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Hope, Knowledge, and Opportunity

March 31, 2016

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Dear Dr. Coronado,

Please find enclosed a final report for the project entitled “Surface water – groundwater interactions in Everglades tree islands” (PO# 4600002784).

Best Regards,

Tiffany Troxler

Florida International University

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SURFACE-GROUNDWATER INTERACTIONS IN EVERGLADES TREE ISLANDS – FINAL REPORT

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March 31, 2016

MANUSCRIPT TITLE

Ecohydrology and phosphorus dynamics of Everglades tree islands along an environmental disturbance gradient

Abstract

Historical information suggests that tree island development was associated with seasonal drying and peat accumulation in the near tail that contributed to differentiation of plant communities within the tree island and high soil P in the high head (community with seasonally dry soils). Further studies showed the high P is associated with CaP, that with concentration of ions through plant transpiration (diurnal drawdown) and evaporation, mineral formation is favored. During diurnal drawdown, rewetting and infiltrating rain water provides a mechanism promoting P release. P release under conditions favoring mineral precipitation permits reformation of mineral-bound P as Ca-P, promoting the maintenance and sequestration of soil P. Seasonal change in regional water table and soil surface vertical elevation interact to create soil water conditions that can either promote mineral precipitation or dissolution. Fluctuation between precipitation and dissolution can enable sequestration, but only where mineral saturated conditions persist. We evaluated conditions for a "pristine" tree island to develop targets for restoration of degraded tree islands.

We found that a "pristine" tree island exhibits: 1) vertical position of the soil surface and water table variation relative to soil surface allows differentiation of annual hydroperiod, with greatest differentiation between high head and wet head, near tail and marsh, 2) differentiation of plant communities, with both mineral soils and peat forming soil plant communities, 3) soil water supersaturated in minerals in the high head plant community seasonal diurnal drawdown that enables evapoconcentration and ion exclusion to create soil water that favors mineral precipitation, 4) consistently low soil water P, and high soil P that persists through the soil profile, and 5) regional hydrologic conditions that favor lateral transport for secondary sequestration of phosphorus.

Comparing these criteria for "pristine" tree islands to tree islands under study in 3A and 3B illustrate how degraded tree islands deviate from characteristics of a "pristine" island. Taken together, we found that islands we intensively studied here deviated from a "pristine" islands in nearly all criteria developed. Furthermore, we developed a new proxy for the drying-rewetting dynamic, and found that very low water level promoted high porewater recharge and potential for soil PO4 release facilitated by strong drying-rewetting throughout the year and very high water level eliminated the potential for evapoconcentration (ion accumulation and supersaturated soil water the contributes to mineral precipitation, potential for soil formation and soil P maintenance). Overall, calcretization was found to decrease porosity and permeability, and very long or very short hydroperiods can degrade the calcrete layer that serves multiple purposes for tree island maintenance.

Introduction

In the late 1800's and the early 1900's, long stretches of canals were dug in attempts to drain the relatively pristine Everglades for agriculture and early development. Natural disturbances such as hurricanes and devastating floods led to construction of the Herbert Hoover Dike around Lake Okeechobee and Federal authorization (1948) of the Central and South Florida (C&SF) Project, creating an elaborate network of canals, levees, and water control structures to improve regional flood control and water supply (Light and Dineen 1994). The C&SF Project combined with more recent urban and agricultural development has led to an approximately 50% reduction in spatial extent of the Everglades, and has fragmented once-continuous Everglades wetlands into a series of large impoundments with dramatically altered flows and hydropatterns. With agricultural and urban runoff, much of the inflow to the Everglades carried higher loads of nutrients into historically oligotrophic wetlands, leading to large-scale ecosystem degradation (McCormick et al. 2002). Collectively, these impingements to the Everglades have created an altered regime of flooding, hydroperiod, fire, and eutrophication that has affected nearly all trophic and landscape components of the ecosystem (Sklar et al. 2005).

A variety of projects are underway to restore the Everglades by optimizing management of hydrology and water quality, two fundamental drivers of Everglades ecology. Central to these efforts is the Comprehensive Everglades Restoration Plan (CERP), a multi-billion dollar, multi-decadal project that is attempting to restore the remnant Everglades. Under the CERP, there will be significant decompartmentalization (i.e., removing levees impounding parts of the Everglades) with increased water storage and flows in the greater Everglades system (USACE and SFWMD 1999). The most significant opportunity to jumpstart restoration will be the Central Everglades Planning Project (CEPP), an integration of multiple CERP projects that will focus on the core Everglades ecosystem, including Everglades National Park (USACE and SFWMD 2014; Davis et al. 2014). As CEPP and other CERP and non-CERP restoration projects (e.g., Tamiami Trail bridging) are built, we expect to see incremental improvement in hydrologic conditions in the coastal Everglades. Yet, across the Water Conservation Areas, large areas continue to experience overdry and overflooded conditions which has significant implications for ecosystems across the landscape, including tree islands. Specifically, drainage and excessive flooding have reduced the area and extent of tree islands. This has resulted not only in the loss of forest structure but also the potential loss of soil P retained in these tree islands (Patterson and Finck, 1999). The effects of P enrichment in Everglades marshes are well-known but generally constrained to point-sources of agricultural run-off (Davis and Ogden, 1994). Loss of tree island soil structure threatens to exacerbate water quality issues related to P enrichment through localized run-off. Reduced landscape habitat quality for Everglades fauna is also of great concern (Gawlik and Rocque, 1998).

The mobility and transfer of limiting resources is a fundamental premise governing ecosystem structure and processes (McClain et al., 2003). In the Florida Everglades, tree islands are exemplary; many tree islands have upland, forested (e.g., High Head or Dry Head) plant communities with high concentrations of phosphorus (P) on mineral soils in an otherwise highly oligotrophic, P-limited marsh landscape (Noe et al., 2001; McCormick et al., 2009; Ross and Sah, 2011;

Wetzel et al., 2011). Tree islands in areas of the remnant deep-water slough often have an elongated "tear-drop" shape that are parallel to the historic flow direction (Wetzel et al., 2005; Ross et al., 2006). This type of tree island is also comprised of forested and herbaceous wetland plant communities downstream of the upland community. Here, aboveground biomass and soil P concentrations are further stratified along a distinct forest-marsh gradient (see reviews by Wetzel et al., 2005, 2011). Observations of this well-delineated patterning suggest that the distribution of P is fundamental to the ecosystem structure and functioning of this type of tree island. Internal P dynamics and relationships with regional hydrologic pattern are fundamental to understanding: (1) processes that have preserved tree island soil P for millennia and (2) the potential for restoring them where they have been lost.

Key Management Questions for tree islands in the Everglades include: 1) How to maintain the soil P reserve to prevent P enrichment of local, oligotrophic marsh communities? 2) How can we restore tree islands structure and function where they have been degraded or lost? 3) How can we determine targets and metrics? One means by which we can answer these questions is by defining characteristcs of a "healthy" or "pristine" tree island, and developing targets based on those conditions. We can use both what we know about the history of tree island development and current conditions of "healthy" tree islands to guide this work. Paleoecological data in association with hydrologic change show that the advent of tree island development associated was with "seasonal drying" (Willard & Bernhardt 2011) and that there was the greatest peat accumulation in the "neartail" (Jones, Bernhardt & Willard 2014). Further studies illustrated that tree island ecosystems are typified by intra-ecosystem (tree island communities) and inter-ecosystem (tree island vs. marsh) variation and high soil phosphorus concentrations in high head soils (Figure 1). For example, The greater the difference between marsh and head elevation, the higher the total phosphorus on the head (Wetzel et al., 2009. Plant Ecology, Irick, Troxler). Current conditions based on these concepts of focusing on seasonal drying, variation within and among islands in vegetation and soil P are useful, especially in the context of regional hydrology. Later studies showed how plant transpiration, evaporation and water flux influence subsurface geochemistry and biogenic calcium phosphate deposition, and that these dynamics are modulated by water depth relative to the soil surface through evapotranspiration and rain events. The TTPR model was applied and was useful in helping to understand these interrelationships and how high P can be maintained in pristine tree islands.

The objectives of this study were to evaluate how 4 tree islands across the WCA3A and 3B exhibited conditions for "pristine" tree islands. We used criteria developed for a "pristine" tree island. We hypothesized that: (1) conditions conducive to mineral precipitation were consistent with seasonal drying-rewetting of surface soils in high head communities and (2) soil P was consistent across the soil depth profile in islands where seasonal drying-rewetting occurred.

Methods

Study Design

Our study was conducted in four tree islands in the southern Water Conservation Area 3A (WCA 3A) and in Water Conservation Area 3B (WCA 3B; Figure 2). These islands were 3AS3 (25°51'24.00"N and 80°46'10.80"W) and Ghost Island (25°54'50.10"N and 80°39'18.10"W) in WCA 3A and Twin Heads (25°49'21.40"N and 80°37'32.11"W) and 3BS2 (25°53'20.92"N and 80°33'45.51"W) in WCA 3B. The tree island 3AS3 is located within a relatively intact ridge-slough mosaic and considered to be a relatively intact tree island. The "Ghost Island" is located in an area of WCA 3A that is considered impounded, resulting in over-flooding on the tree island. The Twin Heads and 3BS2 islands are in an overdry basin. All tree islands of our study are fixed tree islands with vegetative communities described as high head (HH), wet head (WH), and near tail (NT). Downstream of the HH, in a lateral orientation, are the WH and NT plant communities. Due to funding constraints, the sampling design selected was one that would provide the minimum level of information necessary to characterize variation in plant community hydrology and plant-water interactions.

The islands in this study were selected based on their disturbance regime to represent a gradient of hydrologic conditions determined by local water management and degree of island degradation. In WCA3A, a water management basin know to be well-hydrated to overflooded depending on location within the basin, 3AS3 represents a wet, well-preserved island, located in a well-hydrated area of the basin while Ghost Island serves as the wet, degraded island along the hydrologic/disturbance gradient, and is located in an area where ponding frequently occurs. In WCA 3B, islands Twin Head and

3BS2 tend to be overdry, but are thought to have different disturbance regimes. In these islands, High Head plant communities are no longer clearly discernible from other tree island plant communities and exotic plant species have been observed in both islands.

The HH in the 3AS3 tree island is dry with typically no standing water throughout the year. The WH vegetation is of shorter stature and the NT community is intermixed with shrubs and trees with open herbaceous vegetation in areas. In the Ghost Island, vegetation of the HH is more typical of a wetter environment, with pond apple (*Annona glabra*) dominating the canopy throughout the High and Wet Head communities. The NT vegetation on the Ghost Island is more typical of the "far tail" (FT) plant community on 3AS3 and comprised of relatively dense sawgrass (*C. jamaicense*) intermixed with shrub and other herbaceous vegetation. Overall, species composition of 3AS3 vegetation communities is less so whereas species composition of the Ghost Island is fairly uniform with vegetation communities apparently differentiated by their structure (i.e. density, canopy height). The Twin Heads island has vegetation characterized by ruderal species in the driest plant community surrounded by an extensive pond apple (*Annona glabra*) forest. More information is needed about the vegetation structure of 3BS2. Hydrostratigraphic characterization of the 3AS3 tree island provides evidence that the high head coincides with a topographic high that originated with the underlying Pliocene Tamiami sand formation and Pleistocene age marine limestone (McNeill and Cunningham 2003). The hydrostratigraphy of the other three islands has not been reported to our knowledge. Less is know about the hydrostratigraphy of other islands, but elevation data were obtained for each islands.

Hydrogeochemical characterization.

Well design. We installed wells in each of the tree islands, all of which were completed by August 2013. The general schematic of the well installation design entailed installations of wells in each of 7 locations (well clusters), red well clusters having wells installed and cased to 3 depths (0.3m, 0.6m and 0.9m) and black well clusters with wells installed and cased to 2 depths (0.3m and 0.6m) below the soil surface (**Figure 3**). Three well depths were sampled in interior well clusters of the High Head (HH) and Wet Head (WH) locations. In the Neartail (NT) and marsh locations, wells at 2 depths were sampled.

The well design was a 2” PVC slotted along the lower 10 cm of the pipe. We installed each well by excavating an approximately 20cm diameter hole with a gas-powered or hand auger. To ensure that the wells did not migrate due to peat shrinkage or swelling, the pipes were installed with riser and well sections. The bore hole for each well was dug down to limestone where the riser section rested. The slotted section of the well (well screen) was 20-30cm, 50-60cm or 80-90cm below the soil surface for shallow (S), deep (D) and deep deep (DD) wells, respectively. The annular areas surrounding the wells were filled with very fine sand around the riser section and filled with 6/20 filter sand to completely cover the well screen. The annular area was then capped with a thin layer of bentonite (ENVIROPLUG™) and finished with very fine sand. Each well was fit with a pressure transducer (*In-situ*®) water level recorder. All wells have or were referenced to elevations surveyed by a professional surveying company.

Hydrogeochemical Sampling. We conducted four samplings between Fall 2013 – Spring 2015. The sampling periods corresponded to the following dates: September 9 –

November 4, 2013 (Fall 2013), January 23 – March 5, 2014 (Spring 2014), and August 26 – September 24, 2014 (Fall 2014), and January 31 – February 28 (Spring 2015). The Fall 2013 sampling period was characterized as a dry down period, with the exception of the 3AS3 that was sampled during a week-long rain event. The Spring 2014 sampling was characterized as a drydown period, with a few wells in the Ghost island sampled during a brief rewetting period. While both Fall 2013 and Spring 2014 samplings were conducted largely during drydown events, water levels were on average about 30cm lower during the Spring sampling. The Fall 2014 sampling was characterized by a rewetting period. All four islands were sampled, and surface water was collected where present.

Wells were purged of three well volumes and DO, temp, pH and specific conductivity were recorded until three stable readings were obtained. Samples were run through a flow-through vessel and measurements conducted with a YSI. Wells were then purged a fourth time for sample collection and filtered through 0.45µm glass fiber filters. Surface waters were similarly sampled. Chemical analyses of Ca, Cl, Mg, K, Na, SO_4, alkalinity as $CaCO_3$, dissolved organic carbon (DOC), total Kedjhal nitrogen (TKN) and total dissolved phosphate ($TDPO_4$) were conducted by the SFWMD analytical lab following EPA protocols. Mineral saturation indices (*SI*) were determined using Aq-QA® (Rockware Inc.) where $SI = \log Q/K$ and Q=ion activity product and K=equilibrium constant. We determined the charge balance for each water sample in meq L^{-1}.

Results

1. *Regional hydrology - hydrologic disturbance gradient*

We used hydraulic head levels collected at 15-minute intervals to investigate seasonal and diurnal patterns. Seasonal variation in head levels are presented for 3AS3, Ghost Island, Twin Heads and 3BS2 (Figure 5). Diurnal patterns in water levels of the HH, WH, NT and marsh plant communities for two periods are presented.

2. *Soil Phosphorus characterization*

Soil phosphorus concentrations in tree island soils (3AS3, Ghost Island and Twin heads) varied most among communities and secondarily by island and depths (Figure 6). When all islands were grouped, HH TP values (4.77 ± 0.36%) were significantly higher than HH-edge soils (1.58 ± 0.36%) and Wet Head, Near Tail and Marsh soils (0.25 ± 0.06%, 0.08 ± 0.01%, and 0.032 ± 0.003%, respectively), the latter three not significantly different from one another ($F=100$, $p<0.0001$). While it is not possible to determine the development of soil P from this study, comparing soil TP concentrations across the soil depth profile within the High Head of each island suggests the potential for soil P loss in the upper profile of the degraded islands. Assuming that soil TP at lower depths represent the stable TP concentrations in the soil profile, soil TP of both the Ghost Island and Twin Heads are less than half the average of the TP concentration lower in the profile (30-50cm depth). Notably, the deviation from the average soil TP value in the HH suggests stable soil P in 3AS3, loss at 0-10cm depth in the wet, degraded Ghost Island and loss at 0-20cm depth in the dry, degraded Twin Heads island. Evaluating the spatial variability in soil TP concentrations between the central and edge soils of the High Head (Figure 6, HH and HH-edge, respectively) provides some evidence of the spatial extent of the high P soils. These are preliminary observations as the sampling of the HH-edge community was limited. Additional soil cores in these edge habitats would provide an estimate of extent of the high P layers and quite possibly enable a credible estimate of the mass of soil P currently retained in these islands.

Tree island soil TP concentrations varied significantly with organic matter content for each island sampled (Figure 6). Organic matter content explained 92 and 84% of the variance in TP concentration in polynomial relationships in the Ghost Island and Twin Heads, respectively (GI: $y= -0.0016x^2 + 0.079x + 5.72$, $F=193.4$, $p<0.0001$; TH: $y= 0.0012x^2 – 0.201x + 8.73$, $F=107.6$, $p<0.0001$). Organic matter content explained 47% of the variance in TP concentrations in a linear relationship in 3AS3 ($y= -0.047x + 4.05$; $F=33.3$, $p<0.0001$). The lower coefficient of variation for the model describing the 3AS3 pattern was due to a number of samples in the Near Tail with high mineral content (cores extracted near S8 and S9 well clusters). These samples also had high soil specific conductivity.

3. *Tree island hydraulic patterns*

We evaluated diurnal patterns in well locations of the high head, wet head, near tail and marsh for each of the four islands (Figure 7). What is notable is comparing the wetter islands of WCA3A, 3AS3 and Ghost Island, with the drier islands of WCA 3B, Twin Heads and 3BS2. While there is little discernible diurnal signal during drawdown in the wet islands (except for the HH of 3AS3), diurnal patterns are readily observed in Twin Heads and 3BS2. In Twin Heads, there was little difference in the diurnal trend among HH and WH plant communities with a daily drawdown of 2mm in early March. The diurnal signal in the NT was less pronounced when compared with the HH and WH but nearly comparable to the NT of 3BS2. In the marsh of TH, there was no discernible diurnal pattern. These striking differences illustrate the considerably drier condition of the SL and TH islands, especially TH.

New information suggests that the porewater recharge and subsequent potential for P leaching is buffered by mineral, higher density soils formed through evapoconcentration and ion exclusion by plants. A negative linear relationship between average monthly water table relative and porewater recharge is a proxy for the extent of soil drying-rewetting and subsequent potential for soil porewater leaching. In the pristine island, there is a small range in porewater recharge rates throughout the year, and no relationship between water table depth and soil porewater recharge in soils subject to seasonal drying (high head). In the wet, degraded island in 3A, water table nearly always exceeds the soil surface depth, and there is no relationship between water table depth and soil porewater recharge in soils. In the dry islands in 3B, Twin Heads and 3BS2, both high head and wet head soils have an annual average water level below the soil surface, and exhibit a strong, negative linear relationships between water table depth and soil porewater recharge, and a large range in porewater recharge rates. This strong, negative relationship was observed when there was: (1) very low water level promoting high porewater recharge (potential for soil PO4 release facilitated by strong drying-rewetting throughout the year) and (2) very high water level that eliminates the potential for evapoconcentration (ion accumulation and supersaturated soil water the contributes to mineral precipitation, potential for soil formation and soil P maintenance). The calcretization is found to decrease porosity and permeability. Very long or very short hydroperiods can degrade the calcrete layer that serves multiple purposes for tree island maintenance.

4. Surface and groundwater hydrochemical patterns

Ion composition was determined for all water samples collected in wet and dry season samplings 2012-2015. Charge balance for, the balance of cations and anions in a sample, was within acceptable levels (+/- 5%), with a few exceptions. This may be due to the detection of an anion or cation was not included in the charge balance equation or analytical error. Constituent concentrations and parameter values varied little between seasonal samplings, but always showed pronounced variation among plant communities, islands and depths (Figure 10 and Tables 1 and 2). The tree island 3AS3 showed typical patterns of high Cl in High Head samples relative to all other water samples within this island (Table 2A), and relative to all other water samples collected from Ghost island (Table 2B), Twin Heads (Table 2C) and 3BS2 (Table 2D). There was also strong differentiation between High Head water samples and water samples from other tree island plant communities and the marsh of 3AS3 in concentrations of sulfate, magnesium, sodium and total dissolved solids.

Summaries of water quality data including dissolved nutrient and carbon concentrations and indices of calcite and aragonite saturation revealed patterns consistent with what has been observed in our nearly 6-year dataset at 3AS3. Moderate $TDPO_4$ concentrations and indices indicating mineral saturation of calcite and aragonite relative to CaCO3 are a consistent trend found at 3AS3. However, the current sampling schedule that is limited to wet and dry seasons obviates the capacity to detect within-season trends. DOC is also an informative parameter and tends to correlate with tree island soil type (i.e. higher organic matter content, higher DOC). DOC is also consistently low in surface water. Thus, there is a very narrow range of DOC and lab pH for mineral soil water (in the High Head) and surface water in 3AS3. In other islands, only few samples in the High Head showed this pattern.

The wet, degraded Ghost island deviates from the wet, intact 3AS3 island with $TDPO_4$ concentrations that are 2-5 times higher in High Head soil water, and DOC and lab pH values more typical of an organic soil. Mineral saturation indices suggest tendency for mineral saturation in deeper profile soils (60cm below soil surface), with higher pH, but little concentration of Cl. This is also a consistent trend as compared with previous samplings. Twin Head soil water is similar to that found for 3AS3 in the High Head, in some locations and at 60cm depth. These locations generally correspond with low DOC concentrations and above neutral lab pH. Saturation indices suggest near to supersaturated conditions in the High Head, in a few locations in the Wet Head, but also in surface water of the marsh. This likely is an indication of low water levels, in general. Although 3BS2 was sampled soon after the wells were installed, $TDPO_4$ concentrations are in the range of Ghost island water samples except one location in the Wet Head, which was anomalously high. DOC was also out of range, suggesting a contaminated sample at this location. Throughout the island, DOC soil water concentrations are more typical of organic soil and lab pH was generally lower.

Conclusions

Historical information suggests that tree island development was associated with seasonal drying and peat accumulation in the near tail that contributed to differentiation of plant communities within the tree island and high soil P in the high head (community with seasonally dry soils). Further studies showed the high P is associated with CaP, that with concentration of ions through plant transpiration (diurnal drawdown) and evaporation, mineral formation is favored. During diurnal drawdown, rewetting and infiltrating rain water provides a mechanism promoting P release. P release under conditions favoring mineral precipitation permits reformation of mineral-bound P as Ca-P, promoting the maintenance and sequestration of soil P. Seasonal change in regional water table and soil surface vertical elevation interact to create soil water conditions that can either promote mineral precipitation or dissolution. Fluctuation between precipitation and dissolution can enable sequestration, but only where mineral saturated conditions persist.

We evaluated conditions for a “pristine” tree island to develop targets for restoration of degraded tree islands. We found that a “pristine” tree island exhibits: 1) vertical position of the soil surface and water table variation relative to soil surface allows differentiation of annual hydroperiod, with greatest differentiation between high head and wet head, near tail and marsh, 2) differentiation of plant communities, with both mineral soils and peat forming soil plant communities, 3) soil water supersaturated in minerals in the high head plant community AND seasonal diurnal drawdown that enables evapoconcentration and ion exclusion to create soil water that favors mineral precipitation, 4) consistently low soil water P, and high soil P that persists through the soil profile, and 5) regional hydrologic conditions that favor lateral transport for secondary sequestration of phosphorus.

Comparing these criteria for “pristine” tree islands to tree islands under study in 3A and 3B illustrate how degraded tree islands deviate from characteristics of a “pristine” island. We evaluated the geochemical pattern utilizing 5 metrics to describe tree island condition: 1) ion concentration, 2) phosphorus concentration, 3) extent of organic soil type,

4) residence time/redox condition, and 5) accumulation of Cl relative to Ca (Table 9). An assessment of these metrics suggested that Twin Heads and 3BS2 are in the poorest condition. Interestingly, despite the low accumulation of ions in the HH of Twin Heads, TP concentrations were similar to that found in 3AS3. Our soil data from these islands shows that TP is lower in Twin Heads, in the upper part of the soil profile, suggesting that the island has lost TP. So, although soil water TP is similar between 3AS3 and Twin Heads, active ion accumulation and potential for mineral and P accumulation appears to be inactive (limited extent of low organic type soil and high Ca/Cl, when all metrics are considered together. The island 3BS2, while with high TP and low differentiation of ion concentrations among communities, still had moderate total ion concentrations in the High Head community and moderate Ca/Cl. However, the predominance of organic type soils (no indication of extant mineral substrate) in the High Head suggested a different disturbance history for this island, and potentially need for alternative restoration strategies (i.e. substrate augmentation). A trajectory in geochemical pattern described by moderate TP concentrations, low extent of organic soil, and accumulation of total ions and Cl in the High Head, and relative to other communities, would indicate that the foundation community (the High Head) has reestablished its capacity to develop mineral substrate that contributes to stabilization of the tree island system. (Table 3).

Results suggest degraded tree islands exposed to overdrying or overflooding ware associated with decoupling, both in time and space, of environmental conditions that promote water and P uptake and mineral P retention in the High Head. We found evidence that water overlaying high head soils or water level well below plant root zone disrupts connectivity between groundwater and surface water, and reduces capacity for ion accumulation and mineral saturation

Very low water levels can contribute to greater soil area exposed to oxidation, leaching & nutrient loss. Restoring degraded tree islands lies in restoring the hydrological conditions that achieve plant performance across a plant community gradient within tree island promote mineral precipitation and P retention in the High Head and organic matter accumulation in Wet Head and Near Tail communities. However, extensive overdrying that has led to lower elevation “high head” (3BS2) or overflooded conditions (GI) may require active management

Taken together, we found that islands we intensively studied here deviated from a “pristine” islands in nearly all criteria developed. Furthermore, we developed a new proxy for the drying-rewetting dynamic, and found that very low water level promoted high porewater recharge and potential for soil PO4 release facilitated by strong drying-rewetting throughout the year and very high water level eliminated the potential for evapoconcentration (ion accumulation and supersaturated soil water the contributes to mineral precipitation, potential for soil formation and soil P maintenance). Overall, calcretization was found to decrease porosity and permeability, and very long or very short hydroperiods can degrade the calcrete layer that serves multiple purposes for tree island maintenance.

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Acknowledgements

We are grateful to Dr. Steve Krupa for his significant contributions to the development of this work.

Figures and Tables

Figure 1. Generalized soil hydrogeochemical characteristics of an “intact” Everglades “fixed-type” tree island (modified from XXXX).

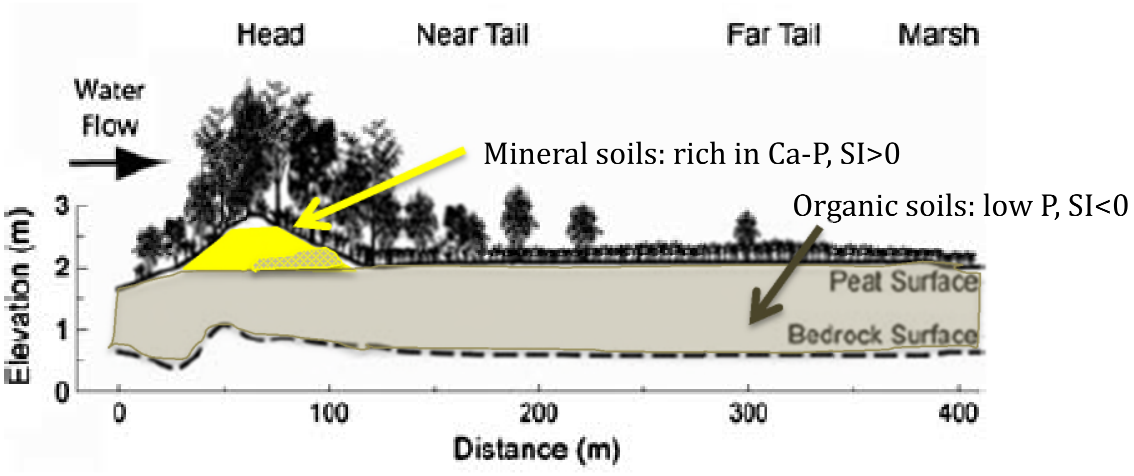
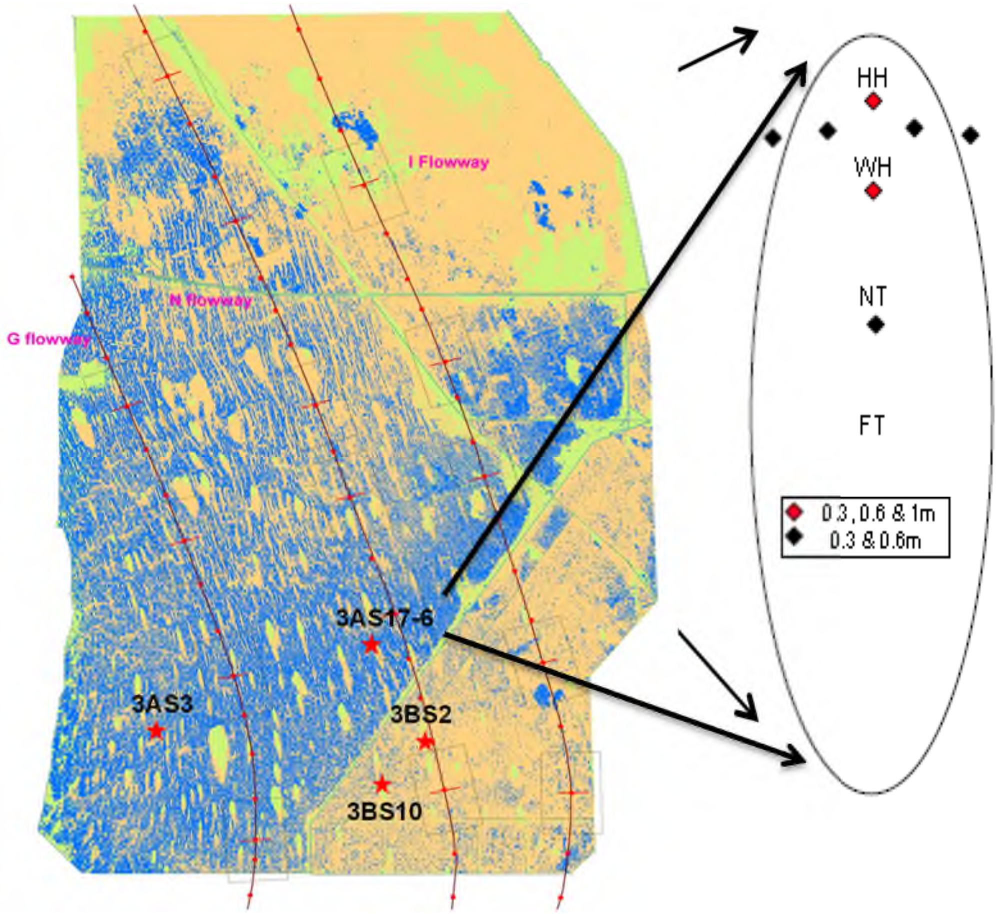


Figure 2. The tree islands to be investigated are located in WCA 3A and 3B. A schematic of well locations and depths on each island to be utilized in this study is shown on the right.



HH: High Head WH: Wet Head NT: Near Tail M: Marsh

Figure 3. Four Everglades tree islands along an environmental disturbance gradient: (A) wet, intact (3AS3-WCA3A), (B) wet, degraded (ghost island-WCA3A), (C) wet, degraded (3BS2-WCA3B), and (D) dry, degraded (Twin Heads-WCA3B)

Figure 4. Regional hydrology relative to high head soil surface on all four islands

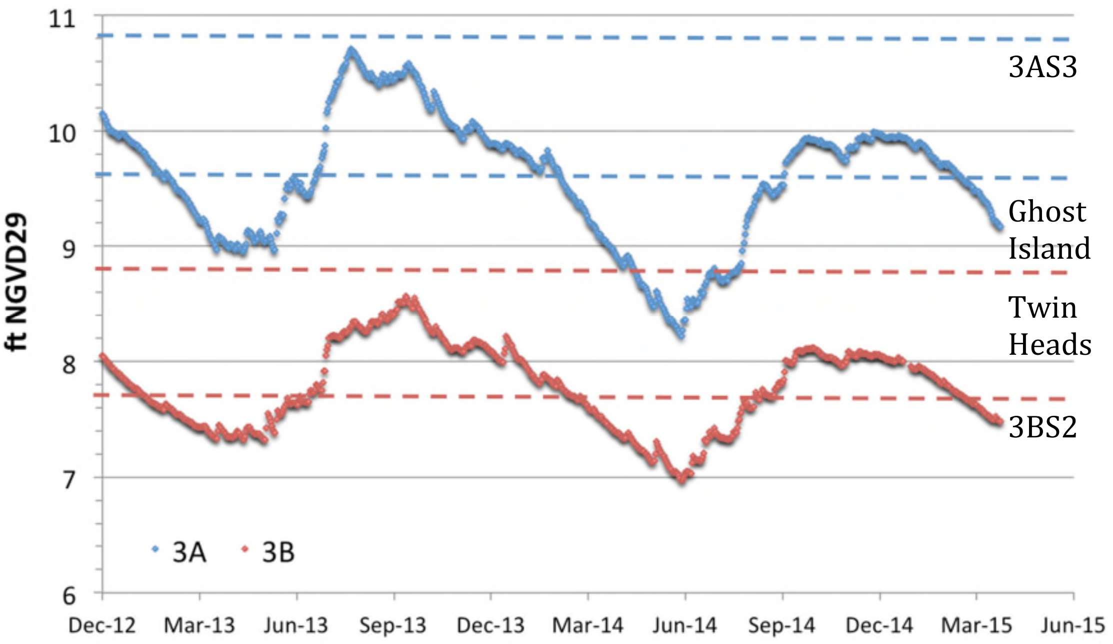
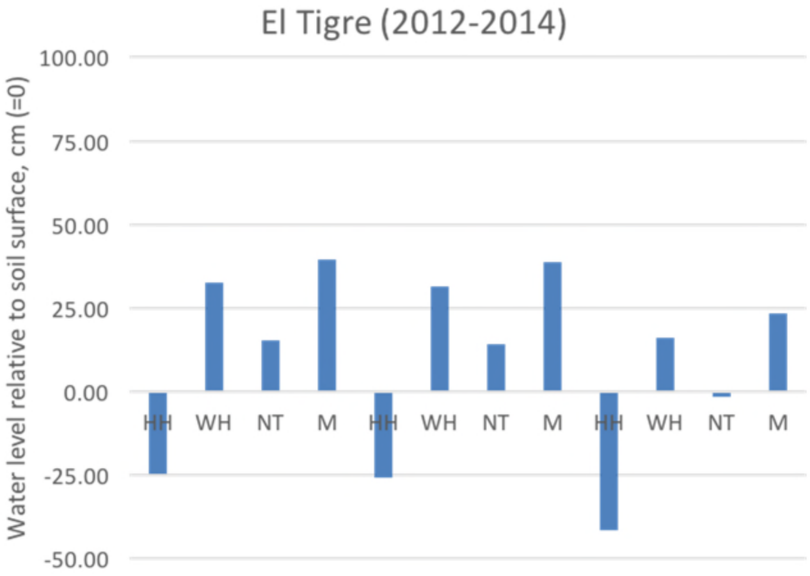
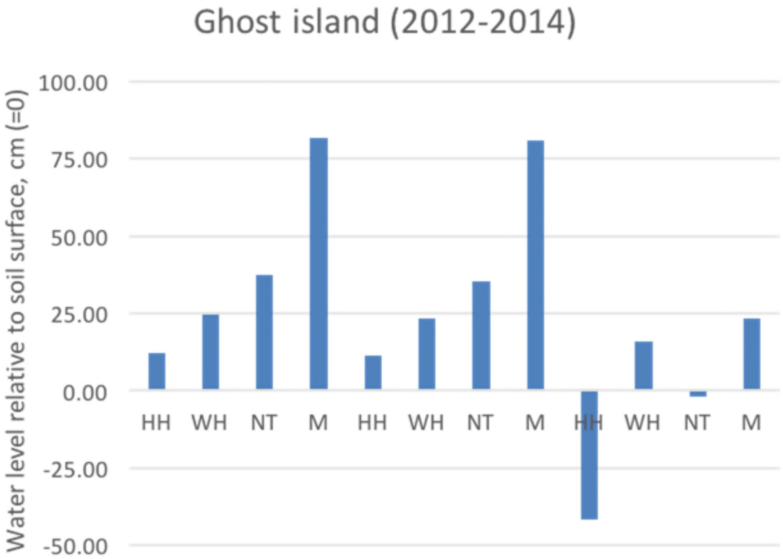
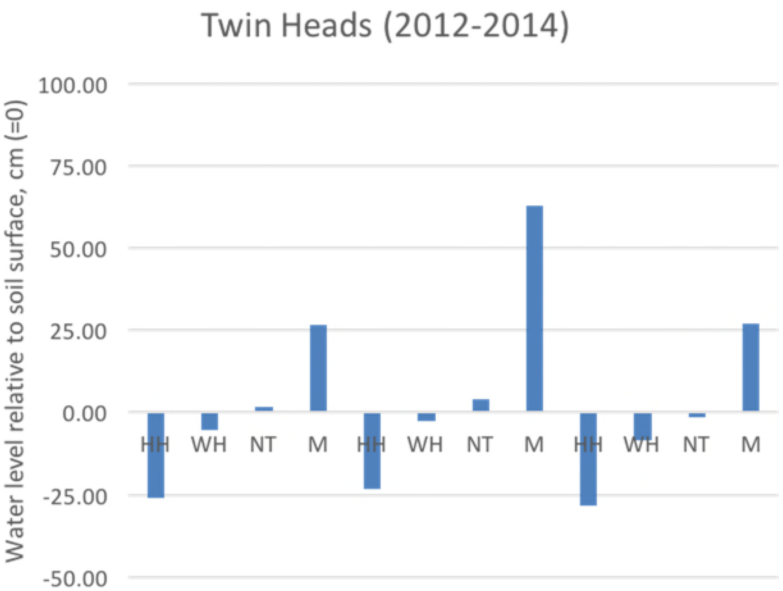


Figure 5. Average water level relative to the soil surface for the four tree islands 2012-2014.






Twin Heads (2012-2014)
Water level relative to soil surface, cm (=0)
100.00
75.00
50.00
25.00
0.00
-25.00
-50.00
HH
WH
NT
M
HH
WH
NT
M
HH
WH
NT
M

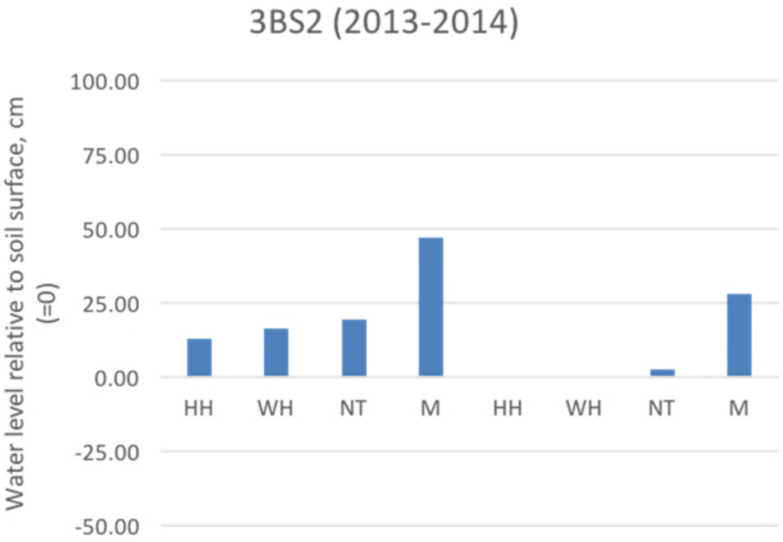

3BS2 (2013-2014)
Water level relative to soil surface, cm (=0)
100.00
75.00
50.00
25.00
0.00
-25.00
-50.00
HH
WH
NT
M
HH
WH
NT
M

Figure 6. Soil phosphorus

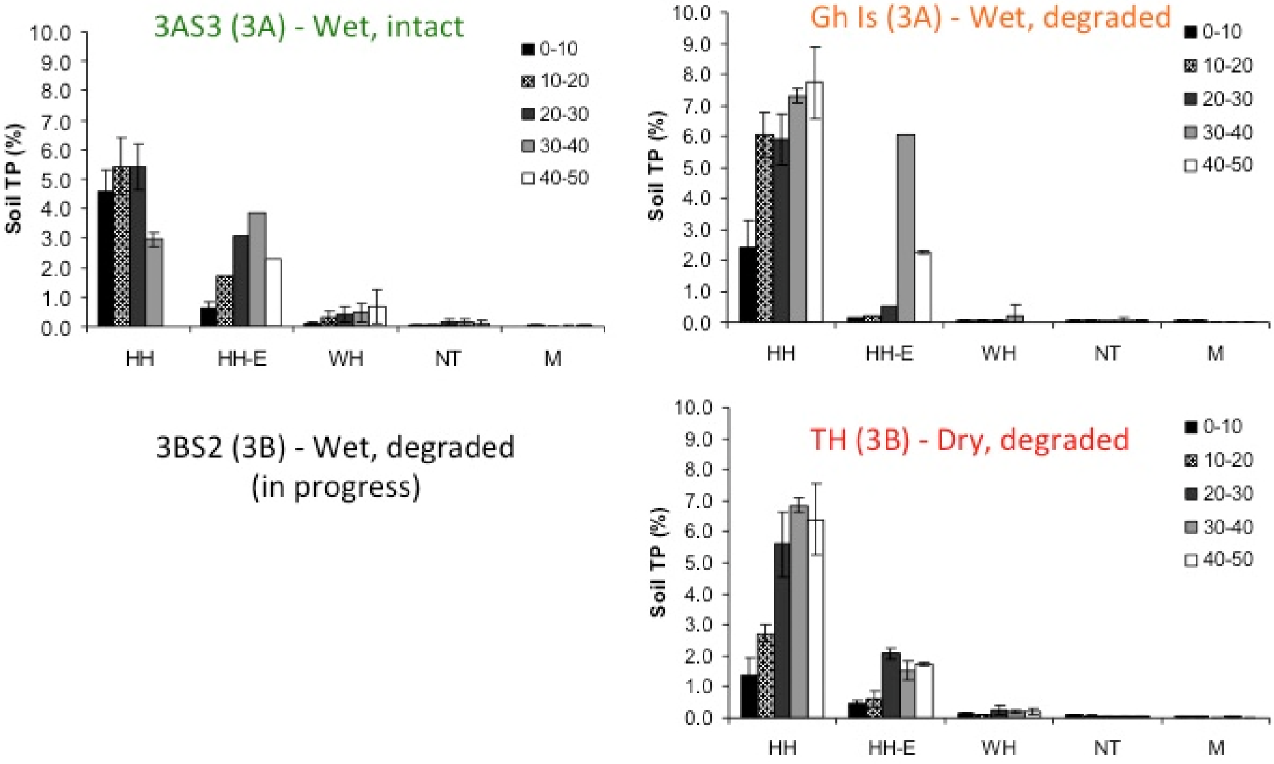
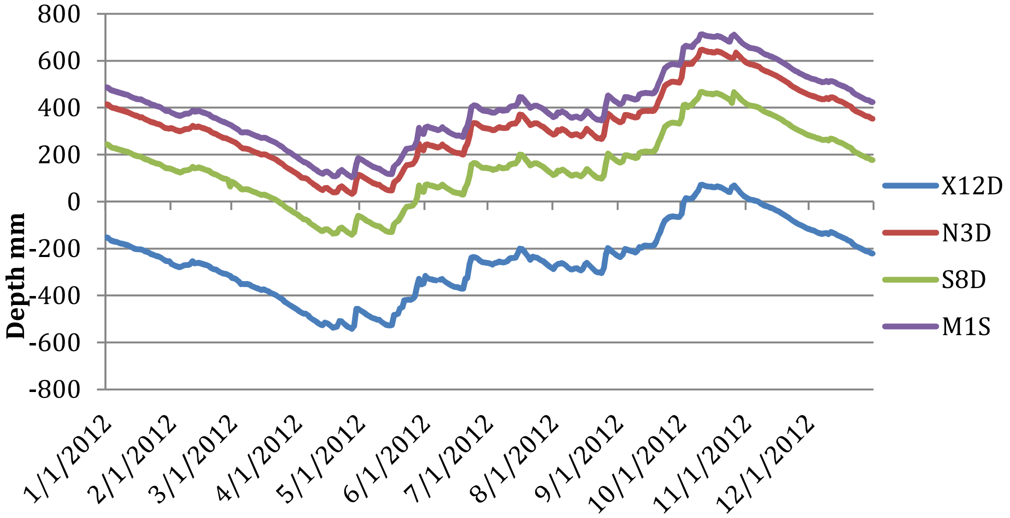
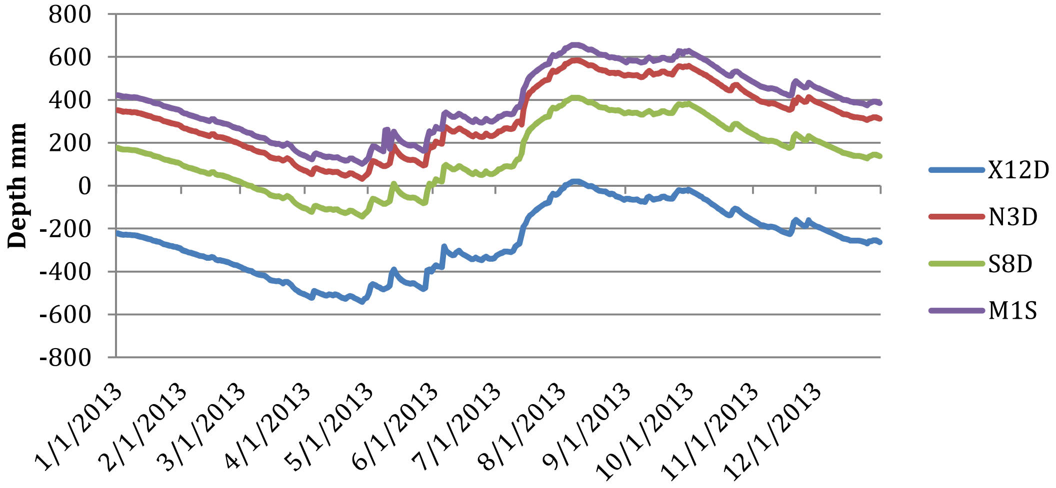
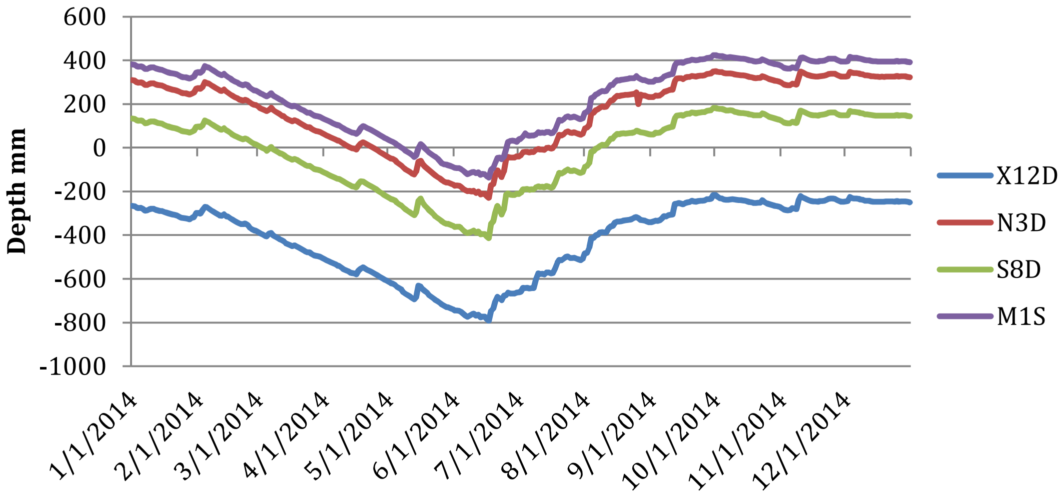


Figure 7. Daily surface water head levels (head level relative to soil surface) in high head (X), wet head (N), near tail (S) and marsh (M) for each of the 4 islands for El Tigre (A), Ghost island (B), Twin Heads (C) and 3BS2 (D).

A.

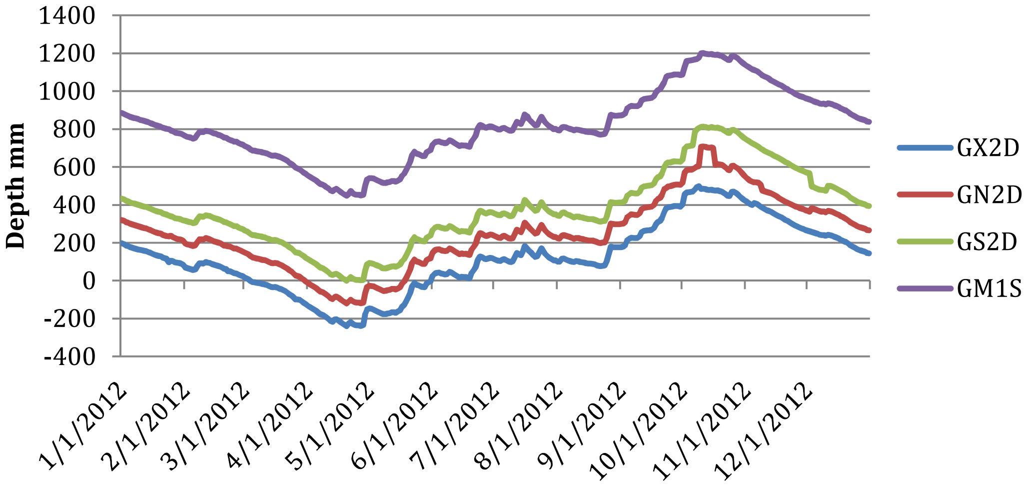




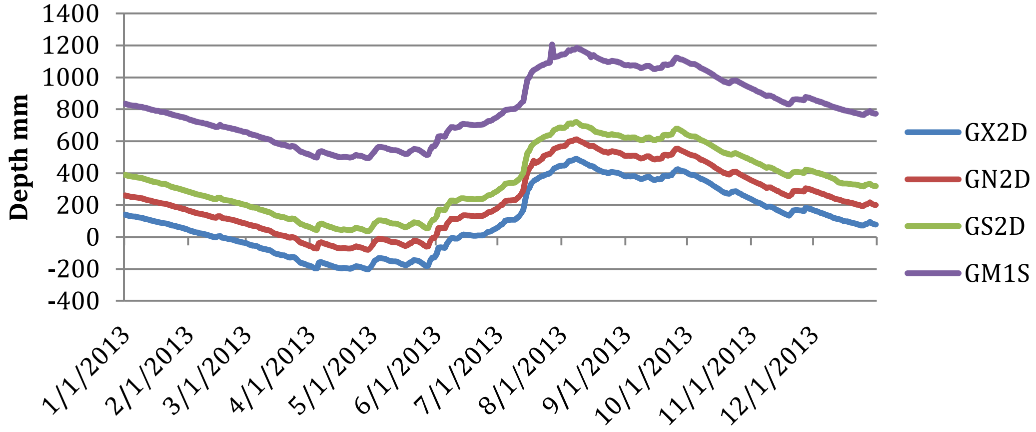


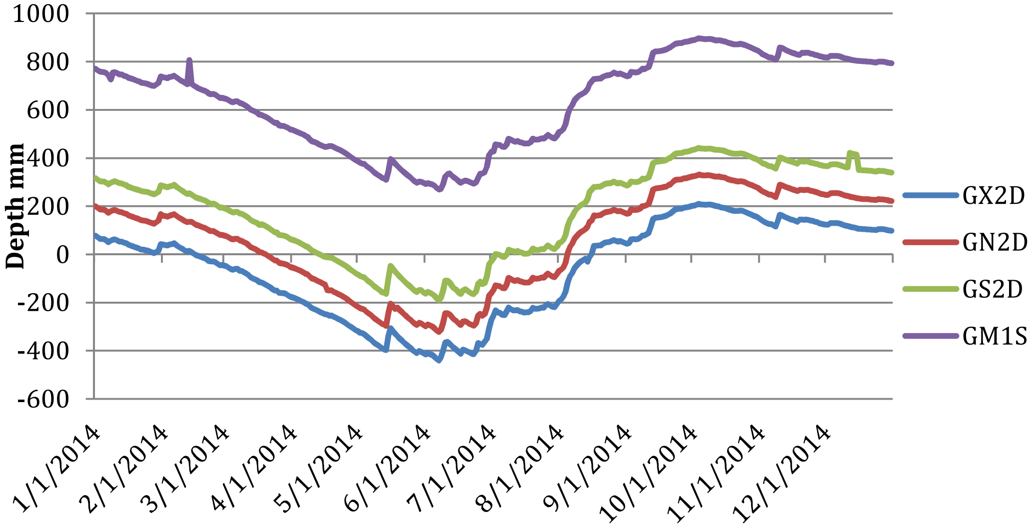
Depth mm
600
400
200
0
-200
-400
-600
-800
-1000
1/1/2014
2/1/2014
3/1/2014
4/1/2014
5/1/2014
6/1/2014
7/1/2014
8/1/2014
9/1/2014
10/1/2014
11/1/2014
12/1/2014
X12D
N3D
S8D
M1S

B.

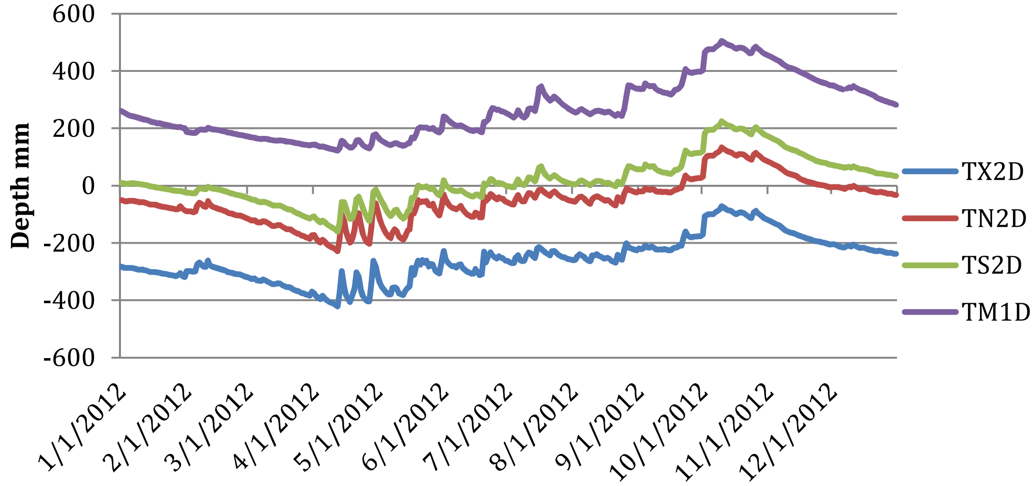


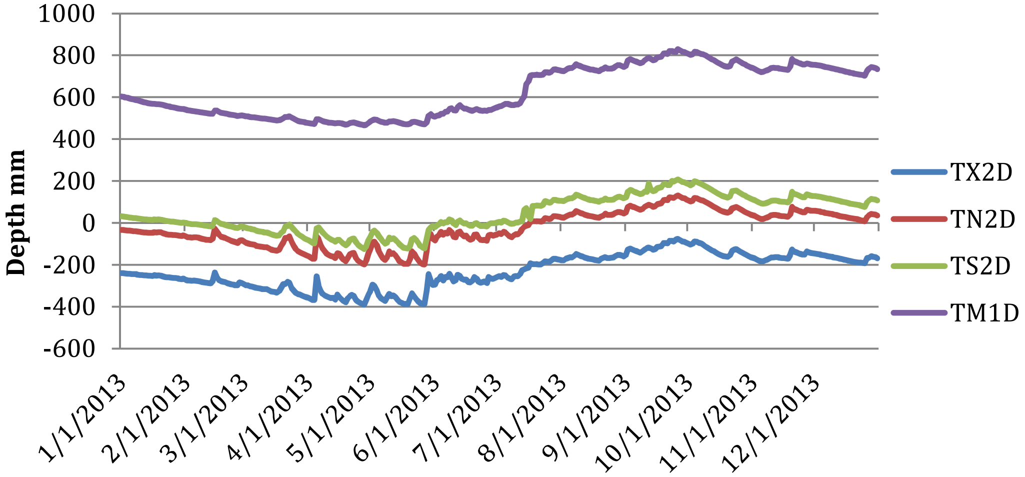
Depth mm
1400
1200
1000
800
600
400
200
0
-200
-400
1/1/2012
2/1/2012
3/1/2012
4/1/2012
5/1/2012
6/1/2012
7/1/2012
8/1/2012
9/1/2012
10/1/2012
11/1/2012
12/1/2012
GX2D
GN2D
GS2D
GM1S

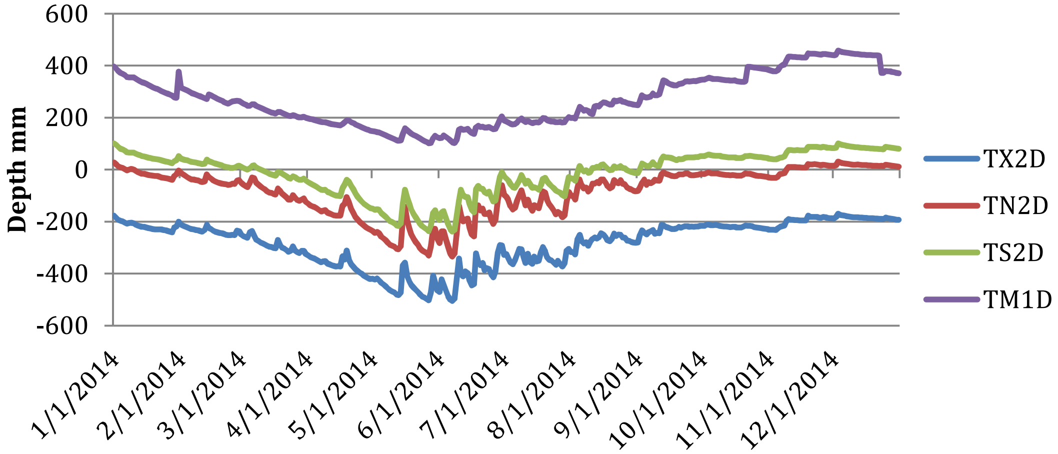

1400
1200
1000
800
600
400
200
0
-200
-400
Depth mm
1/1/2013
2/1/2013
3/1/2013
4/1/2013
5/1/2013
6/1/2013
7/1/2013
8/1/2013
9/1/2013
10/1/2013
11/1/2013
12/1/2013
GX2D
GN2D
GS2D
GM1S


1000
800
600
400
200
0
-200
-400
-600
Depth mm
1/1/2014
2/1/2014
3/1/2014
4/1/2014
5/1/2014
6/1/2014
7/1/2014
8/1/2014
9/1/2014
10/1/2014
11/1/2014
12/1/2014
GX2D
GN2D
GS2D
GM1S

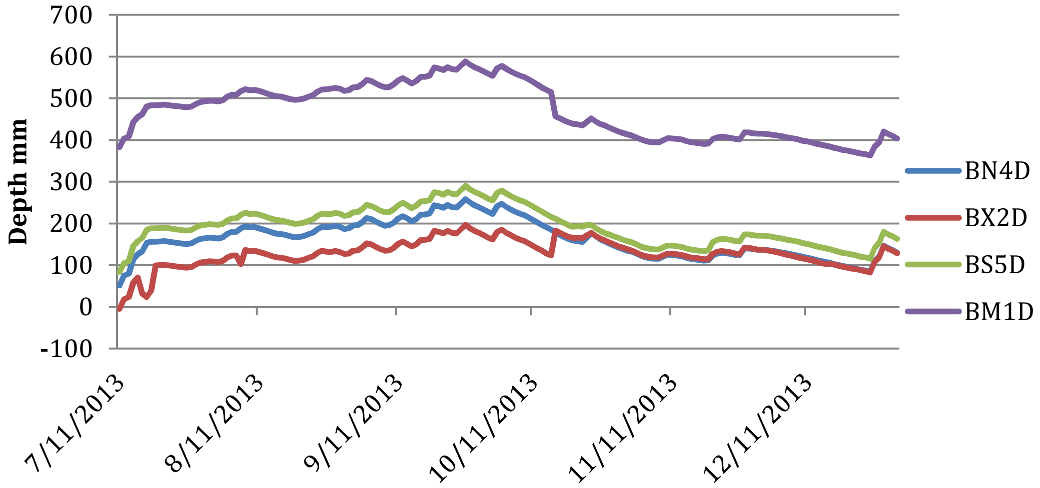
C.


Depth mm
600
400
200
0
-200
-400
-600
1/1/2012
2/1/2012
3/1/2012
4/1/2012
5/1/2012
6/1/2012
7/1/2012
8/1/2012
9/1/2012
10/1/2012
11/1/2012
12/1/2012
TX2D
TN2D
TS2D
TM1D

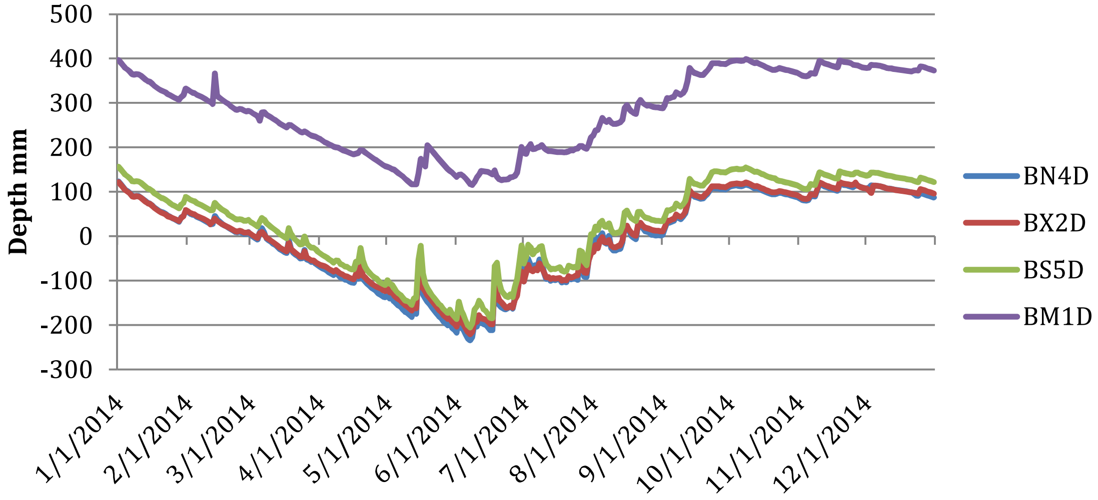

Depth mm
1000
800
600
400
200
0
-200
-400
-600
1/1/2013
2/1/2013
3/1/2013
4/1/2013
5/1/2013
6/1/2013
7/1/2013
8/1/2013
9/1/2013
10/1/2013
11/1/2013
12/1/2013
TX2D
TN2D
TS2D
TM1D


Depth mm
600
400
200
0
-200
-400
-600
1/1/2014
2/1/2014
3/1/2014
4/1/2014
5/1/2014
6/1/2014
7/1/2014
8/1/2014
9/1/2014
10/1/2014
11/1/2014
12/1/2014
TX2D
TN2D
TS2D
TM1D

D.



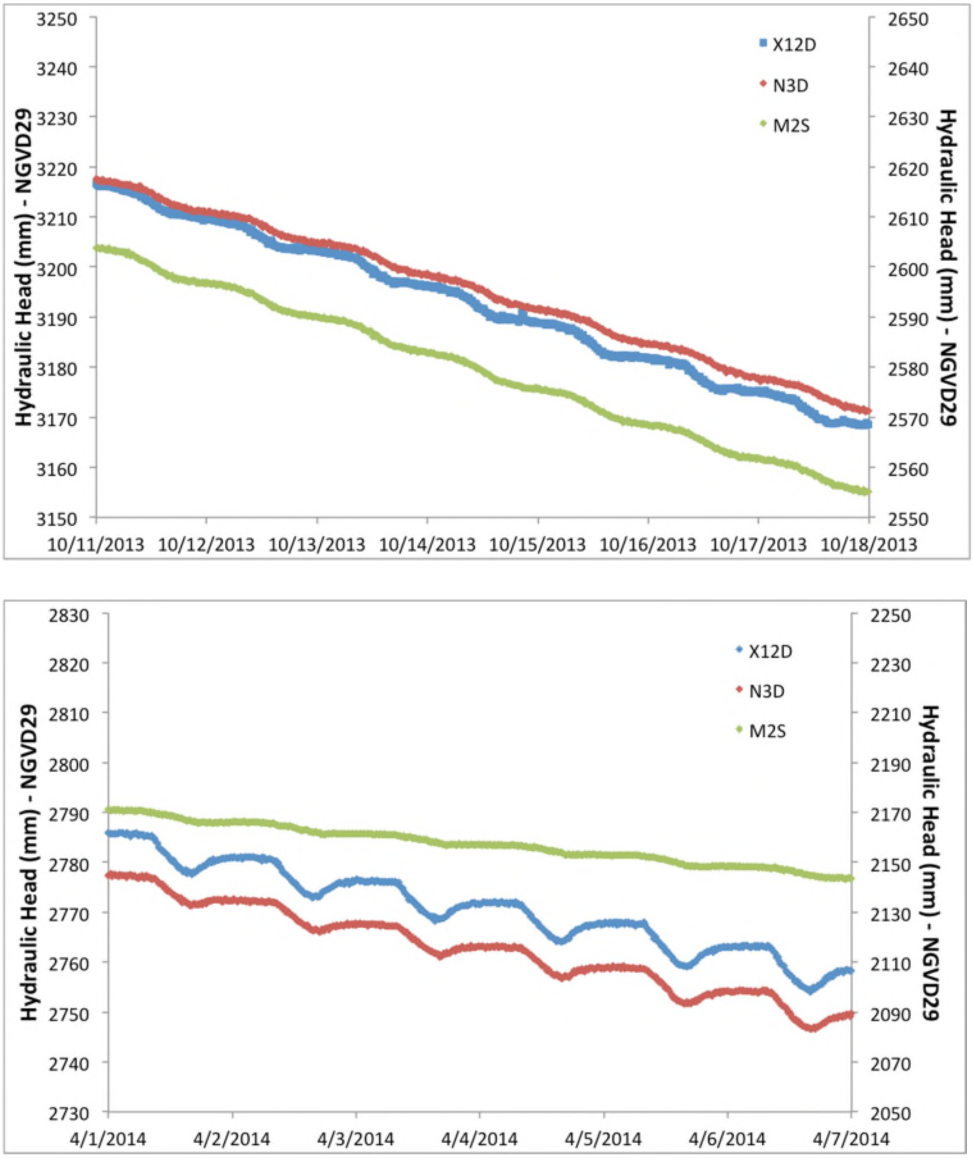
700
600
500
400
300
200
100
0
-100
Depth mm
7/11/2013
8/11/2013
9/11/2013
10/11/2013
11/11/2013
12/11/2013
BN4D
BX2D
BS5D
BM1D



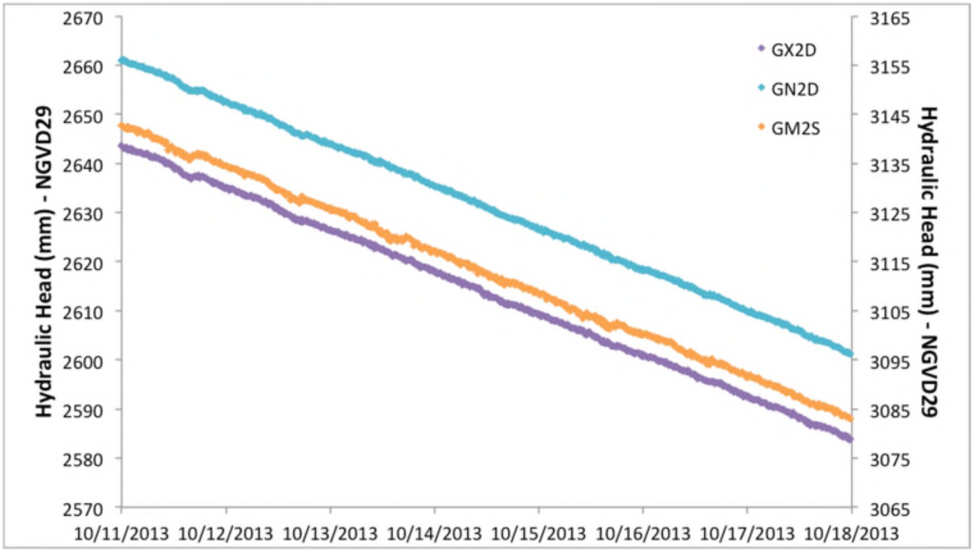
500
400
300
200
100
0
-100
-200
-300
Depth mm
1/1/2014
2/1/2014
3/1/2014
4/1/2014
5/1/2014
6/1/2014
7/1/2014
8/1/2014
9/1/2014
10/1/2014
11/1/2014
12/1/2014
BN4D
BX2D
BS5D
BM1D

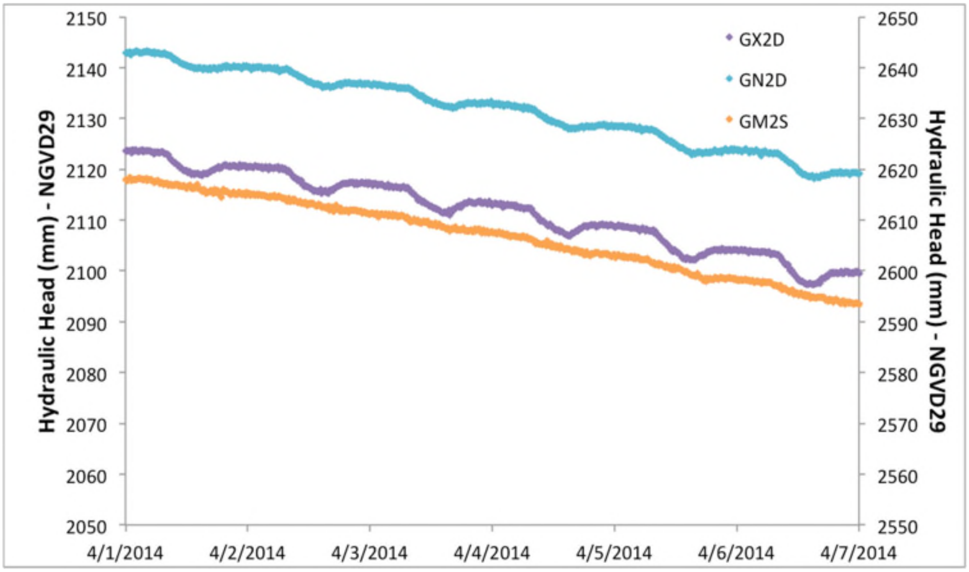
Figure 8. Plant community evapotranspiration pattern & diurnal drawdown. Evapotranspriational pattern is shown for islands 3 communities (high head = X, wet head = wet head, and M = marsh) in El Tigre (A), Ghost island (B) in WCA3A and Twin heads (C) and 3BS2 (D) in WCA3B for wet (October 2013) and dry (April 2014) seasons.

A.

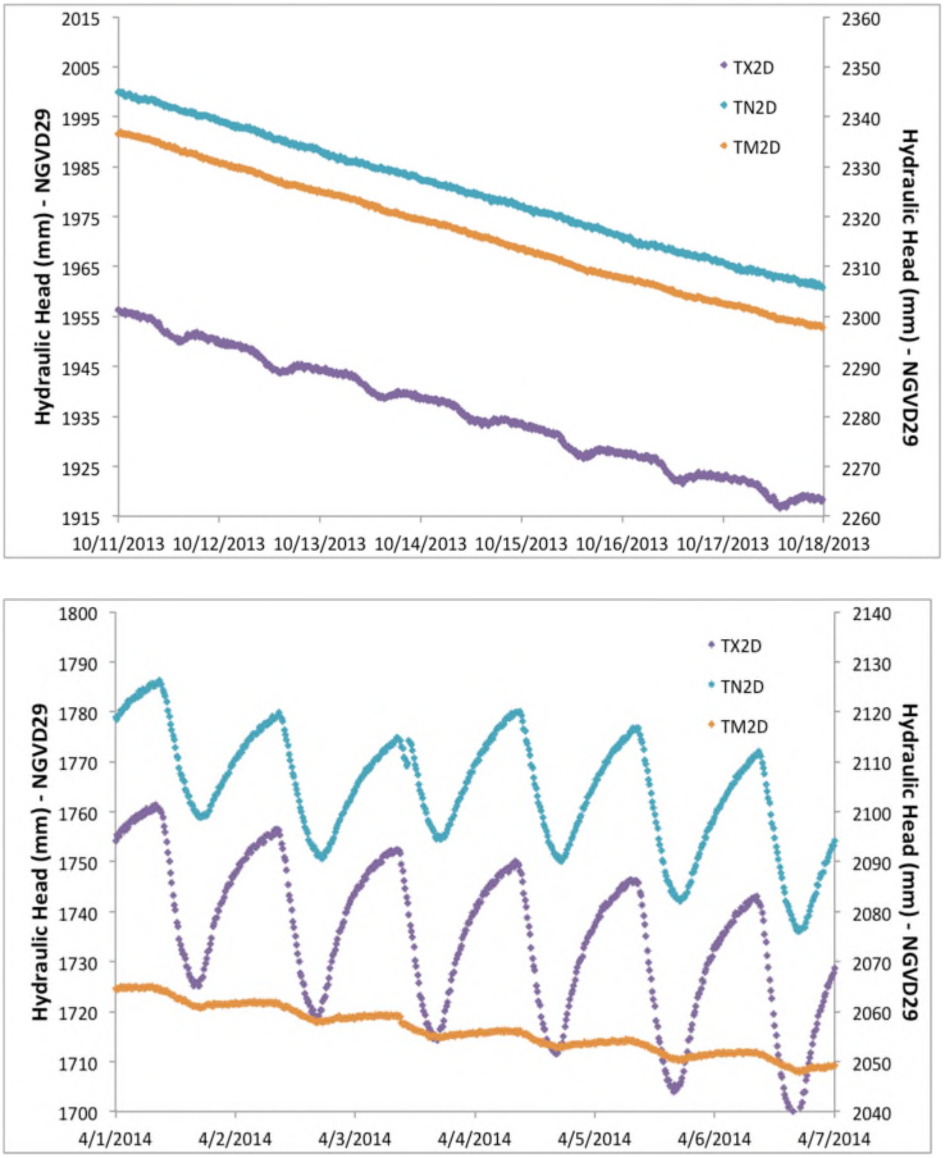


B.


2670
2660
2650
2640
2630
2620
2610
2600
2590
2580
2570
Hydraulic Head (mm) - NGVD29
3165
3155
3145
3135
3125
3115
3105
3095
3085
3075
3065
Hydraulic Head (mm) - NGVD29
10/11/2013
10/12/2013
10/13/2013
10/14/2013
10/15/2013
10/16/2013
10/17/2013
10/18/2013
◆ GX2D
◆ GN2D
◆ GM2S

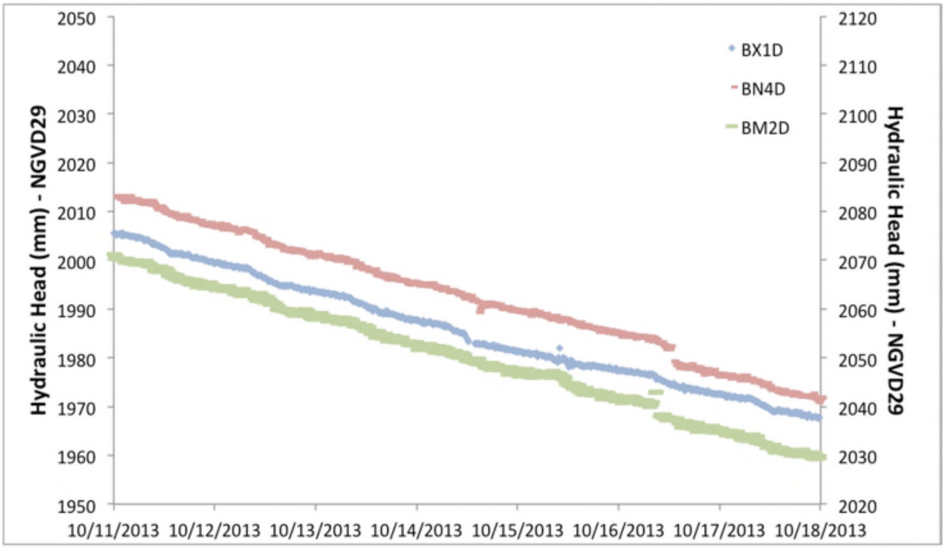

2150
2140
2130
2120
2110
2100
2090
2080
2070
2060
2050
Hydraulic Head (mm) - NGVD29
2650
2640
2630
2620
2610
2600
2590
2580
2570
2560
2550
Hydraulic Head (mm) - NGVD29
4/1/2014
4/2/2014
4/3/2014
4/4/2014
4/5/2014
4/6/2014
4/7/2014
◆ GX2D
◆ GN2D
◆ GM2S

C.

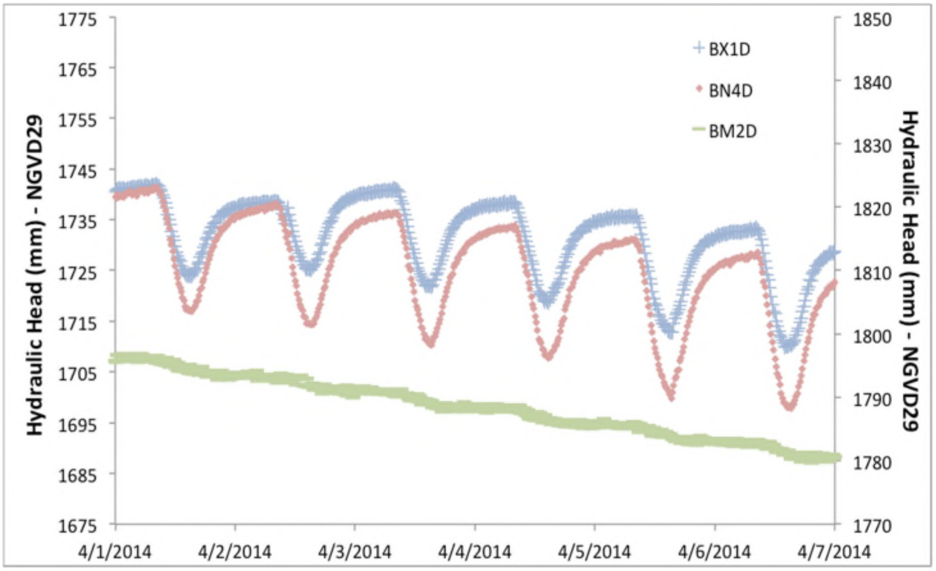


Hydraulic Head (mm) - NGVD29
2015
2005
1995
1985
1975
1965
1955
1945
1935
1925
1915
Hydraulic Head (mm) - NGVD29
2360
2350
2340
2330
2320
2310
2300
2290
2280
2270
2260
10/11/2013
10/12/2013
10/13/2013
10/14/2013
10/15/2013
10/16/2013
10/17/2013
10/18/2013
TX2D
TN2D
TM2D
Hydraulic Head (mm) - NGVD29
1800
1790
1780
1770
1760
1750
1740
1730
1720
1710
1700
Hydraulic Head (mm) - NGVD29
2140
2130
2120
2110
2100
2090
2080
2070
2060
2050
2040
4/1/2014
4/2/2014
4/3/2014
4/4/2014
4/5/2014
4/6/2014
4/7/2014
TX2D
TN2D
TM2D

D.



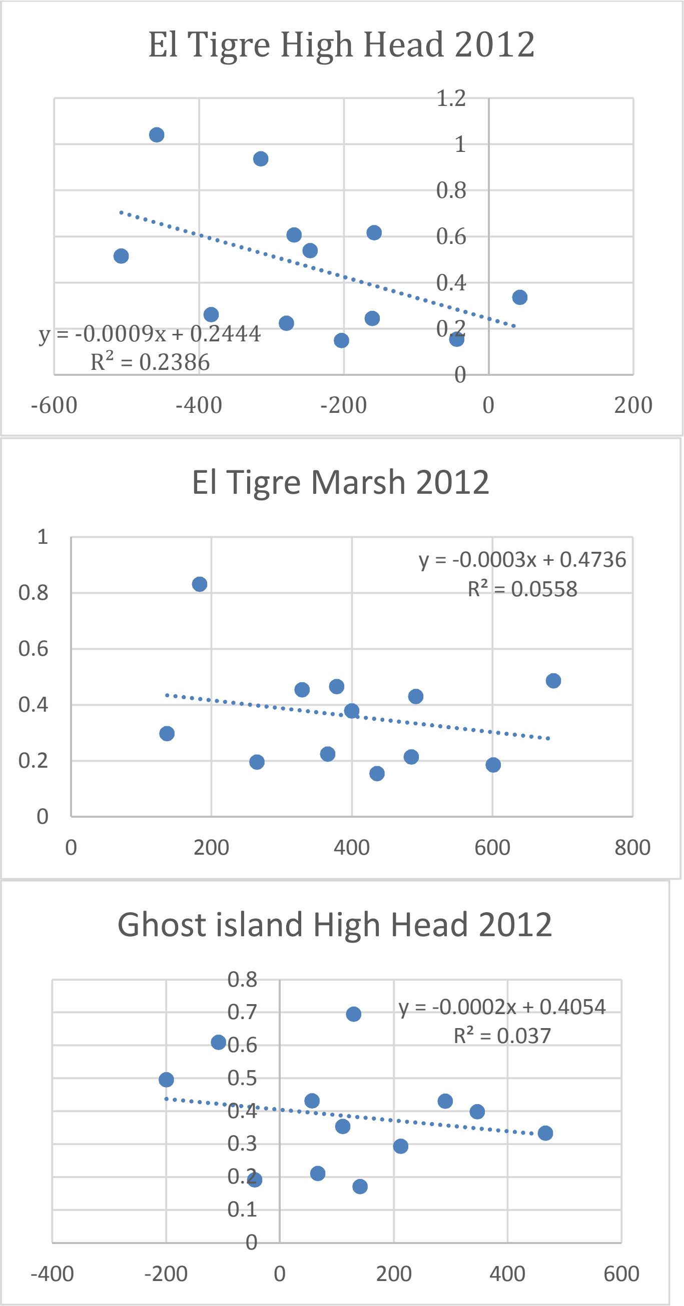
2050
2040
2030
2020
2010
2000
1990
1980
1970
1960
1950
Hydraulic Head (mm) - NGVD29
2120
2110
2100
2090
2080
2070
2060
2050
2040
2030
2020
Hydraulic Head (mm) - NGVD29
BX1D
BN4D
BM2D
10/11/2013
10/12/2013
10/13/2013
10/14/2013
10/15/2013
10/16/2013
10/17/2013
10/18/2013

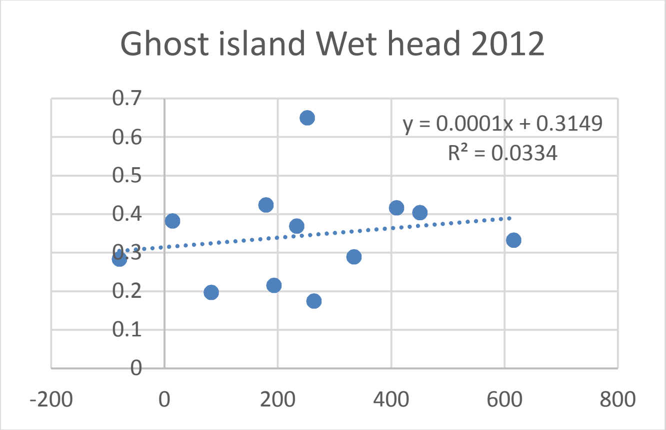


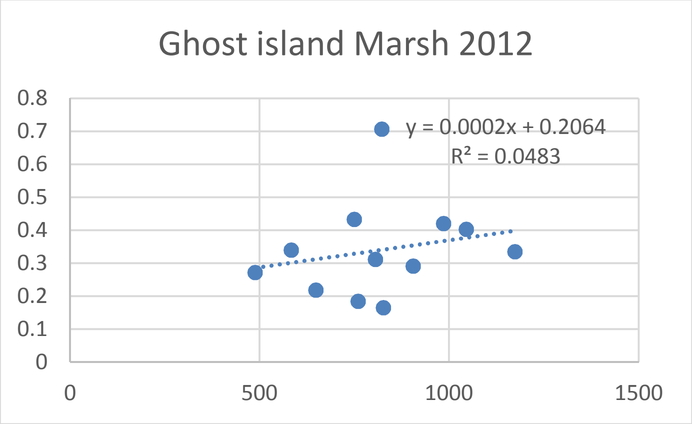
1775
1765
1755
1745
1735
1725
1715
1705
1695
1685
1675
Hydraulic Head (mm) - NGVD29
1850
1840
1830
1820
1810
1800
1790
1780
1770
Hydraulic Head (mm) - NGVD29
BX1D
BN4D
BM2D
4/1/2014
4/2/2014
4/3/2014
4/4/2014
4/5/2014
4/6/2014
4/7/2014

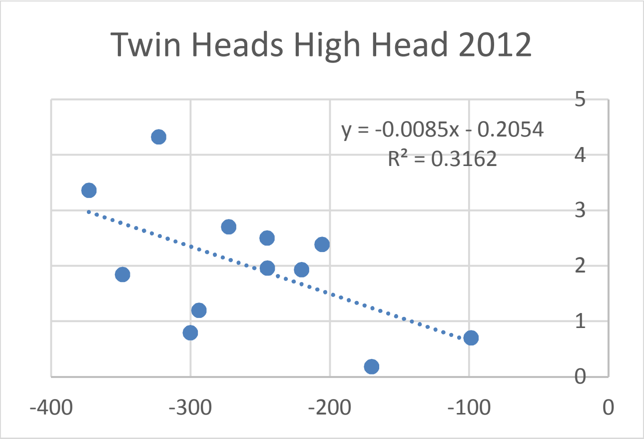
Figure 9. Relationships between average monthly water table relative and porewater recharge - a proxy for the extent of soil drying-rewetting and subsequent potential for soil porewater leaching. 2012 (A), 2013 (B), and 2014 (C).

A.

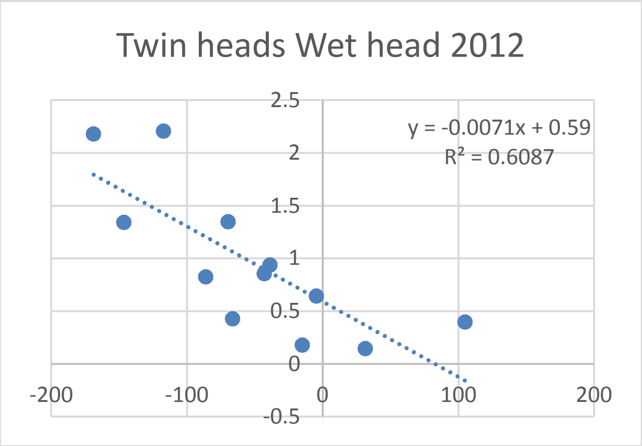



Ghost island Wet head 2012
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-200
0
200
400
600
800
y = 0.0001x + 0.3149
R² = 0.0334


Ghost island Marsh 2012
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
500
1000
1500
y = 0.0002x + 0.2064
R² = 0.0483

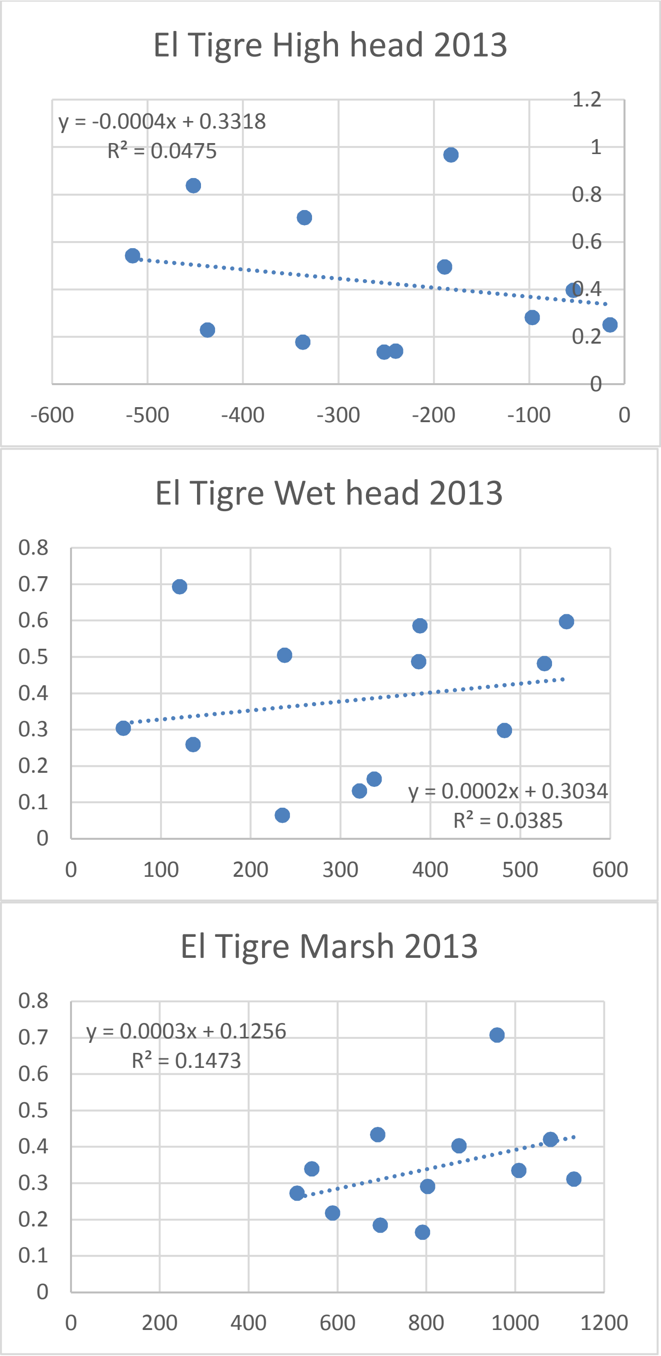


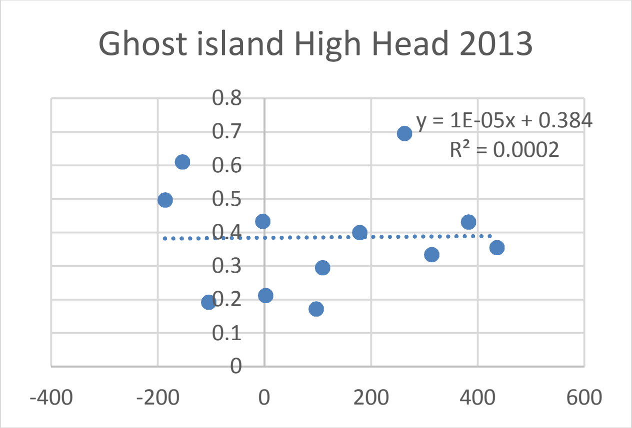
Twin Heads High Head 2012

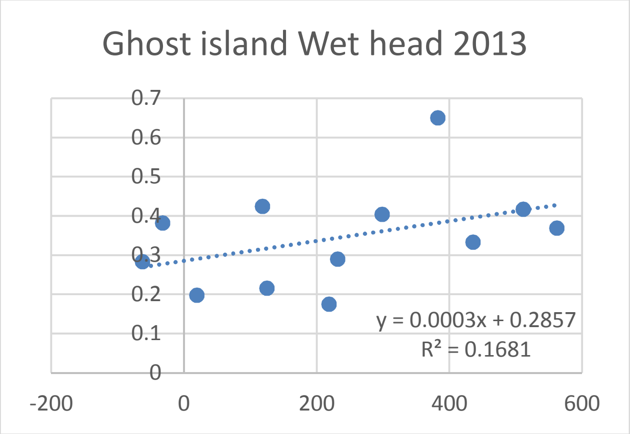


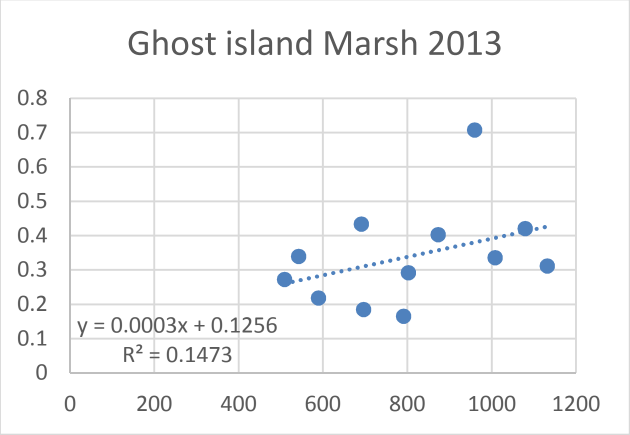
Twin heads Wet head 2012

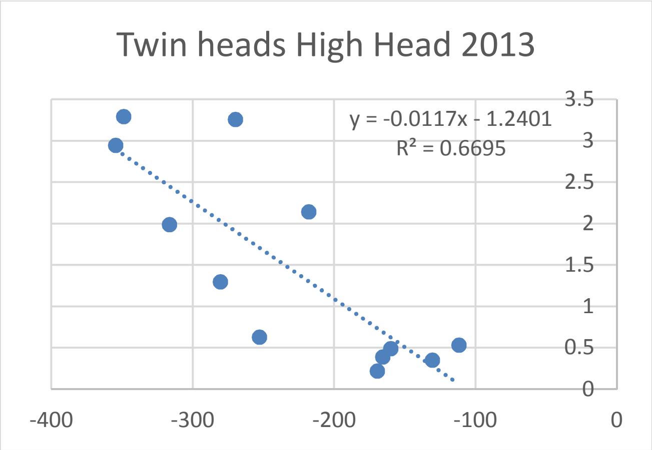
B.

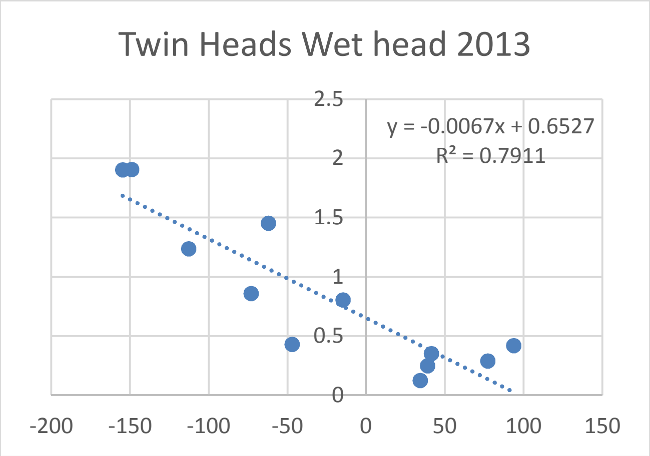

El Tigre High head 2013
y = -0.0004x + 0.3318
R² = 0.0475
1.2
1
0.8
0.6
0.4
0.2
0
-600
-500
-400
-300
-200
-100
0
El Tigre Wet head 2013
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
y = 0.0002x + 0.3034
R² = 0.0385
0
100
200
300
400
500
600
El Tigre Marsh 2013
y = 0.0003x + 0.1256
R² = 0.1473
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200

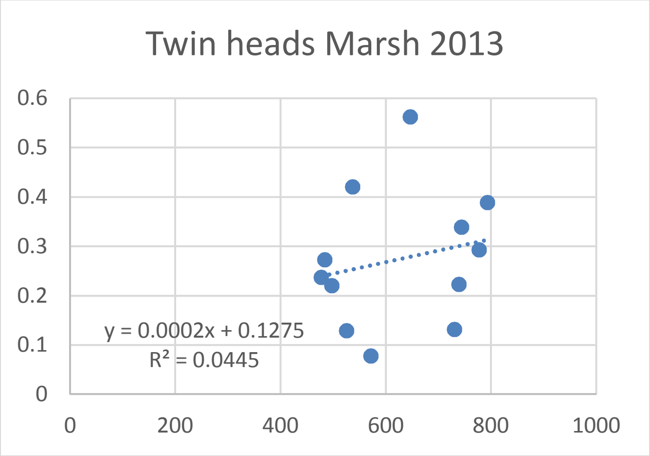

Ghost island High Head 2013
y = 1E-05x + 0.384
R² = 0.0002
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-400
-200
0
200
400
600

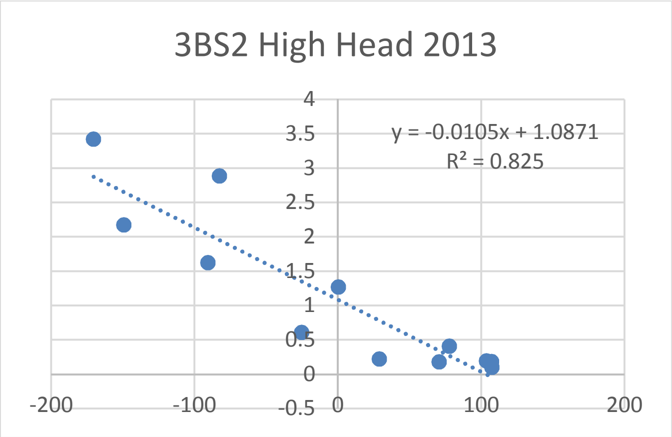

Ghost island Wet head 2013
y = 0.0003x + 0.2857
R² = 0.1681
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-200
0
200
400
600

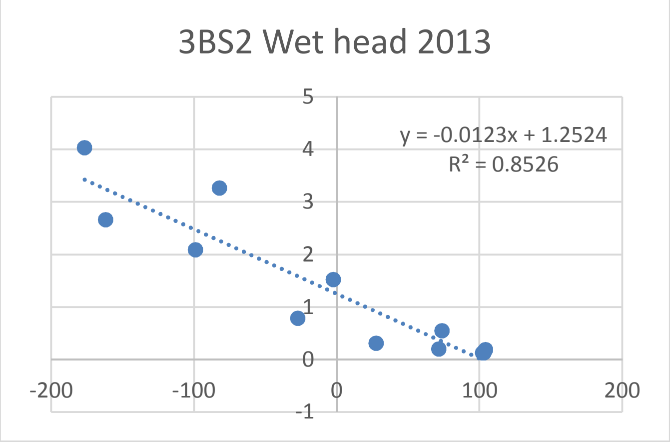

Ghost island Marsh 2013
y = 0.0003x + 0.1256
R² = 0.1473
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200

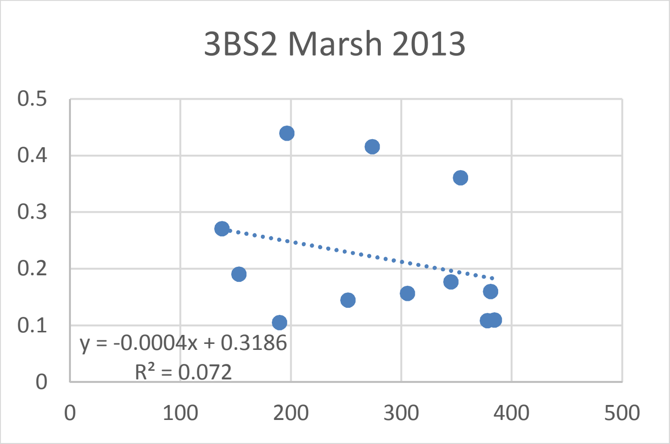

Twin heads High Head 2013


Twin Heads Wet head 2013

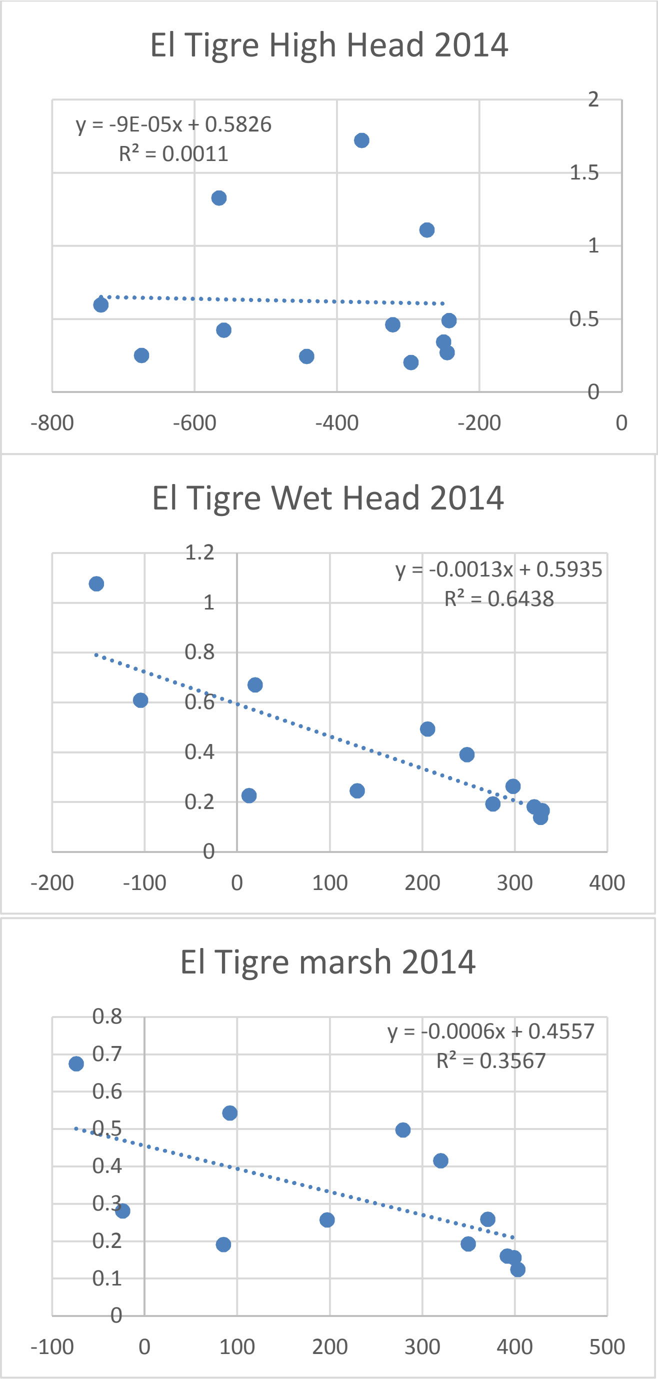

Twin heads Marsh 2013

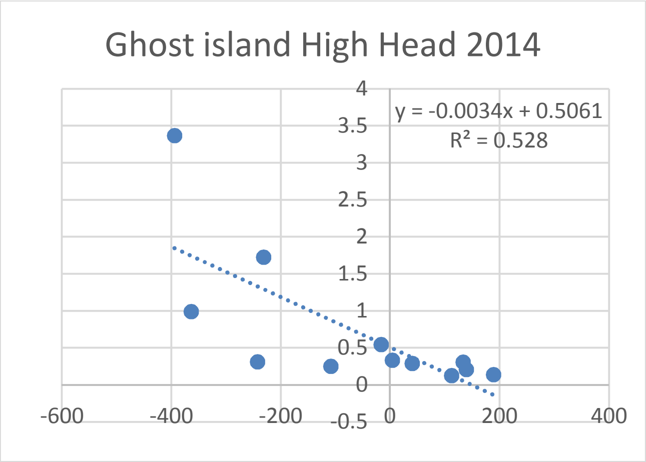

3BS2 High Head 2013
y = -0.0105x + 1.0871
R² = 0.825
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-200
-100
0
100
200

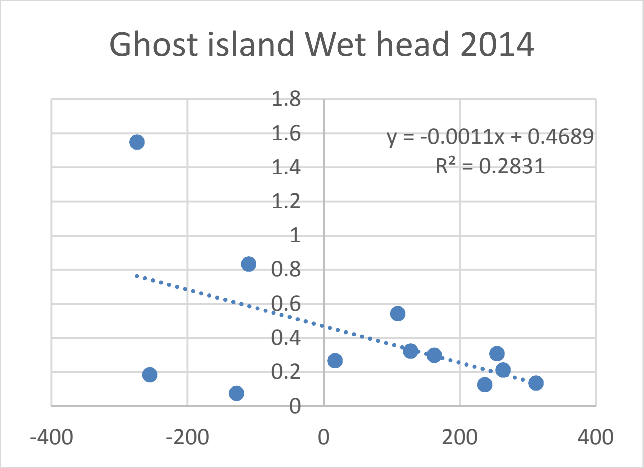

3BS2 Wet head 2013
y = -0.0123x + 1.2524
R² = 0.8526
5
4
3
2
1
0
-1
-200
-100
0
100
200

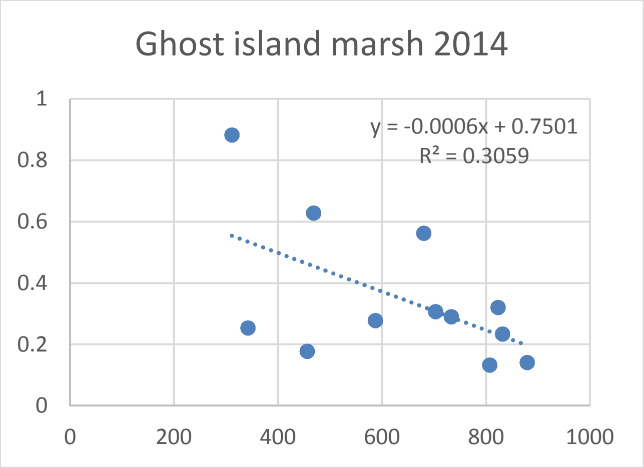

3BS2 Marsh 2013
y = -0.0004x + 0.3186
R² = 0.072
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500

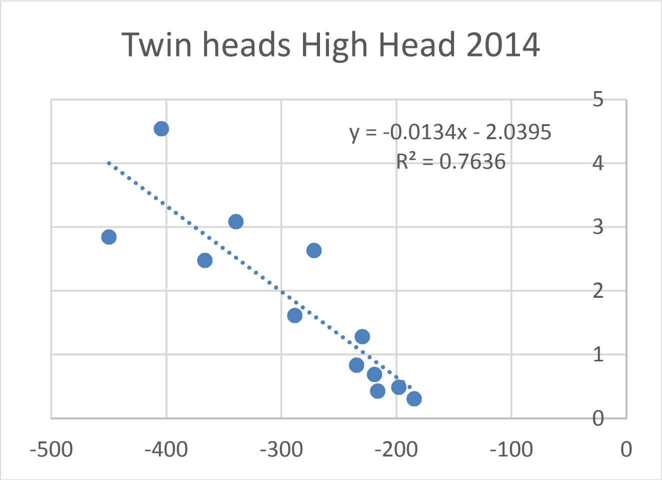
C.

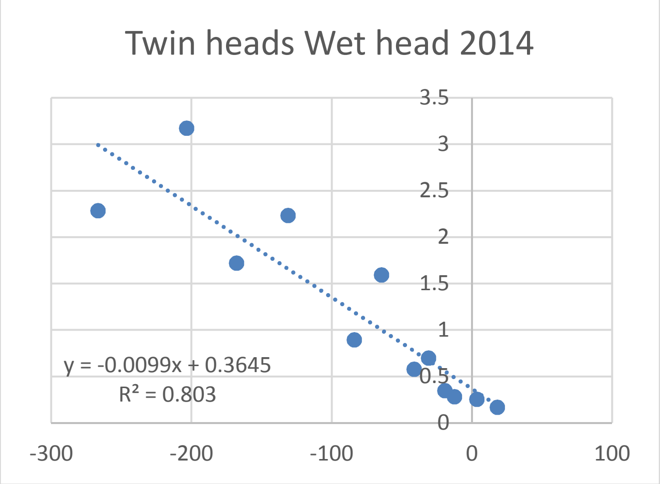

El Tigre High Head 2014
y = -9E-05x + 0.5826
R² = 0.0011
2
1.5
1
0.5
0
-800
-600
-400
-200
0
El Tigre Wet Head 2014
y = -0.0013x + 0.5935
R² = 0.6438
1.2
1
0.8
0.6
0.4
0.2
0
-200
-100
0
100
200
300
400
El Tigre marsh 2014
y = -0.0006x + 0.4557
R² = 0.3567
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-100
0
100
200
300
400
500


Ghost island High Head 2014
y = -0.0034x + 0.5061
R² = 0.528
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-600
-400
-200
0
200
400


Ghost island Wet head 2014
y = -0.0011x + 0.4689
R² = 0.2831
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-400
-200
0
200
400


Ghost island marsh 2014
y = -0.0006x + 0.7501
R² = 0.3059
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000


Twin heads High Head 2014
y = -0.0134x - 2.0395
R² = 0.7636
5
4
3
2
1
0
-500
-400
-300
-200
-100
0


Twin heads Wet head 2014
3.5
3
2.5
2
1.5
1
0.5
0
y = -0.0099x + 0.3645
R² = 0.803
-300
-200
-100
0
100

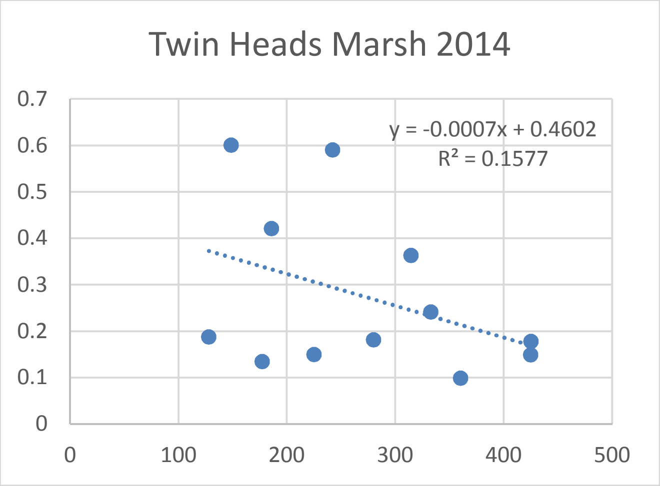
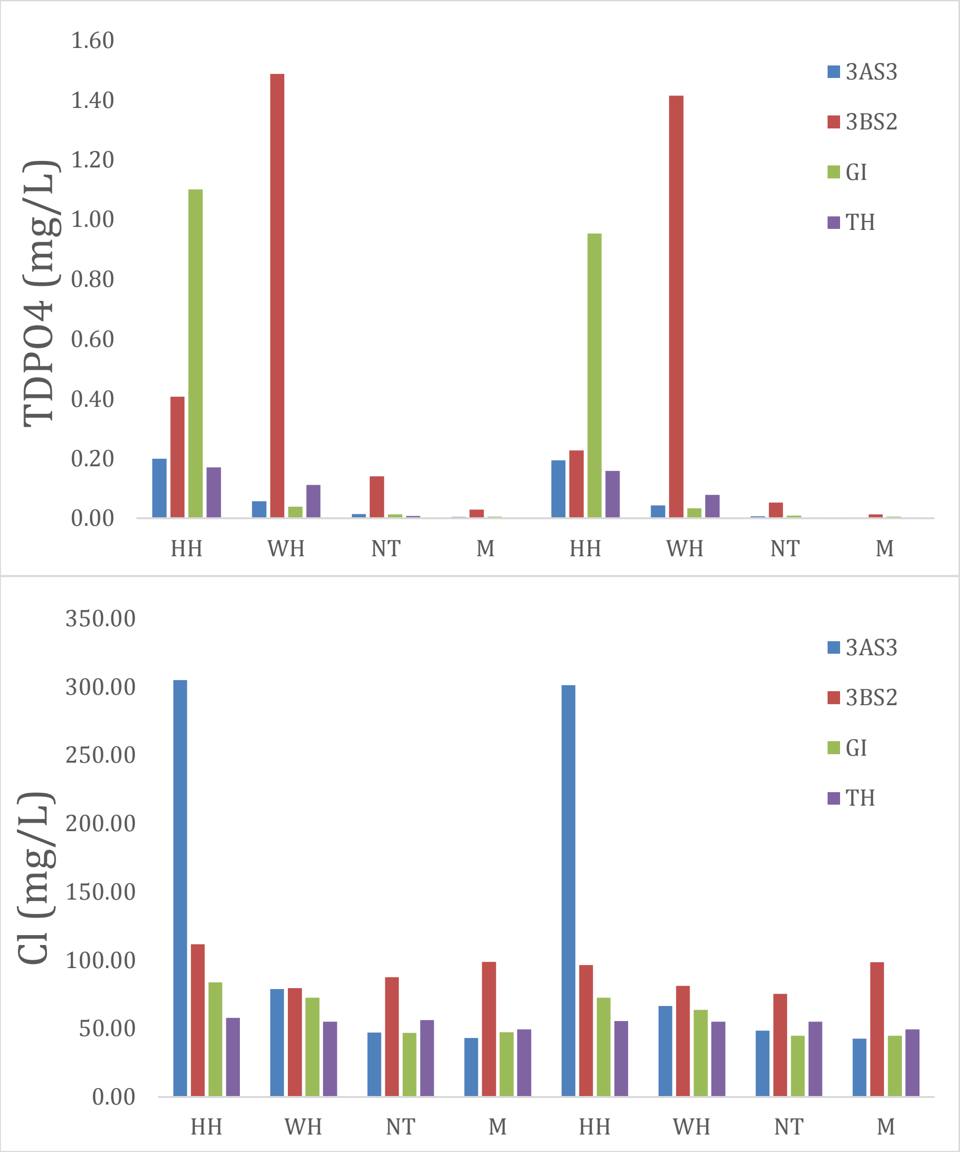
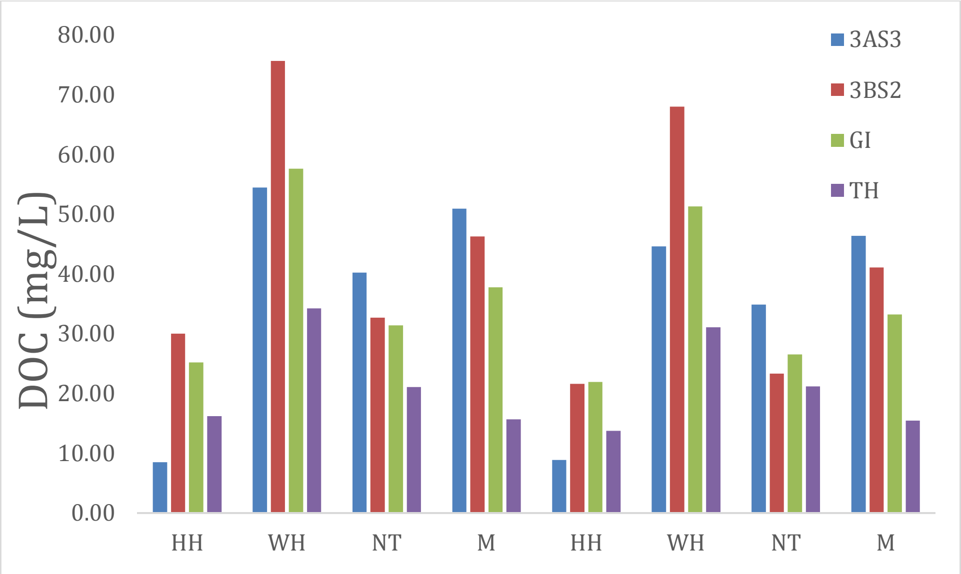
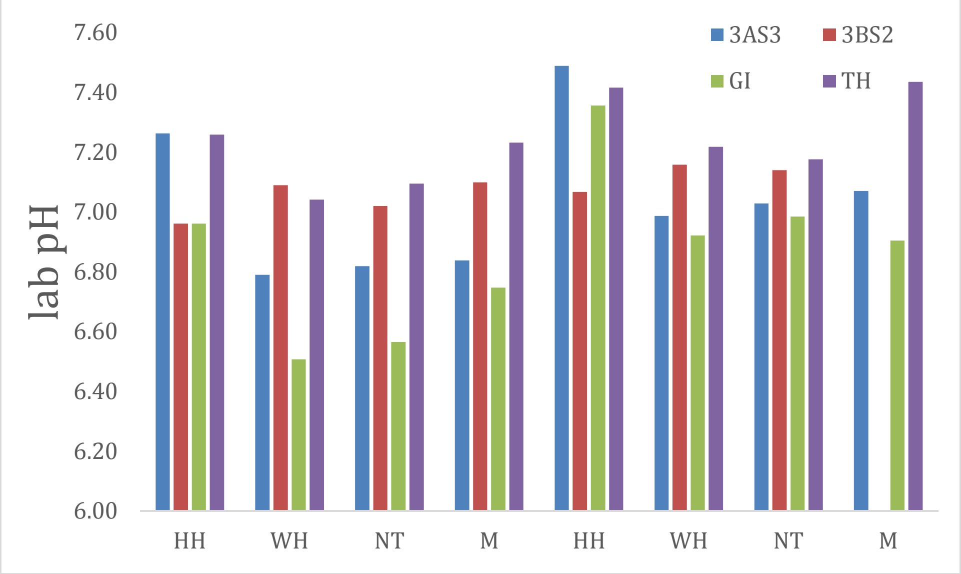

Twin Heads Marsh 2014
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
y = -0.0007x + 0.4602
R² = 0.1577
0
100
200
300
400
500

Figure 10. Average of seasonal samplings and constituents total dissolved phosphate ($TDPO_4$), dissolved organic carbon (DOC), chloride (Cl), and lab pH for each island in four communities – high head (HH), wet head (WH), near tail (NT), and march (M).



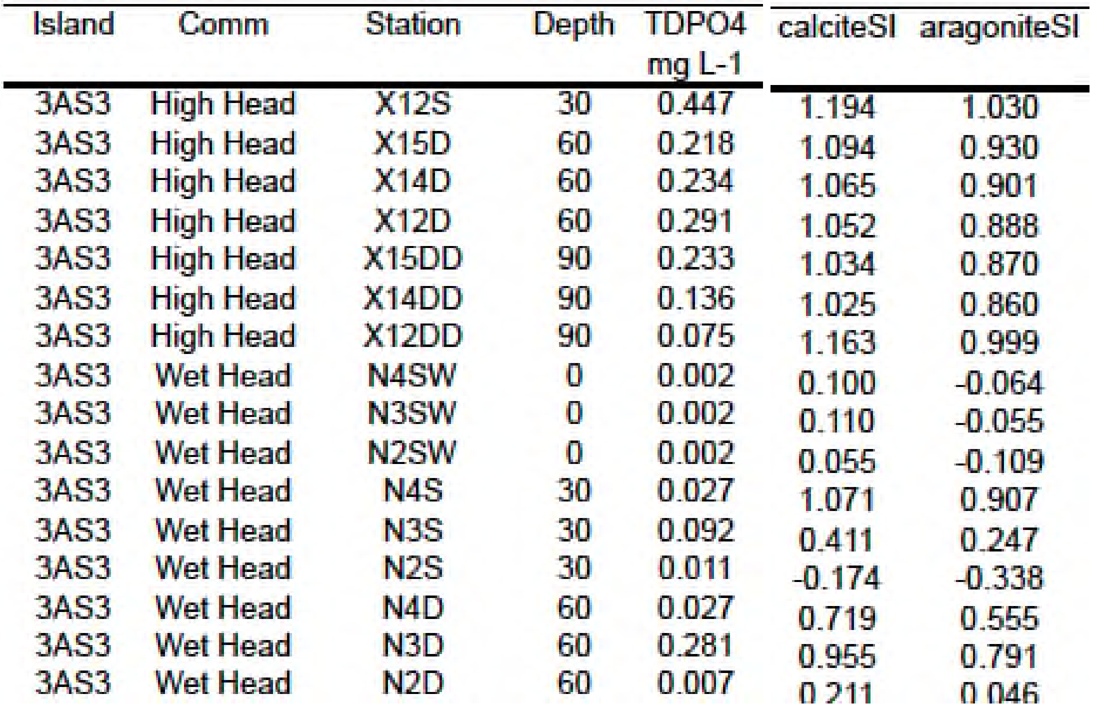


DOC (mg/L)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
HH
WH
NT
M
HH
WH
NT
M
3AS3
3BS2
GI
TH

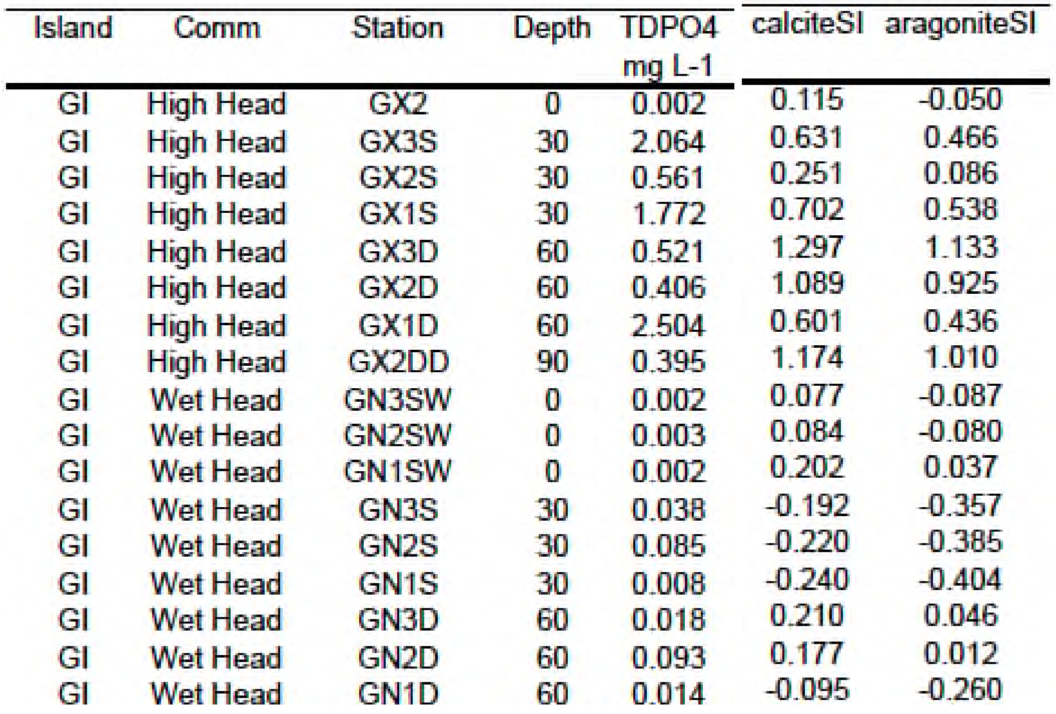


lab pH
7.60
7.40
7.20
7.00
6.80
6.60
6.40
6.20
6.00
HH
WH
NT
M
HH
WH
NT
M
3AS3
3BS2
GI
TH

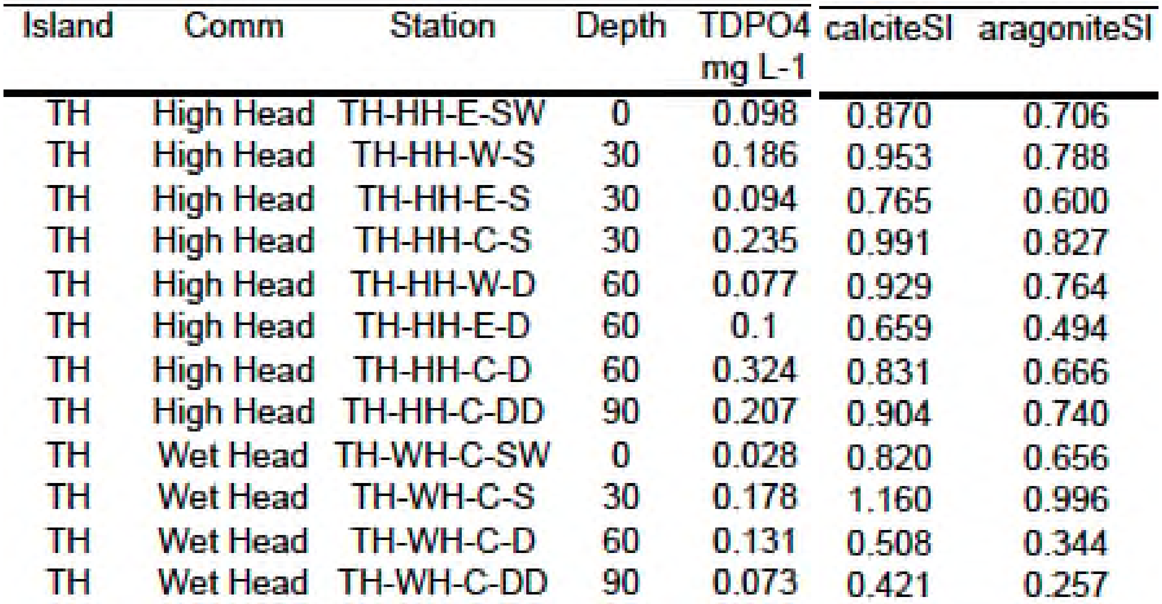
Table 1. Geochemical constituents TDPO$_4$ and calcite and aragonite saturation index (SI) by island, community and depth in October 2013 illustrating typical patterns found for each sampling.



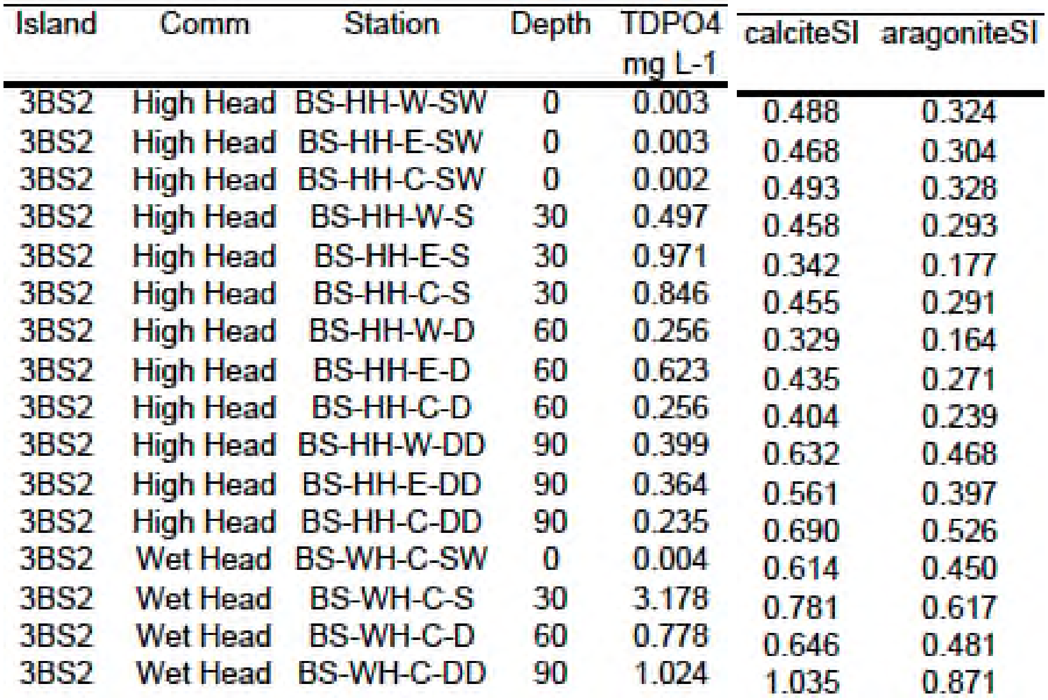
Island	Comm	Station	Depth	TDPO4 mg L-1	calciteSI	aragoniteSI
3AS3	High Head	X12S	30	0.447	1.194	1.030
3AS3	High Head	X15D	60	0.218	1.094	0.930
3AS3	High Head	X14D	60	0.234	1.065	0.901
3AS3	High Head	X12D	60	0.291	1.052	0.888
3AS3	High Head	X15DD	90	0.233	1.034	0.870
3AS3	High Head	X14DD	90	0.136	1.025	0.860
3AS3	High Head	X12DD	90	0.075	1.163	0.999
3AS3	Wet Head	N4SW	0	0.002	0.100	-0.064
3AS3	Wet Head	N3SW	0	0.002	0.110	-0.055
3AS3	Wet Head	N2SW	0	0.002	0.055	-0.109
3AS3	Wet Head	N4S	30	0.027	1.071	0.907
3AS3	Wet Head	N3S	30	0.092	0.411	0.247
3AS3	Wet Head	N2S	30	0.011	-0.174	-0.338
3AS3	Wet Head	N4D	60	0.027	0.719	0.555
3AS3	Wet Head	N3D	60	0.281	0.955	0.791
3AS3	Wet Head	N2D	60	0.007	0.211	0.046



Island	Comm	Station	Depth	TDPO4 mg L-1	calciteSI	aragoniteSI
GI	High Head	GX2	0	0.002	0.115	-0.050
GI	High Head	GX3S	30	2.064	0.631	0.466
GI	High Head	GX2S	30	0.561	0.251	0.086
GI	High Head	GX1S	30	1.772	0.702	0.538
GI	High Head	GX3D	60	0.521	1.297	1.133
GI	High Head	GX2D	60	0.406	1.089	0.925
GI	High Head	GX1D	60	2.504	0.601	0.436
GI	High Head	GX2DD	90	0.395	1.174	1.010
GI	Wet Head	GN3SW	0	0.002	0.077	-0.087
GI	Wet Head	GN2SW	0	0.003	0.084	-0.080
GI	Wet Head	GN1SW	0	0.002	0.202	0.037
GI	Wet Head	GN3S	30	0.038	-0.192	-0.357
GI	Wet Head	GN2S	30	0.085	-0.220	-0.385
GI	Wet Head	GN1S	30	0.008	-0.240	-0.404
GI	Wet Head	GN3D	60	0.018	0.210	0.046
GI	Wet Head	GN2D	60	0.093	0.177	0.012
GI	Wet Head	GN1D	60	0.014	-0.095	-0.260



Island	Comm	Station	Depth	TDPO4 mg L-1	calciteSI	aragoniteSI
TH	High Head	TH-HH-E-SW	0	0.098	0.870	0.706
TH	High Head	TH-HH-W-S	30	0.186	0.953	0.788
TH	High Head	TH-HH-E-S	30	0.094	0.765	0.600
TH	High Head	TH-HH-C-S	30	0.235	0.991	0.827
TH	High Head	TH-HH-W-D	60	0.077	0.929	0.764
TH	High Head	TH-HH-E-D	60	0.1	0.659	0.494
TH	High Head	TH-HH-C-D	60	0.324	0.831	0.666
TH	High Head	TH-HH-C-DD	90	0.207	0.904	0.740
TH	Wet Head	TH-WH-C-SW	0	0.028	0.820	0.656
TH	Wet Head	TH-WH-C-S	30	0.178	1.160	0.996
TH	Wet Head	TH-WH-C-D	60	0.131	0.508	0.344
TH	Wet Head	TH-WH-C-DD	90	0.073	0.421	0.257



Island	Comm	Station	Depth	TDPO4 mg L-1	calciteSI	aragoniteSI
3BS2	High Head	BS-HH-W-SW	0	0.003	0.488	0.324
3BS2	High Head	BS-HH-E-SW	0	0.003	0.468	0.304
3BS2	High Head	BS-HH-C-SW	0	0.002	0.493	0.328
3BS2	High Head	BS-HH-W-S	30	0.497	0.458	0.293
3BS2	High Head	BS-HH-E-S	30	0.971	0.342	0.177
3BS2	High Head	BS-HH-C-S	30	0.846	0.455	0.291
3BS2	High Head	BS-HH-W-D	60	0.256	0.329	0.164
3BS2	High Head	BS-HH-E-D	60	0.623	0.435	0.271
3BS2	High Head	BS-HH-C-D	60	0.256	0.404	0.239
3BS2	High Head	BS-HH-W-DD	90	0.399	0.632	0.468
3BS2	High Head	BS-HH-E-DD	90	0.364	0.561	0.397
3BS2	High Head	BS-HH-C-DD	90	0.235	0.690	0.526
3BS2	Wet Head	BS-WH-C-SW	0	0.004	0.614	0.450
3BS2	Wet Head	BS-WH-C-S	30	3.178	0.781	0.617
3BS2	Wet Head	BS-WH-C-D	60	0.778	0.646	0.481
3BS2	Wet Head	BS-WH-C-DD	90	1.024	1.035	0.871

Table 2. Ion composition for El Tigre, Ghost Island, Twin Heads and 3BS2 during wet period (late August - September 2014). Calcium, total dissolved solids (TDS), alkalinity, magnesium, sodium, potassium, sulfate, chloride and calculated charge balance by vegetation type, well depth and sampling station.

Island	Comm	Station	Depth cm	Ca mg L^{-1}	Mg mg L^{-1}	Na mg L^{-1}	K mg L^{-1}	SO_4 mg L^{-1}	Cl mg L^{-1}	TDS mg L^{-1}	Alkalinity mg L^{-1}	charge balance
3AS3	High Head	X12S	30	112.6	31.3	197.3	0.2	22	284	972	401	0.87
3AS3	High Head	X12D	60	155.9	45.8	145.8	0.3	16.4	294	966	482	-1.05
3AS3	High Head	X14D	60	127.2	27.4	222.2	0.1	23.3	284	1026	496	-0.41
3AS3	High Head	X15D	60	167	15.8	281.2	0.4	18.2	442	1238	450	0.06
3AS3	High Head	X12DD	90	166.6	20.4	101	0.7	3	141	778	512	0.42
3AS3	High Head	X14DD	90	142.6	21.1	102	0.7	15.2	132	744	490	-1.97
3AS3	High Head	X15DD	90	141.2	18	148.1	0.5	10.1	213	902	526	-5.55
3AS3	Wet Head	N2SW	0	35.7	2.7	8.6	0.8	0.1	12.4	142	101	0.55
3AS3	Wet Head	N3SW	0	39.7	3	10.2	0.8	0.1	14.6	170	112	0.71
3AS3	Wet Head	N4SW	0	39.1	2.9	9.8	0.9	0.1	12.7	144	102	4.73
3AS3	Wet Head	N2S	30	56.9	3.9	18.2	0.2	0.1	24.9	270	152	2.76
3AS3	Wet Head	N3S	30	149.4	8.2	46.3	0.1	0.2	176	646	331	-6.64
3AS3	Wet Head	N4S	30	170.9	9.2	45.9	0.1	0.1	81	650	392	5.40
3AS3	Wet Head	N2D	60	110	6.2	31.5	0.1	0.1	54.6	506	266	3.58
3AS3	Wet Head	N3D	60	217.2	8.9	56.4	0.1	0.1	100	820	503	4.25
3AS3	Wet Head	N4D	60	241.8	9.4	46.4	0.1	0.1	78.6	837	537	6.83
3AS3	Wet Head	WXD	60	157.5	7.2	36.1	0.1	0.6	53.3	542	416	0.95
3AS3	Near Tail	S7SW	0	40.8	3.3	11.4	1.1	0.1	13.6	130	106	6.10
3AS3	Near Tail	S8SW	0	46.3	3.6	12.4	1.1	0.1	16.7	152	120	4.97
3AS3	Near Tail	S9SW	0	42.4	3.1	12.1	0.8	0.1	13.9	146	107	7.03
3AS3	Near Tail	S7S	30	56.9	4.8	17.4	0.3	0.2	19	192	143	8.09
3AS3	Near Tail	S8S	30	73.1	5.3	21.8	0.4	N/A	27.7	246	175	8.16
3AS3	Near Tail	S9S	30	122.1	6.8	34.1	0.2	0.1	53.1	486	281	6.69
3AS3	Near Tail	S7D	60	99.1	5.6	30	0.1	0.1	44.7	414	224	7.79
3AS3	Near Tail	S8D	60	270	14.6	53.9	0.1	0.1	86.8	932	622	6.67
3AS3	Near Tail	S9D	60	164.1	7.6	32.6	0.2	0.1	54.1	556	394	4.22
3AS3	Marsh	M1	0	38.2	2.7	8.9	0.8	0.1	12.2	152	102	3.04
3AS3	Marsh	M2	0	40	3	9.9	0.9	0.1	12.1	138	104	5.33
3AS3	Marsh	M1S	30	134	9.5	40.6	3	0.1	40.7	552	381	2.99
3AS3	Marsh	M2S	30	110.7	9.6	82	3.2	0.1	57.5	536	351	7.08
3AS3	Marsh	M2D	60	138.3	9	88.3	5.4	0.1	43.4	648	461	5.31

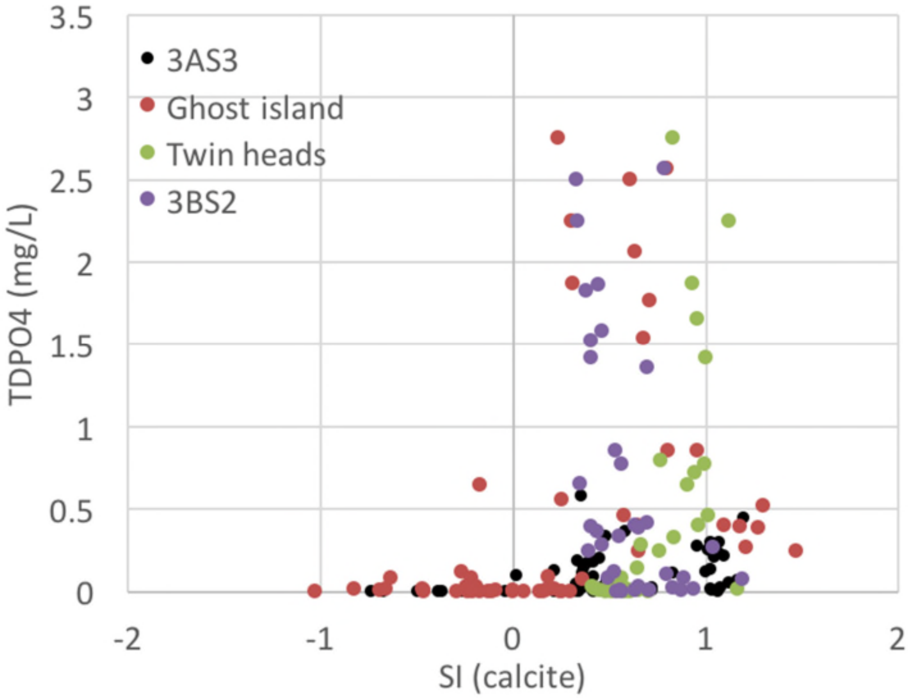
Island	Comm	Station	Depth cm	Ca mg L^{-1}	Mg mg L^{-1}	Na mg L^{-1}	K mg L^{-1}	SO_4 mg L^{-1}	Cl mg L^{-1}	TDS mg L^{-1}	Alkalinity mg L^{-1}	charge balance
Ghost Island	High Head	GX2	0	44	3.9	15.9	1.5	0.1	22.5	172	119	3.66
Ghost Island	High Head	GX1S	30	143.6	13.9	81	0.3	4.7	90.5	664	430	2.55
Ghost Island	High Head	GX2S	30	159.4	11.2	60.9	0.2	6	65.8	670	476	0.12
Ghost Island	High Head	GX3S	30	166.5	13.1	63.4	0.2	11.7	89.4	712	463	0.51
Ghost Island	High Head	GX1D	60	182.6	13.7	84.3	0.4	0.1	155	842	457	1.46
Ghost Island	High Head	GX2D	60	215.6	11.7	75.5	0.2	9.7	87.1	822	592	1.73
Ghost Island	High Head	GX3D	60	242.1	14.7	93.5	0.3	12.1	130	928	635	2.19
Ghost Island	Wet Head	GN1SW	0	43.7	3.9	15.9	1.4	0.1	22.4	194	119	3.44
Ghost Island	Wet Head	GN2	0	44.9	4	16.5	1.5	0.1	22.6	172	120	4.49
Ghost Island	Wet Head	GN3SW	0	44.3	4	16.1	1.5	0.1	22.4	182	120	3.87
Ghost Island	Wet Head	GN1S	30	67.8	7.8	36.2	0.6	0.1	51.2	364	179	5.53
Ghost Island	Wet Head	GN2S	30	71	8.5	35.6	0.3	0.1	44.4	392	191	6.65
Ghost Island	Wet Head	GN3S	30	113.4	10.7	58.4	0.3	0.1	91.4	648	287	4.40
Ghost Island	Wet Head	GN1D	60	78.5	8.2	51.7	0.4	0.1	64	426	216	5.57
Ghost Island	Wet Head	GN2D	60	111.2	8.9	64.7	0.3	0.1	78.8	618	288	6.54
Ghost Island	Wet Head	GN3D	60	109.1	11.2	71.2	0.5	0.1	89.9	640	305	4.62
Ghost Island	Near Tail	GS2	0	44.7	3.9	15.8	1.5	0.1	22.3	114	123	2.92
Ghost Island	Near Tail	GS2S	30	49.1	7.8	28.3	1.2	0.1	31.2	284	177	-0.79
Ghost Island	Near Tail	GS2D	60	66.7	6.7	39.4	1	0.1	47.4	350	216	-0.36
Ghost Island	Marsh	GM1	0	43.3	3.9	15.5	1.5	0.1	22	200	121	2.42
Ghost Island	Marsh	GM2	0	43.7	4	15.8	1.5	0.1	21.9	176	120	3.44
Ghost Island	Marsh	GM1S	30	85.6	12.9	44.2	0.3	0.2	38.9	488	309	-0.13
Ghost Island	Marsh	GM2S	30	65.5	9.5	40	2.7	0.1	46.8	354	221	1.00
Ghost Island	Marsh	GM1D	60	98.9	10.5	66.1	1.2	0.1	46.3	548	379	-1.05
Ghost Island	Marsh	GM2D	60	82.4	9.9	75.6	4.9	0.1	55.9	524	348	-1.19

Island	Comm	Station	Depth cm	Ca mg L^{-1}	Mg mg L^{-1}	Na mg L^{-1}	K mg L^{-1}	SO_4 mg L^{-1}	Cl mg L^{-1}	TDS mg L^{-1}	Alkalinity mg L^{-1}	charge balance
Twin Heads	High Head	TH-HH-E-SW	0	165.4	15	36.3	2	2.4	52	598	462	1.65
Twin Heads	High Head	TH-HH-C-S	30	121.7	9.6	52	0.5	5.1	52.2	508	381	-0.34
Twin Heads	High Head	TH-HH-E-S	30	177.6	16.3	35.9	0.3	4.6	50.9	564	486	2.26
Twin Heads	High Head	TH-HH-W-S	30	174.7	9.6	36.8	0.9	0.1	50.5	630	486	-0.07
Twin Heads	High Head	TH-HH-C-D	60	170.1	11.9	48.8	0.3	5.3	70.5	630	467	0.68
Twin Heads	High Head	TH-HH-E-D	60	151.1	13.3	35.4	0.4	0.1	51.9	590	425	1.08
Twin Heads	High Head	TH-HH-W-D	60	175.3	12.4	37.8	0.8	0.1	54.1	638	500	-0.42
Twin Heads	High Head	TH-HH-C-DD	90	164.6	11.6	45.1	0.2	3.1	68.4	594	462	-0.45
Twin Heads	Wet Head	TH-WH-C-S	30	151.8	16.5	43.8	0.4	0.1	57.6	678	445	1.50
Twin Heads	Wet Head	TH-WH-C-D	60	107.8	10.3	31.9	1.6	0.1	48.8	444	325	-1.44
Twin Heads	Wet Head	TH-WH-C-DD	90	102.6	9.7	33.8	1.6	0.1	49.7	432	314	-1.69
Twin Heads	Near Tail	TH-NT-C-SW	0	109.6	8.8	27.9	0.5	0.1	42.5	428	303	1.08
Twin Heads	Near Tail	TH-NT-C-S	30	147.8	13.3	39.7	0.2	1.6	64.8	572	427	-0.97
Twin Heads	Near Tail	TH-NT-C-D	60	135.2	11.4	34	0.3	0.1	52.5	522	394	-1.04
Twin Heads	Marsh	TH-SL-E-SW	0	57.9	6.4	18.1	1.6	0.1	28	260	177	-1.03
Twin Heads	Marsh	TH-SL-W-SW	0	59.6	6.7	21.3	2	0.1	32	258	184	-0.90
Twin Heads	Marsh	TH-SL-E-S	30	106.6	8.8	30.8	0.7	0.1	43.8	424	318	-1.31
Twin Heads	Marsh	TH-SL-W-S	30	95.6	10.9	34.3	1.2	0.1	50.4	424	303	-2.01
Twin Heads	Marsh	TH-SL-E-D	60	102.3	11.8	31.8	1.4	0.1	44.4	444	327	-1.97
Twin Heads	Marsh	TH-SL-W-D	60	88.2	11.9	34.8	1.9	0.1	47.8	402	298	-2.59

Island	Comm	Station	Depth cm	Ca mg L^{-1}	Mg mg L^{-1}	Na mg L^{-1}	K mg L^{-1}	SO_4 mg L^{-1}	Cl mg L^{-1}	TDS mg L^{-1}	Alkalinity mg L^{-1}	charge balance
3BS2	High Head	BS-HH-C-SW	0	56.3	9.8	36.5	3.3	2.7	61.1	332	191	-2.87
3BS2	High Head	BS-HH-E-SW	0	59.3	10	38	3.2	2.5	62.5	336	196	-1.95
3BS2	High Head	BS-HH-W-SW	0	56.7	9.7	36.6	3.2	2.4	61.1	296	192	-2.87
3BS2	High Head	BS-HH-C-S	30	147.7	12.2	72.5	0.2	52.2	124	790	370	-1.93
3BS2	High Head	BS-HH-E-S	30	128.3	13.9	62.3	0.2	8.6	105	596	363	-0.68
3BS2	High Head	BS-HH-W-S	30	128.6	16.1	69	0.2	14.4	120	670	367	-1.27
3BS2	High Head	BS-HH-C-D	60	152.5	13	102.6	0.2	59.1	172	850	374	-1.56
3BS2	High Head	BS-HH-E-D	60	138.4	14.2	62.8	0.2	6.6	105	614	395	-0.87
3BS2	High Head	BS-HH-W-D	60	130.9	15.6	65.2	0.2	9.9	113	622	372	-0.83
3BS2	High Head	BS-HH-C-DD	90	156.6	15.4	68.1	0.2	17.2	111	712	433	-0.42
3BS2	High Head	BS-HH-E-DD	90	136.6	16.2	65	0.2	6.8	113	642	397	-1.30
3BS2	High Head	BS-HH-W-DD	90	137.7	15.1	58.8	0.2	6	100	642	398	-1.07
3BS2	Wet Head	BS-WH-C-SW	0	61.1	9.9	37	3.2	2.4	61.1	362	202	-2.28
3BS2	Wet Head	BS-WH-C-S	30	136.4	7.4	47.1	0.7	1.2	50.4	668	392	1.04
3BS2	Wet Head	BS-WH-C-D	60	166.5	12	50.4	0.2	0.1	80.5	708	474	-1.12
3BS2	Wet Head	BS-WH-C-DD	90	206.5	12.7	49.5	1	0.1	77.7	812	572	-0.39
3BS2	Near Tail	BS-NT-C-SW	0	58.2	9.4	34.8	3.4	2.7	57.8	296	186	-1.21
3BS2	Near Tail	BS-NT-C-S	30	159.1	16.1	64.5	0.3	0.1	105	694	442	1.14
3BS2	Near Tail	BS-NT-C-D	60	108.9	12.4	47.3	0.2	0.1	76.5	494	327	-1.07
3BS2	Marsh	BS-SL-E-SW	0	55.7	9.7	36.7	3.4	2.7	61.2	322	185	-2.07
3BS2	Marsh	BS-SL-W-SW	0	55.2	9.5	36.8	3.3	2.8	60.4	300	180	-1.34
3BS2	Marsh	BS-SL-E-S	30	121.1	14.3	55.5	2.2	0.1	82.4	568	365	0.32
3BS2	Marsh	BS-SL-W-S	30	162.3	19.8	78.2	4.3	0.1	112	788	501	0.21
3BS2	Marsh	BS-SL-E-D	60	128.1	14.6	57.6	1.7	0.1	84.7	592	384	0.35
3BS2	Marsh	BS-SL-W-D	60	173.7	19.8	82	4.6	0.1	118	838	532	0.03

Figure 11. Scatterplots of $TDPO_4$ and calcite saturation index for all islands, all depths for all communities (A) and for high head communities only (B).

A.



B.

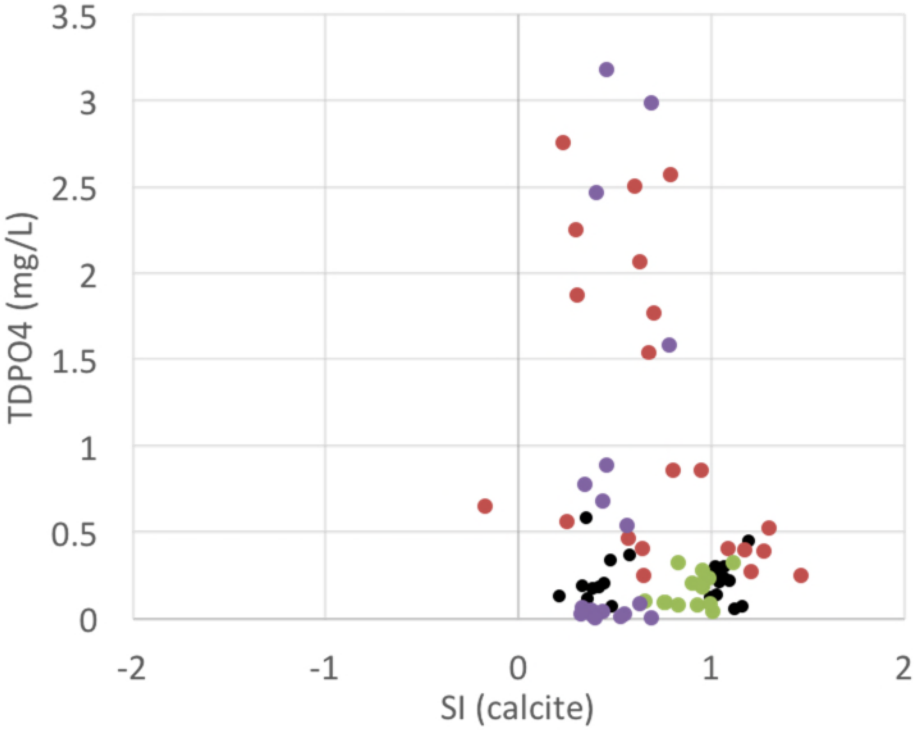


Figure 12. Patterns of mineral saturation and phosphorus availability along a environmental disturbance gradient

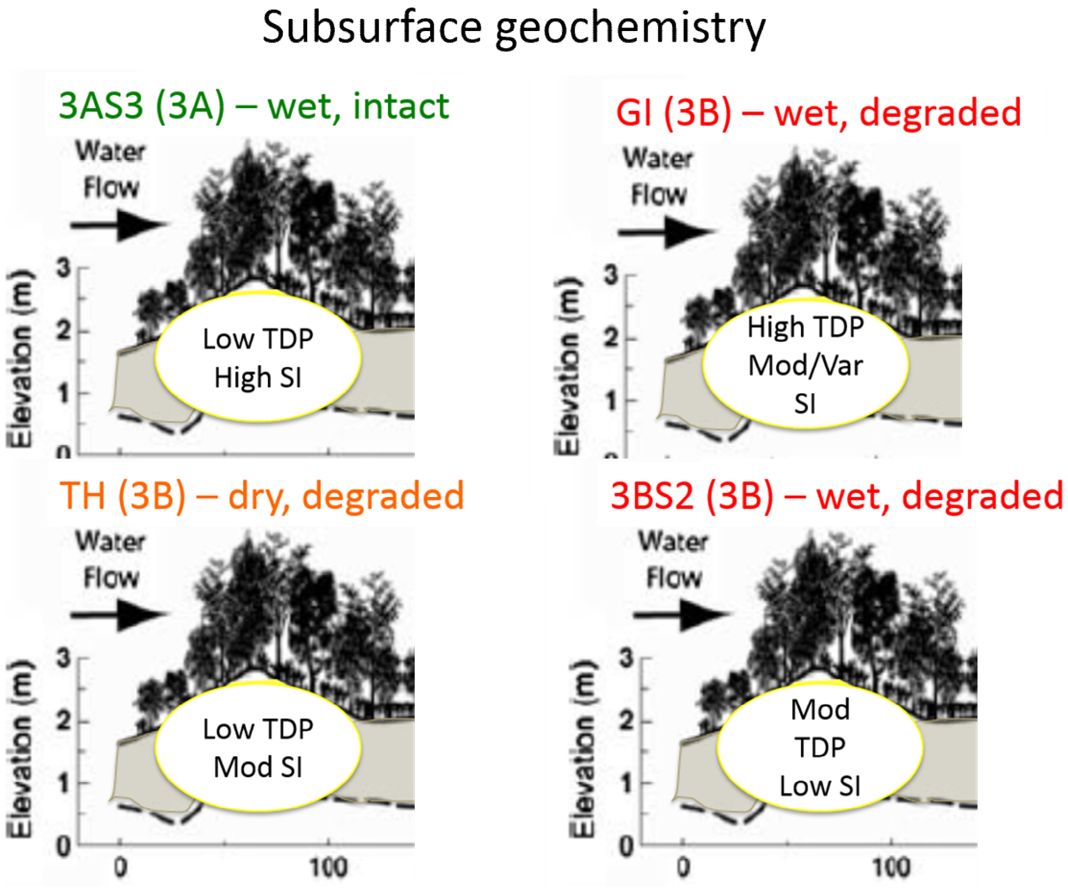


Table 3. Five metrics for interpreting tree island geochemical patterns and stoplight indicators of tree island condition for the five metrics.

TREE ISLAND	**Ion concentration in HH and differentiation among communities (TDS)**	**Phosphorus concentration in High Head ($TDPO_4$)**	**Extent of organic soil type (DOC)**	**Residence time or soil/redox condition (SO_4) in HH**	**Cl concentration (Ca/Cl) in HH S & D**
3AS3	Strong among communities, highest in HH, and in center of community (750-1250 mg L-1 in HH)	Moderate (0.07-0.26 mg L-1), Moderate in WH center (0.08-0.11 mg L-1)	Low organic in HH (<10 mg L-1), high organic in other (>20 mg L-1)	Moderate (10-23 mg L-1)	Low (0.4-0.5), otherwise 2-3
Twin Heads	Low/moderate among communities (500-650 mg L-1 in HH)	Moderate (0.07-0.34 mg L-1), Moderate in WH center (0.05-0.06 mg L-1)	Low organic in central HH (<10 mg L-1), moderate organic in other (10-20 mg L-1)	Low (0-5 mg L-1)	High (2.5-3.5)
Ghost Island	Moderate among communities, highest in HH, and in center of community (650-950 mg L-1 in HH)	High (0.3-1.5 mg L-1), Moderate in WH center (0.04-0.08 mg L-1)	Low organic in D, HH only (<12 mg L-1), high organic in other (>20 mg L-1)	Low (0-12 mg L-1)	Moderate (1 – 2.5)
3BS2	Low among communities (600-800 mg L-1 in HH)	High (0.1-0.9 mg L-1), High in WH center (0.6-2.4 mg L-1)	High organic (>20 mg L-1)	High (17-60 mg L-1)	Moderate (0.9-1.5)

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