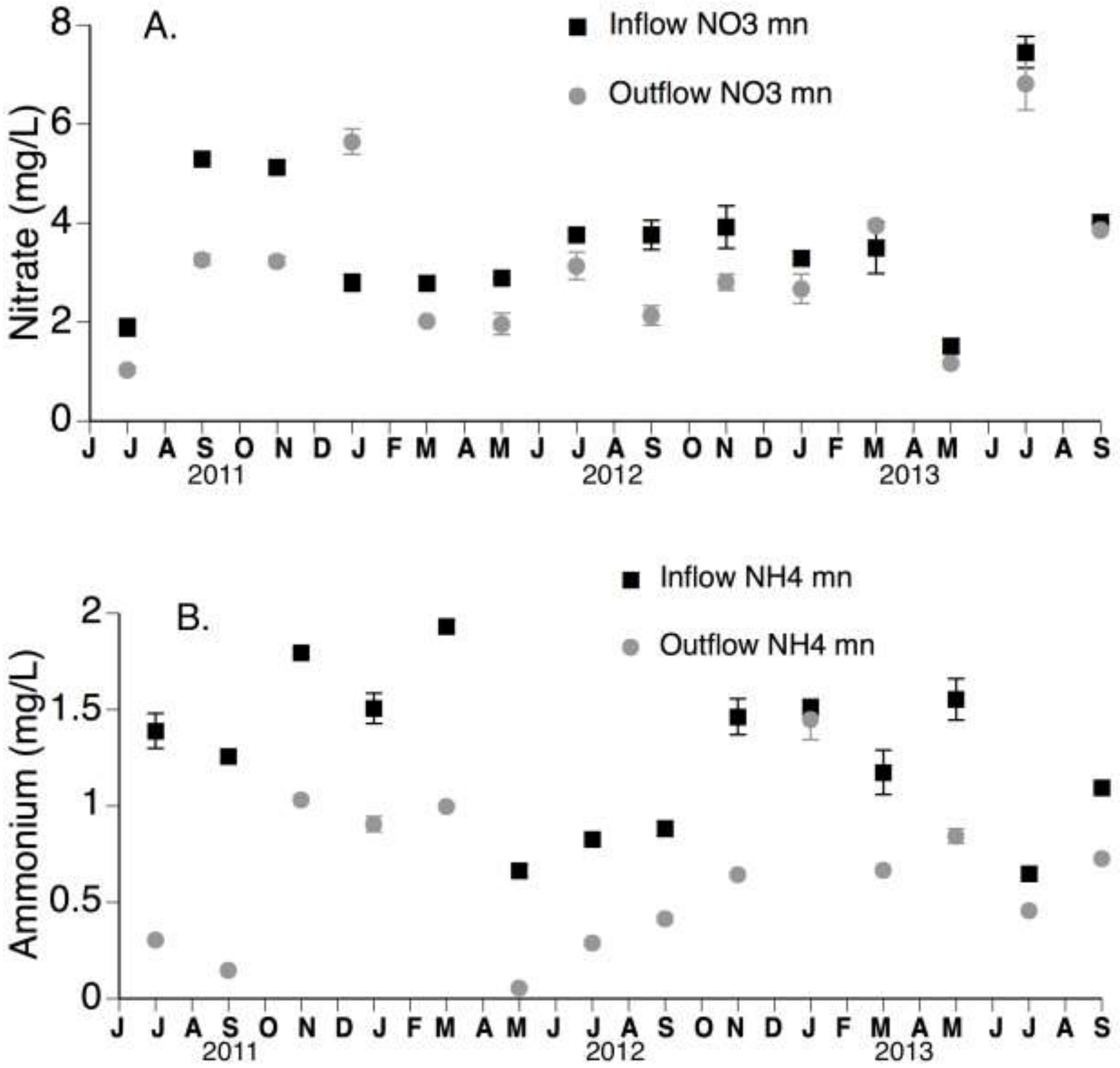
A.
Inflow NO3 mn
Outflow NO3 mn
Nitrate (mg/L)
0
2
4
6
8
J J A S O N D J F M A M J J A S O N D J F M A M J J A S
2011
2012
2013
B.
Inflow NH4 mn
Outflow NH4 mn
Ammonium (mg/L)
0
0.5
1
1.5
2
J J A S O N D J F M A M J J A S O N D J F M A M J J A S
2011
2012
2013

Figure 6:

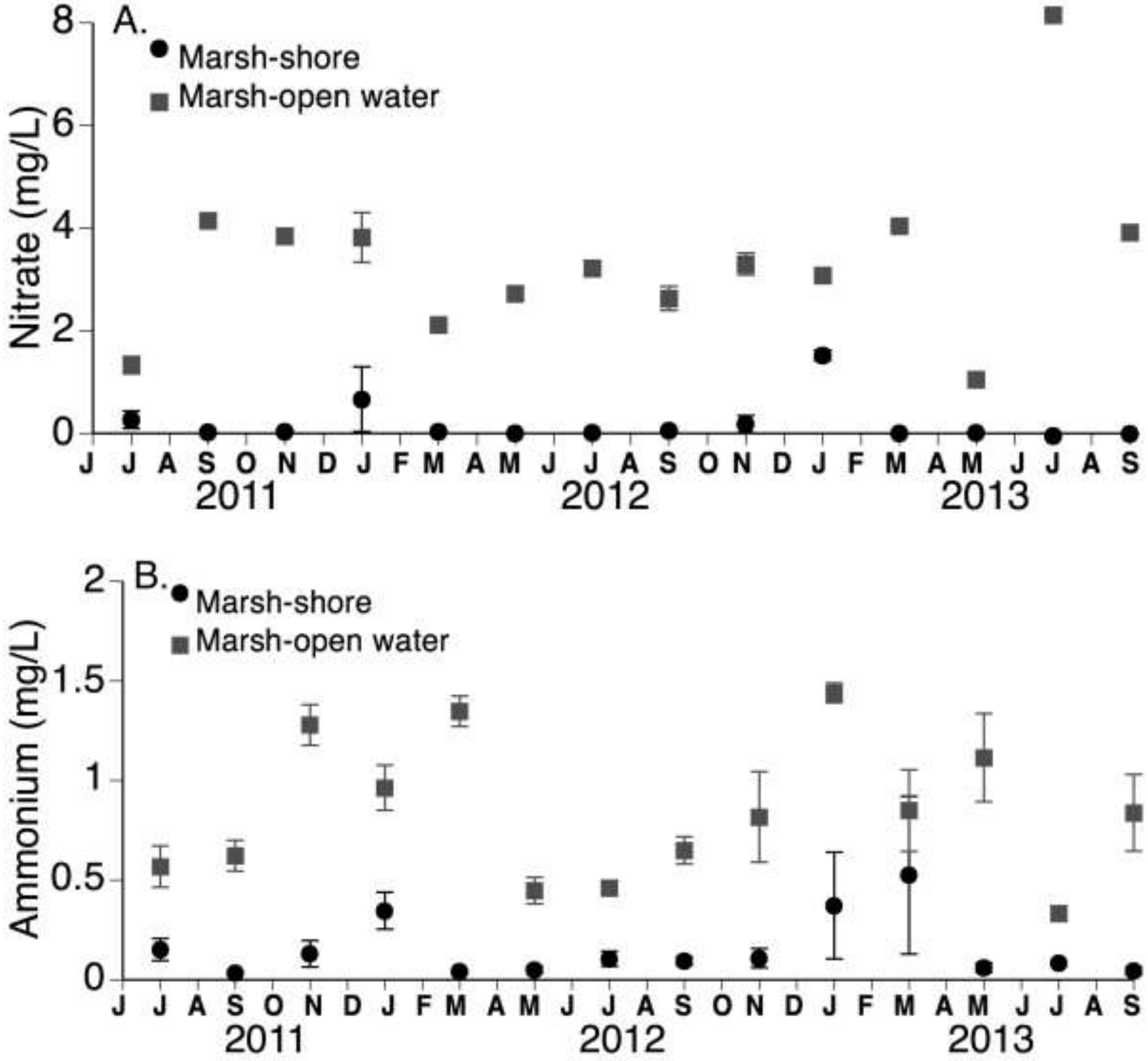
A.
● Marsh-shore
■ Marsh-open water
Nitrate (mg/L)
8
6
4
2
0
J J A S O N D J F M A M J J A S O N D J F M A M J J A S
2011
2012
2013
B.
● Marsh-shore
■ Marsh-open water
Ammonium (mg/L)
2
1.5
1
0.5
0
J J A S O N D J F M A M J J A S O N D J F M A M J J A S
2011
2012
2013

Figure 7:

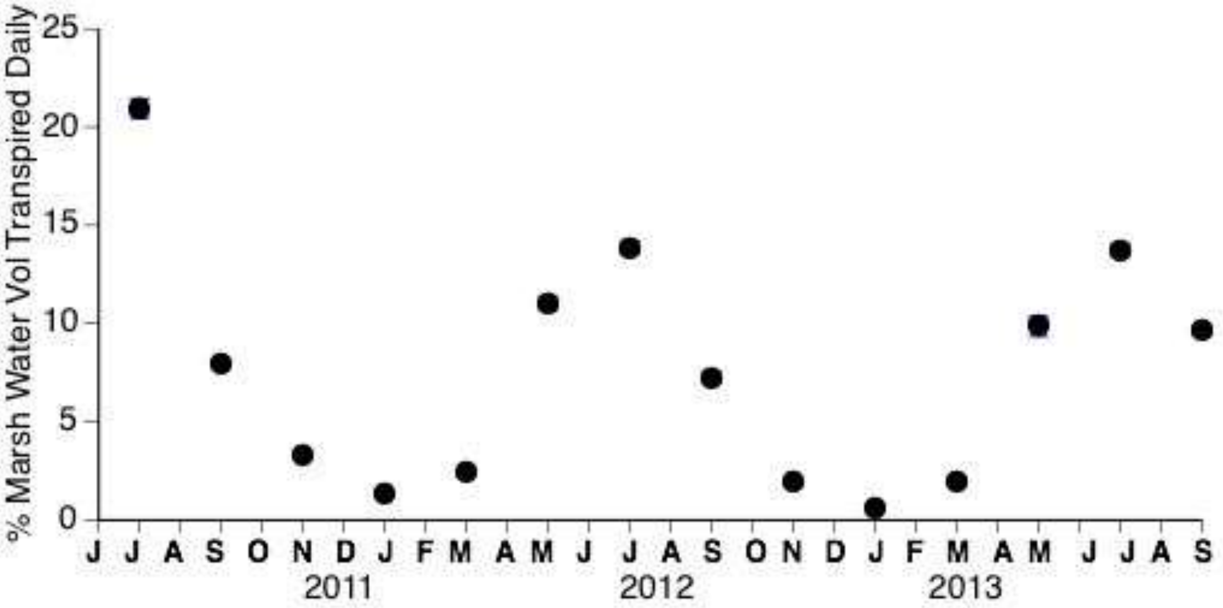
% Marsh Water Vol Transpired Daily
25
20
15
10
5
0
J J A S O N D J F M A M J J A S O N D J F M A M J J A S
2011
2012
2013

Figure 8:

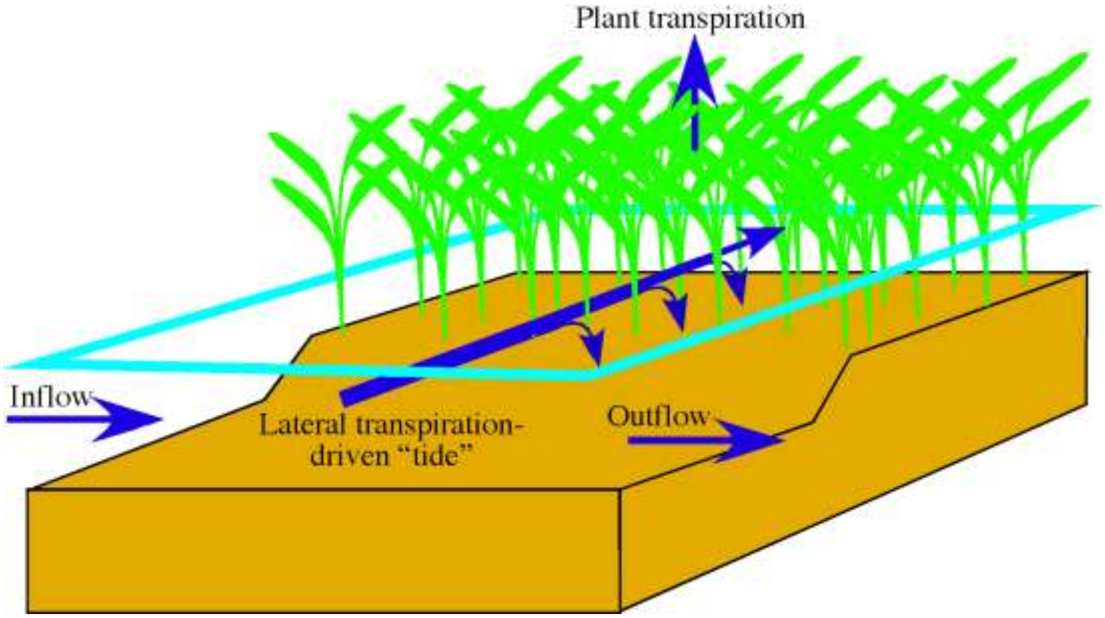
Plant transpiration
Inflow
Lateral transpiration-driven “tide”
Outflow

TABLE LEGENDS

Table 1: Summary of the parameters, applications, methods, and sampling frequencies for all variables used to estimate whole-system plant transpiration, open water evaporation, and water budgets.

TABLES

Table 1:

Parameter and Application	Methods	Data Frequency
Transpiration, leaf area, leaf-level RH, leaf-level PAR, leaf-level T; used to estimate whole system plant transpiration	Infrared Gas Analyzer (IRGA)	Bi-monthly
Ambient RH, ambient PAR, ambient T, wind speed, vapor pressure deficit, R; used to calculate open water evaporation and to scale plant transpiration in time	On-site meteorological station (City of Phoenix)	Hourly
Surface water inflow, surface water outflow; used to calculate water budget deficit	Acoustic Doppler flow gauges (City of Phoenix)	Daily
Aboveground plant biomass for 4 species groups; used to scale plant transpiration in space	Non-destructive phenometric technique (Weller et al. this issue)	Bi-monthly