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ABSTRACT

Restoring wetlands on agricultural land can release soil P to surface waters. Phosphorus is a limiting nutrient in many freshwater systems, thus restricting its release will improve surface water quality. A P balance was used to examine how P was cycling in a Carolina Bay wetland eight years after restoration from prior-drained agricultural land. The change in soil P was evaluated between archived samples taken at restoration (2005), and eight years after restoration (2013). Measured P fluxes included atmospheric deposition, plant uptake, and loss to surface water outflow. The soil total P pool at the time of restoration was 810 kg P ha^{-1}. No significant (α=0.05) decrease in the soil P pool was observed. Atmospheric deposition contributed 7 kg P ha^{-1}, plants accumulated 28 kg P ha^{-1} and incorporated 27 P ha^{-1} into woody biomass and 1 kg P ha^{-1} on the forest floor litter, and 1.7 kg P ha^{-1} was lost to surface waters draining the wetland. Because the loss of P to surface waters was small, and because runoff water concentrations of P declined through this period of study to concentrations below those likely to cause eutrophication (< 0.1 mg L^{-1}), we concluded that the wetland was not contributing to the degradation of surface water quality of nearby streams following restoration. Further, relatively “isolated” wetlands such as that studied may be promising sites for future wetland mitigation projects due to limited impacts on surface water quality.

KEY WORDS

Wetland restoration; water quality; isolated wetlands; converted wetlands; phosphorus

INTRODUCTION

Over 50% of the original wetlands in the conterminous 48 states of the U.S. were drained primarily for food production between 1780 and 1980 (Dahl and Allord 1996). Since 1977, federal and state programs have been enacted to reverse the loss by restoring drained areas to their original wetland condition, frequently by plugging or filling drainage ditches. Wetland restoration is accomplished, in part, to improve water quality. However, in cases where wetlands are restored from agricultural land that is high in P from years of fertilization, saturated and reduced soil conditions cause P to be released from the newly flooded wetland contributing to eutrophication of nearby surface waters. Between 1997 and 2001 there was an estimated annual net gain of 13,400 ha of wetlands nationally due to restoration of agricultural fields, while between 2001 and 2003 the annual net gain more than doubled from previous periods (USDA-NRCS 2013). Based on estimates from the North Carolina Division of Mitigation Services, approximately two-thirds of restored wetlands in North Carolina originated from drained and fertilized agricultural lands – equivalent to approximately 1500 ha since 1999 (Smith 2011). Given that wetland restoration is increasing in the U.S., in part to improve water quality, it is critical to determine whether restoration will actually contribute to pollution of P-sensitive watersheds.

The problem of P dissolution in wetlands restored on agricultural fields has been observed around the world. Recent studies of P dissolution have been done on peat soils in the Netherlands (Van Dijk et al. 2004), soils used for dairy production in Florida (Pant and Reddy 2003), restored lake fringe in Oregon (Aldous et al. 2007; Duff et al. 2009), and agricultural soils in the North

Carolina Coastal Plain (Ardon et al. 2010), and a Carolina Bay complex in North Carolina (Bruland et al. 2003). These studies have shown that P dissolution is largely driven by Fe reduction processes (Reddy and DeLaune 2008), along with other mechanisms including ligand exchange (Earl et al. 1979; Lopez-Hernandez et al. 1986; Violante et al. 1991; Gerke 1992), P mineralization from drying and rewetting cycles (Song et al. 2007), changes in pH (Jackson 1964; Ponnamperuma 1972; Stumm and Morgan 1981), and increased P diffusion (Turner and Gilliam 1974a; Turner and Gilliam 1974b).

To ensure that wetland restoration and management practices do not contribute to pollution of nutrient sensitive streams, a better understanding of P fluxes within and out of wetlands restored from agricultural land is greatly needed in order to identify potential management strategies that will reduce P loss. This study focused on a previously cultivated Carolina Bay wetland, known as Juniper Bay, that was restored as a wetland and then monitored for P in drainage waters in subsequent years (Vepraskas et al. 2010; Moorberg et al. 2014; Moorberg et al. 2017). The objectives of this study were to estimate a P budget for a restored wetland by determining P fluxes for soil storage, plant uptake, atmospheric input, and loss from drainage water.

MATERIALS AND METHODS

Juniper Bay is located in Robeson County, NC approximately 10 km south of Lumberton, NC (34˚30’30”N 79˚01’30”W). In 1999, the North Carolina Department of Transportation (NCDOT) purchased this drained Carolina Bay wetland to mitigate the destruction of nearby wetlands caused by highway construction (Ewing 2003). The Bay is oval-shaped, oriented lengthwise along a northwest-southeast transect, and is virtually flat with an area of 291 ha. Soils in Juniper Bay include approximately 60% mineral soils (Leon sand; sandy, siliceous, thermic Aeric Alaquods, USDA Soil Taxonomy) primarily at the edges (Figure 1, SC and SS mapping units), with organic soils (Ponzer muck; loamy, mixed, dysic, thermic Terric Haplosaprists, USDA Soil Taxonomy), occupying the remainder at the center (Figure 1, OC and OS mapping units). This Bay was drained for agriculture beginning in 1971 by excavating a perimeter ditch around the edge of the Bay, and installing primary and secondary ditches within the Bay to facilitate drainage into a single surface water outlet on the southwestern edge of the wetland (Vepraskas et al. 2005). Juniper Bay was fertilized and limed annually to meet soil-test recommendations. It remained in crop production until 2001. Preliminary restoration efforts began in June 2003, and wetland hydrology was restored in 2005 by filling primary ditches and plugging tertiary ditches, leaving only the perimeter ditch intact. That perimeter ditch drains into one outlet on the southwest side of the Bay.

A P-balance was developed to better understand the nature and relationships of P fluxes into and out of Juniper Bay following restoration. The proposed P-balance in simplest form is shown in Equation 1:

$$\Delta P_{soil} = P_{inputs} - P_{outputs} \pm E \qquad [1]$$

where ΔP_{soil} is the change to the soil's total P (TP) pool to a depth of 1 m since restoration (2005-2013). The P_{inputs} are sources of "new" P, while $P_{outputs}$ include all mechanisms that remove P from the soil. The E is an error term that accounts for errors in the determination of the change of P in the soil, errors in P fluxes, and/or error or fluxes that have gone unrecognized.

We hypothesized that atmospheric deposition (P_{ATM}) is a major mechanism adding new P into the Bay, but groundwater inflow (P_{GI}) could also be contributing P. Major ways for P to be removed from the soils in Juniper Bay include: plant uptake (P_{PL}), groundwater outflow (P_{GO}) and surface water outflow (P_{SO}). Previous work by Pati (2006) showed that the perimeter ditch would intercept most groundwater inflow into the Bay, thus transforming P_{GI} into P_{SO} which would drain out of the Bay through the outflow structure. In addition, Pati (2006) showed that the groundwater outflow component would be intercepted by the perimeter ditch as well, as long as the water levels in the ditch were managed to stay below a critical elevation. Such management of the perimeter ditch is currently practiced so that groundwater outflow from the Bay should be small. Huffman et al. (2007) estimated the net flow of ground and surface water into the Bay from the surrounding landscape was equivalent to 125 mm during the wet months of 2004, with inflows entering the perimeter ditch on the NW, NE, and SE sides of the Bay, and groundwater outflows exiting on the SW side of the Bay. The impact of the perimeter ditch is such that the terms for P_{GO}, P_{SO}, and P_{GI} were combined with the assumption that contributions from groundwater inflow are minimal, and that surface water outflow is primarily from drainage from Juniper Bay. This assumption was tested and validated, as described in the supplementary material (SI Table 1 and SI Table 2; SI Figure 1, SI Figure 2, SI Figure 3, and SI Figure 4)

The P balance for Juniper Bay can be written with the defined inputs and outputs as:

$$\Delta P_{soil}=P_{ATM} - P_{PL} - [P_{GO} + P_{SO} - P_{GO}] \qquad [2]$$

For simplicity, we combined the components P_{GO}, P_{SO} and P_{GI} into one term called $P_{OUTFLOW}$ which was measured collectively at the outflow structure. The modified P balance used for this study is:

$$\Delta P_{soil}=P_{ATM} - P_{PL} - P_{OUTFLOW} \pm E \qquad [3]$$

The volume of soil considered for Juniper Bay has a horizontal area defined by the perimeter ditch (Figure 1B) with the soil depth starting at the soil surface and extending to a depth of 1 m.

The 1 m depth was selected because previous work showed that the P increases from agricultural applications in Juniper Bay were not observed below 1 m (Ewing 2003).

The change in the soil P pool was determined by measuring total phosphorus (TP_{soil}) in archived soil samples (2005) and comparing those values with TP_{soil} found in present day samples extracted from the same locations. The TP_{soil} concentrations for time-zero (2005) were determined from two groups of archived soil samples. Prior to restoration, soils were sampled in 2000 from 48 soil pit locations to a depth of 1 m (Figure 1B) by Ewing et al. (2012), and in 2004 on a grid of 700 locations across the Bay to depths of 0-0.15 m and 0.15-0.3 m using soil push probe. It was assumed that P concentrations in the subsoil (0.15-0.3 m) had not changed between 2000 and restoration in 2005 based on the observations made by Ewing et al. (2012) which noted that subsoil P concentrations were low and did not exceed those found in nearby reference Carolina Bay wetlands. Since Juniper Bay remained artificially drained from 2000 to 2004, soil P should have remained immobile prior to restoration.

For each archived soil sample location, GPS coordinates were recorded in 2005 at the time of sampling, thus allowing new samples to be extracted from the same locations. For the 0-0.15 m and 0.15-0.3 depths 138 locations of the 700 total were selected for re-sampling and analysis using an area-weighted, stratified random sampling scheme (Figure 1B). The samples were separated into four strata based on the soil mapping units developed for restoration of Juniper Bay during the NCDOT soil survey. All archived surface and subsoil sites were located using GPS receivers with a wide area augmentation system correction and 2-5 m accuracy.

The study by Ewing et al. (2012) included 48 soil pit locations. These locations consisted of 24 pairs of pits - one at the crest (middle) of the fieldlet, and one adjacent to the ditch. They observed large amounts of disturbance in the ditch pits due to maintenance and dredging of the drainage ditches during agricultural production; therefore, only the crest pits were used in this study. Also, Ewing et al. (2012) studied five pits from soils with histic epipedons at the transition from mineral to organic soils. Because these histic soils represent a small area of the Bay, they were also omitted from this study. The remaining 19 soil pits used in this study are shown in Figure 1B. The 2013 soil samples were extracted using a soil auger for all three depths.

All soil samples were submitted to the North Carolina Department of Agriculture Soil Testing Service for analysis of extractable P by the Mehlich-3 method (Mehlich 1984). Soil TP analysis was performed on 25% of the re-sampled 0-15 cm and 15-30 cm depth soil samples that were selected at random within each stratum (Figure 1B). Soil TP analysis was also performed on four representative horizons from each pit location (Figure 1B). Soil TP was determined by nitric-perchloric acid digestion (Carter 1993). The TP_{soil} determined on a mass per mass basis were re-expressed as mass P per volume of soil for inclusion into the P-balance. Bulk densities reported by Ewing et al. (2012) for the pre-restoration samples at all depths were used to convert the mass of soil to its equivalent volume. Bulk density was determined again for the 2013 samples for the 0-15 and 15-30 cm depths using the core method (Grossman and Reinsch 2002). Samples were collected in triplicate at each of the 19 soil pit locations and averaged across the four soil mapping units for the 0-15 and 15-30 cm depths. Bulk densities for the 0.3 to 1.0 m depths were assumed to be the same as the pre-restoration values as reported by Ewing et al. (2012).

Atmospheric deposition of P was monitored from May 2012 through June 2013 at three locations within the wetland (Figure 1A), as described by Kreiser (2003). Samplers were installed adjacent to existing rain gauges using a bulk rain water collection apparatus (SI Figure 5) modeled after Likens et al. (1967) and Johnson and Swank (1973). Samples were collected every two to four weeks and acidified for preservation. Samples were submitted to the North Carolina State University Environmental and Agricultural Testing Service (Raleigh, North Carolina, USA) for determination of dissolved reactive P (DRP) and dissolved total P (DTP). The average concentration of DTP for this time period, along with historic rainfall data collected on site were used to estimate P_{atm} from 2005 to 2013 over the entire area of the wetland.

Phosphorus uptake and accumulation by trees was estimated for the entire area of Juniper Bay. The North Carolina Department of Environment and Natural Resources (now the North Carolina Department of Environmental Quality, NCDEQ) planted wetland tree saplings throughout Juniper Bay at the time of restoration (NCDEQ 2010). Between 2005 and 2010, NCDEQ (2010) established and maintained 19 vegetation plots for wetland mitigation purposes at Juniper Bay. Those 10 m by 10 m plots were located and expanded by 20 m on all sides to create 30 m x 30 m plots for this tree survey, as shown in Figure 1A (plots not drawn to scale). Tree species, height, and diameter at breast height (DBH) were recorded for all trees greater than 10 cm DBH within each vegetation plot. Wood biomass was then estimated for each tree using allometric equations from Gonzalez-Benecke (2011) for loblolly pine (*Pinus taeda* L.) and pond pine (Pinus serotina Michx.), and allometric equations from Schroeder et al. (1997) and Jenkins et al. (2003) for all other species. Biomass P content was estimated for all species using P concentrations presented by Bedford et al. (1999). The total plot woody biomass per hectare and woody biomass P per hectare was determined by summing all of the tree biomass and biomass P within each plot, and dividing by the plot area. The total biomass and P_{plant} for the entire Bay was estimated by multiplying the woody biomass per hectare and the woody biomass P per hectare by the area of the Bay.

Plant litter (the fibric, Oi soil horizon) samples were collected in October of 2014 from eight randomly selected vegetation plots. A 1 m by 1 m square PVC frame was laid in the center of each plot. Then, five large nails were driven into the ground until the nail head was at the surface of the litter at each of the four corners and one at the center. The litter was then collected for analysis. The heights of each nail above the soil surface were measured and averaged to determine the average depth of plant litter per square meter.

The litter was dried in an oven at 70°C for four days, then weighed to determine total litter biomass. Subsamples were ground and analyzed by the Environmental and Agricultural Testing Laboratory at North Carolina State University (Raleigh, North Carolina, USA) for C and P analysis. The percent P by weight (% w/w) for the subsamples was multiplied by the litter dry weight per square meter (g m^{-2}) to estimate the mass of P per square meter (g P m^{-2}) for each site. The P_{lit} for Juniper Bay was estimated by multiplying the average mass of P per square meter by the total area of the Bay (2,910,000 m^2).

The perimeter ditch surrounding Juniper Bay drains into a single surface water outflow structure at the edge of the Bay (Figure 1A). Samples from the drainage outlet were taken four times daily from 2010 to 2013 using a Teledyne ISCO automatic water sampler (Teledyne ISCO, Lincoln, Nebraska, USA) and composited into one sample. From 2005 to 2010, manually collected samples (1 L volume) were collected from the center of the channel at the outflow on a monthly basis using a bottle attached to a pole. All water samples were acidified for preservation, and submitted to the North Carolina State University Environmental and Agricultural Testing Service (Raleigh, North Carolina, USA) for DRP and DTP analysis. Only DRP was measured on the grab samples (2005-2010), while both DRP and DTP were analyzed for the daily samples (2010-2013). Organic P (difference between DTP and DRP) was not determined from 2005-2010 and was assumed to contribute to the error term in the P balance as an un-accounted loss. A subset of samples was also analyzed for total P, but no significant difference between total P and DTP was observed. This indicated that particulate P was not present at this site in measureable amounts, so DTP was used for calculating $P_{outflow}$ instead of total P.

Surface outflow in the perimeter ditch was measured at the main outlet using two v-notch weirs that were installed in 2001. Discharge rates were measured from December 2010 through 2013. Discharge measurements were made using pressure transducers located upstream and downstream of the weir to determine the stage of the water. Discharge measurements were recorded using a Campbell Scientific CR-10X data logger.

Surface water discharge was estimated prior to December 2010 using a monthly water balance. Rainfall was measured on site at three rainfall stations (SI Table 3). Evapotranspiration rates from the MODIS Land Subsets Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC, 2011) were used from January 2005 through December 2013. The MODIS Land Subset ET is remotely sensed ET with a 500 m resolution that is determined from leaf area index (LAI) and radiation at the earth's surface. That dataset provides total ET over 8 days. To estimate monthly ET, the 8-day ET values were divided by eight to estimate the daily ET value on the day it was reported. Missing daily ET values were then interpolated using MatLab (MathWorks, Natick, MA, U.S.A.) and summed for each month to estimate total monthly ET from January 2005 to December 2009. Evapotranspiration from January 2010 to November 2010 was estimated using the Thornthwaite method (Thornthwaite 1948) and monthly mean temperature data from the Lumberton Regional Airport (NOAA NCDC 2013) approximately 11 km northwest of Juniper Bay. The total amount of P lost in the drainage water was calculated by multiplying P concentrations in the drainage water by the volume of drainage water leaving through the outflow. This calculation was performed on a daily basis from December 2010 to 2013, and on a monthly basis for 2005 through November 2010.

The ΔP_{soil} was determined for an 8-year period, between time zero (date of wetland restoration, 2005) and 2013. The error (E) term in Equation 3, based on measured fluxes, was calculated as the remainder term between the soil ΔP_{soil} and flux ΔP.

Statistical analysis was performed on the soil total P data using PROC GLIMMIX in SAS 9.3 (SAS Institute Inc., Cary, NC, USA) with a gamma distribution. The LSMeans presented were back-transformed using an “ilink” command. Mehlich-3 extractable P data were analyzed with a natural log transformation using PROC MIXED in SAS 9.3. The LSMeans reported were back-transformed using a procedure described by Jørgensen and Pedersen (2013). Confidence intervals were corrected for multiple comparisons using a Tukey adjustment. A t-test was performed in SigmaPlot 12.5 (Systat Software, Inc., San Jose, CA, USA) to test for differences in woody biomass and biomass P content between the mineral and organic soils. Summary statistics were determined for P_{atm} using SigmaPlot 12.5.

RESULTS

Total soil P concentrations in 2005 and 2013 are summarized in Table 1. No difference in soil TP was detected between 2005 and 2013 ($p=0.42$) for the entire Bay to a depth of 1m. The organic soils at Juniper Bay had higher ($p<0.0001$) concentrations of TP (0.131 kg m^{-3}, se 0.013) than the mineral soils (0.072 kg m^{-3}, se 0.005) across all three depths and both sampling years. The fixed effect of soil depth was highly significant ($p<0.0001$). The concentrations were highest at the surface and declined with depth. There was no significant difference between years for any soil type-depth combination. Significantly higher TP concentrations were found in the 0-15 cm depth than in the 15-30 cm and 30-100 cm depths for both the mineral and organic soils for both years. There was no significant difference in TP concentration between the 15-30 cm depth and the 30-100 cm depth for either soil in 2005, or in the mineral soil in 2013. However, in 2013 the organic soil had significantly more TP in the 15-30 cm depth than in the 30-100 cm depth. Differences between mineral and organic soil TP concentrations were significant for the 0-15 cm depth and 15-30 cm depth, but not the 30-100 cm depth. This was consistent for both sampling years.

Rainfall P concentrations during the duration of the study averaged 0.11 mg DTP L^{-1} (se 0.02). There was no significant difference in P between the three stations. The average concentration of rainfall DTP from 2005 to 2012 was assumed to be equal to the 0.11 mg DTP L^{-1} observed in this study. That concentration and daily rainfall data for Juniper Bay were used, along with the total area of the Bay, to estimate the P_{atm} following restoration in 2005 – a total of 2.4 Mg (8 kg ha^{-1}) over eight years, or 0.3 Mg (1 kg ha^{-1}) annually. Monthly rainfall is summarized in SI Table 3. Estimated monthly P_{atm} is summarized in (Table 2).

There was no significant difference in woody biomass or woody biomass P between soil types (mineral versus organic), and the average values across all plots were used for further calculations. The average woody biomass was 29,300 kg ha^{-1} (se = 5,400), and the average woody biomass P was 26.6 kg P ha^{-1} (se = 4.9). Extrapolated over the total 291 ha of Juniper Bay, only 7.7 Mg P was extracted by the trees over the eight years following restoration. Woody biomass across Juniper Bay totaled 8,500 Mg. The plant litter biomass and P contents are shown in Table 3. The average P content was 0.32 g P m^{-2} (se = 0.07), and the estimated P_{lit} for all of Juniper Bay was 0.93 Mg P (se = 0.21).

Discharge rates from Juniper Bay were estimated prior to December 2010 based on a simple water balance as the difference between monthly rainfall (SI Table 3) and monthly ET (SI Table 4). Rainfall was compared to normal values for the AgACIS WETS table for the Lumberton Regional Airport which had an observation period of 1971-2000 (USDA-NRCS 2021). Less than normal rainfall was observed for 2005, 2006, 2007, 2011 and 2012, while 2008-2010 had normal rainfall. Remotely measured ET (ORNL DAAC 2011) for 2005-2009, and Thornthwaite-estimated ET rates from 2010-2012 are summarized in SI Table 4. Discharge from the single outflow at Juniper Bay was measured directly starting in December 2010. Monthly discharge rates are summarized in SI Table 5. For months where the estimated discharge was negative (ET>rainfall) the discharge was assumed to be 0 mm.

The concentration of DRP over time at the Juniper Bay outflow is shown in Figure 2. The concentration of DRP increased following restoration in 2005, and remained at elevated concentrations until 2010. Following 2010 the concentrations declined to pre-restoration levels. The P discharge, estimated on a monthly basis for 2005-2010 and a daily basis for 2011-2012, totaled 0.5 Mg P. The P balance for Juniper Bay is summarized in Figure 3. The main flux of P entering the Bay during this study was from the atmosphere, at 2.4 Mg P since restoration. Plant uptake into woody biomass was the largest P flux out of the soil, and was estimated at 7.7 Mg P since restoration. Phosphorus that had accumulated in the forest floor litter totaled 0.3 Mg P. Phosphorus leaving the site through the drainage water totaled 0.5 Mg P since restoration. This leaves the error term of -6.1 Mg P, which is larger than all fluxes except Ppl.

DISCUSSION

The primary focus of this study was to determine if Juniper Bay has been, is currently, or will be a source of P for downstream surface waters following restoration of its prior-drained agricultural land. The increase in soil P over 30 years of agricultural fertilization did lead to soil P concentrations significantly higher than un-farmed reference Carolina Bays (Ewing et al. 2012) and a total P pool of 234 Mg P at the time of restoration in 2005. However, no statistical difference was detected between the 234 Mg P in 2008 and 216 Mg P in 2013 the soil P pool.

A P balance was estimated in order to better understand P fluxes at Juniper Bay, and to guide future management. The main flux of P into the Bay was P_{atm}. Atmospheric deposition of P was small, at 2 Mg P over 8 years. The concentration of DTP in the rainwater was also approximately the same concentration as in the drainage water. Because the runoff ratio (ratio of runoff to total rainfall) of Juniper Bay is very small, very little of that rain (and P) actually reached the outflow structure. The flux of P out of Juniper Bay in the drainage water was under 0.5 Mg P since restoration. The largest P loss was due to plant uptake. The trees at Juniper Bay acquired 7.7 Mg of P since restoration, and resulted in an additional accumulation of 0.3 Mg P into plant litter. This flux of P from the soil and into woody biomass and plant litter should slow any potential release of P to drainage waters.

The error term of 6.1 Mg P of loss is larger than all of the other fluxes except plant uptake. One potential source of error was having only DRP and not DTP measurements of the drainage water prior to 2010. The organic P missed may account for a larger flux of P out of the wetland. However, the measured flux of P in the drainage water was still very small, and even doubling that flux would only increase it to 1 Mg P over 8 years. Plant uptake is likely larger than was predicted due to P taken up by trees <10 cm DBH, shrubs, and herbaceous plants, which were not measured in this study.

The agreement of measured runoff volumes at the outflow with runoff predicted with a water balance suggest that losses or gains of water from the surrounding landscape are relatively minimal (see supplemental information). This is further evidenced by the small hydrologic gradients in four transects around the Bay (SI Table 1), and the resulting relatively-slow porewater velocities (SI Table 2). However, further study of the hydrology of Juniper Bay and the surrounding landscape, and of P concentrations in underlying aquifers may be warranted if a reduction of the P balance error term is desired.

While post-restoration concentrations of P in the Juniper Bay drainage water did depict a small release of P out of Juniper Bay, concentrations have since declined to pre-restoration levels ($\leq$ 0.1 mg P L^{-1}) within five years of restoration (Figure 2). Phosphorus concentrations above 0.1 mg L^{-1} would be expected to contribute to eutrophication in freshwater systems (Correll 1998). The concentration of P in the drainage water was also equal to P concentrations found in the rainwater. In addition, the 0.5 Mg P that has left Juniper Bay through the outflow since restoration accounts for approximately 0.2% of the total amount of P at the site in 2005. Because of the low concentrations of P in the drainage water, and the low magnitude of P losses to the drainage water relative to the total P pool, P export from Juniper Bay to surface waters is not expected to be a major concern in the future. Bruland et al. (2003) determined that in a restored Carolina Bay wetland complex the export of soluble reactive phosphorus and total phosphorus from the restored wetland was less than that of an actively farmed wetland, thus concluding that wetland restoration after just two years resulted in a net improvement to water quality. While this study did not include measurements of phosphorus export during active agricultural production in Juniper Bay, concentrations of phosphorus following restoration did eventually decrease to post-agricultural production prior to restoration of wetland hydrology. Ewing et al. (2012) estimated that Juniper Bay had three times as much extractable P than in nearby reference Carolina Bays. If that proportion of extractable P is also true for total P, and if Juniper Bay continues to lose total P at the rate of approximately 1% per year, then it will take at least 60 years for Juniper Bay to return to “natural” P concentrations. Plant uptake may reduce the amount of plant available P – the P fraction most easily exported. However P loss to plant uptake alone will take decades to centuries to reduce soil P concentrations down to natural concentrations.

The results of this study indicate that while most of the residual soil P that was left over from agricultural production is still in the Juniper Bay soils, it is not moving off site. This indicates that Carolina Bays, like Juniper Bay, make excellent potential sites for wetland restoration. However, Carolina Bays that are drained by streams may be exceptions to this rule. Such wetlands would be expected to have more P leaving the site through surface outflow because of higher hydraulic gradients caused by the dissecting streams. The ideal areas for wetland restoration are the closed depressions that have precipitation as the main water source and evapotranspiration as the main water loss.

In weighing the potential risks and benefits of restoring Carolina Bay wetlands that have been previously been used for production agriculture, it is important to consider the conversions between land uses for these wetlands within the region. In a concurrent study, separate from that presented here, Sullivan et al. (2017) inventoried Carolina Bays in Bladen, County, North Carolina a representative “Bay-dense” region within the southeastern Coastal Plain close to Robeson, County, North Carolina where the present study was conducted . They documented land-use change from 1972 through 2010 using decadal Landsat imagery. They found that during that time period, 43% of Bays and 91% of Bay area was associated with land-use change between 1972 and 2010. In 1972, Bays were predominantly forested (79% by count); with remaining Bays converted to agriculture or urban use prior to 1972. Land-use changes were predominantly from forest to agriculture (46%) and agriculture to forest (37%). Conversion to forest remained low from 1984 to 1991 and from 2000 to 2010, with a net loss in agricultural land use of 2,085 and 1,457 ha, respectively. A surge in conversion from forest to agriculture occurred between 1991 and 2000, which was surprising given the 1990 US Army Corps of Engineers/Environmental Protection Agency agreement targeting no net wetland loss. From 1972 through 2010, there was an estimated net gain of 744 ha of Bay forest relative to Bay agriculture. Sullivan et al. (2019) conducted a follow-up study assessing the risk of phosphorus export to nearby or intersecting streams. They found that 1360 Carolina Bays in Bladen County, North Carolina representing 43% of the Bays and 80% of the total Bay area had streams that either intersected the Bays or came within 15 m of the edge of a the Bays. These wetlands posed a risk of P export depending on the land use or changes in land use of each Bay. Isolated wetlands without a nearby or intersecting stream were determined to pose little risk of P export.

SUMMARY & CONCLUSIONS

The objective of this study was to create a P balance for a Carolina Bay restored from agricultural land. Juniper Bay was restored by filling in primary ditches, plugging secondary ditches, and maintaining the perimeter ditch surrounding the site. This resulted in a low hydraulic gradient for drainage water. The soil P pools were determined to be 234 Mg in 2005 and 216 Mg in 2013, though no significant difference was detected. Phosphorus fluxes into and out of Juniper Bay included a gain in P from atmospheric deposition, and losses of P to surface water outflow and plant uptake. The error term depicts an unaccounted loss of 6.1 Mg P, which was larger than all fluxes except plant uptake by trees. Phosphorus loss to surface waters was minimal both in magnitude (0.5 Mg P over eight years), and in current concentrations (approximately 0.1 mg P/L). That concentration of P exiting the Bay is approximately the same as was found in rainwater at Juniper Bay, and is not expected to contribute to eutrophication of downstream surface waters. Contributions of water and P to and from the surrounding landscape were determined to be minimal based on a comparison of observed runoff values with those predicted from a water balance, and from an evaluation of existing transects of P concentration and hydrologic gradients around the perimeter of Juniper Bay. A P balance for Juniper Bay was estimated based on measured changes in total P and fluxes of P. It will likely take 60 years or longer for Juniper Bay to return to “natural” concentrations of P. There is a possibility that future restorations of Carolina Bays from drained agricultural production back to wetlands may contribute agrichemicals to nearby streams and drainageways. However, in regard to P, if restoration methods as described for Juniper Bay are employed, impairment of nearby streams and drainageways is unlikely.

Based on these results, we conclude that Carolina Bay wetlands similar to Juniper Bay are promising sites for wetland restorations due to the low risk of P contributions following restoration from agricultural production. The broad, nearly level Carolina Bays result in very low hydraulic gradients following restoration back to wetlands, thus reducing movement of P to nearby streams or drainageways. However, internal drainage ditches must be filled and/or plugged during the restoration process. Carolina Bays that are deeply dissected by streams or ditches may have sufficient hydraulic gradients to facility P transport, so restoration of such sites must be done with care.

DECLARATIONS

Funding

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Conflicts of Interest

The authors have no conflicts of interest.

Availability of Data and Material

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability

The code used during the current study is available via Moorberg (2014)

Authors' Contributions

CJM lead efforts for sample collection, sample analysis, data analysis, data presentation, and writing. MJV was the principle investigator for both sources of funding, supervised the research activities of CJM, and was a major contributor to writing the manuscript. CPN contributed to sample collection and analysis. JGW assisted with sample collection for the archived soil samples. DDR assisted soil total P analysis. All authors provided revisions to manuscript drafts and read and approved the final draft.

Ethics Approval

Not applicable

Consent to Participate

Not applicable

Consent for Publication

Not applicable

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TABLES

Table 1. Soil TP concentrations by soil type, depth, and year.

		2005						2013					
Soil	**Depth**	**LSMean**		**se**	**Significance**			**LSMean**		**se**	**Significance**		
	cm	kg TP m^{-3}			[a]	[b]	[c]	kg TP m^{-3}			[a]	[b]	[c]
Mineral	15	0.122	±	0.013	A	A	A	0.132	±	0.015	A	A	A
Mineral	30	0.069	±	0.008	A	B	A	0.058	±	0.007	A	B	A
Mineral	100	0.051	±	0.007	A	B	A	0.044	±	0.006	A	B	A
Organic	15	0.257	±	0.039	A	A	B	0.207	±	0.032	A	A	B
Organic	30	0.118	±	0.018	A	B	B	0.160	±	0.025	A	B	B
Organic	100	0.076	±	0.017	A	B	A	0.065	±	0.015	A	C	A

[a]Comparison of TP concentration between years for a given soil type and depth in column
[b]Comparison of TP concentration between depths within a given year and soil type in column
[c]Comparison of TP concentration between soil types within a given year at a given depth in column
Means with the same letter not significantly different (α=0.05).

Table 2. Monthly P_{atm} deposition (kg TP) between January 2005 and December 2012.

Month	2005[a]	2006	2007	2008	2009	2010	2011	2012
Jan	16.3	22.3	5.2	23.0	10.3	26.3	10.9	22.4
Feb	13.4	22.6	14.1	33.8	13.6	33.7	38.6	22.4
Mar	15.7	4.5	11.5	30.2	27.1	26.0	32.6	29.4
Apr	16.1	13.6	20.5	29.4	8.8	5.5	19.6	17.1
May	11.9	40.0	13.1	23.7	76.1	24.7	29.8	49.2
Jun	15.3	42.6	26.9	22.6	36.9	54.2	12.0	33.3
Jul	36.7	35.6	4.3	28.0	32.4	80.5	28.7	28.8
Aug	4.4	44.8	19.3	52.1	47.1	23.9	57.6	68.8
Sep	10.9	8.3	3.5	66.7	2.6	61.7	29.5	26.3
Oct	19.5	5.6	14.0	6.5	21.8	9.8	17.7	9.7
Nov	26.2	28.3	0.7	37.3	56.5	10.3	26.3	0.1
Dec	15.8	23.1	32.8	23.2	48.0	18.5	5.8	22.3
Total	**202.1**	**291.2**	**165.8**	**376.6**	**381.2**	**375.2**	**309.0**	**329.8**

[a]Rainfall data was acquired from a nearby weather station at the Lumberton, NC airport (NOAA NCDC 2013).

Table 3. Plant litter biomass and P content.

Plot	Dominant Trees Present	Average Litter Depth (cm)	Litter Dry Weight	P Concentration	P Content
		cm	g	% (w/w)	g P/m
1	Pine	4.50	850.6	0.08	0.71
8	Bald Cypress	2.60	337.7	0.09	0.30
9	Pine, Oak, Sweetgum	4.82	870.4	0.05	0.46
12	Bald Cypress, Pine, Willow	2.76	274.4	0.05	0.14
14	Pine, Bay	1.38	259.5	0.07	0.18
15	Bay, Bald Cypress	2.58	290.5	0.10	0.30
16	Oak	3.90	488.8	0.07	0.36
19	Bald Cypress	0.76	82.5	0.11	0.09
	Average P Content				0.32 (se 0.07)

FIGURES

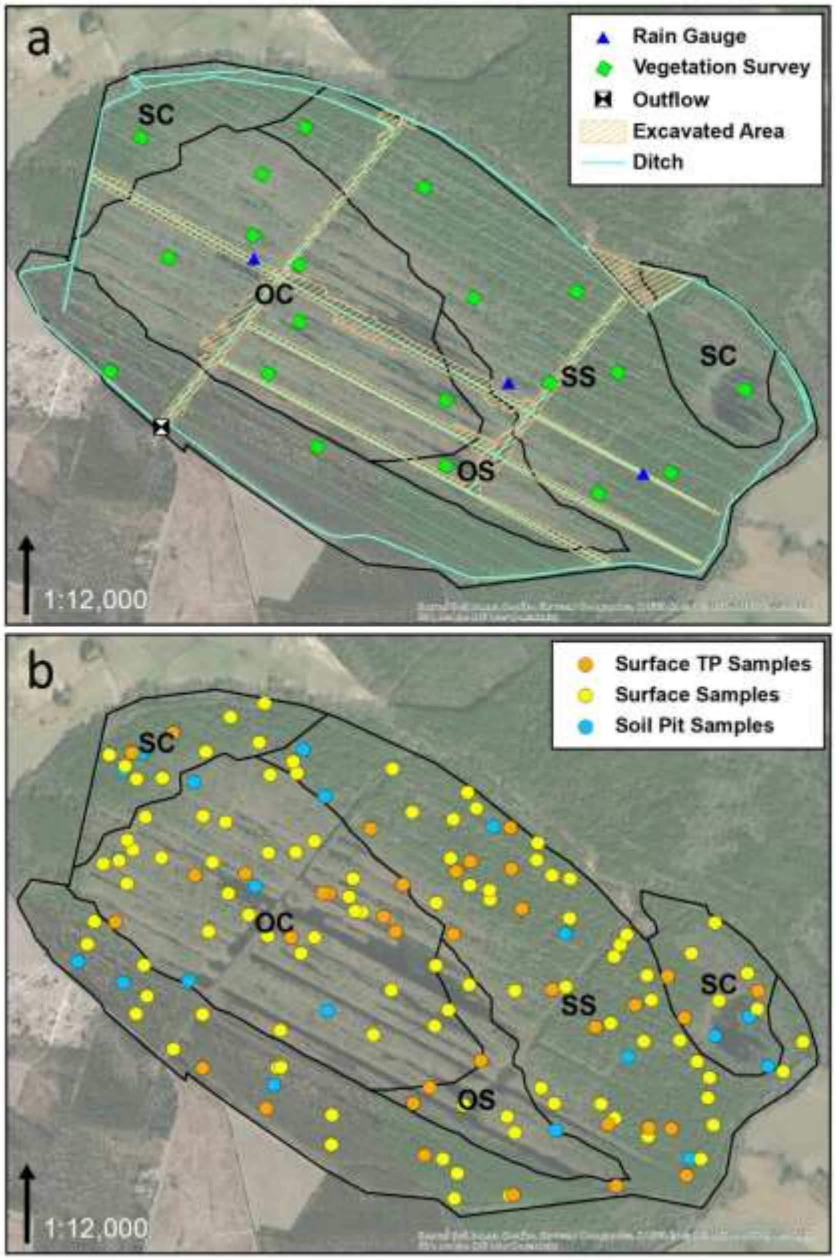

Figure 1. Maps of Juniper Bay depicting locations of a) previous and existing drainage ditches, perimeter ditch outflow, vegetation survey locations (not drawn to scale), rain gauge location, and mineral and organic soil distribution; and b) resampled surface soil locations for extractable and total P, and resampled soil pit locations. The mapping units depict four soil conditions, including sands over clayey subsoil (SC), sands over sandy subsoil (SS), organic soil over clayey subsoil (OC), and organic soil over sandy subsoil (OS).

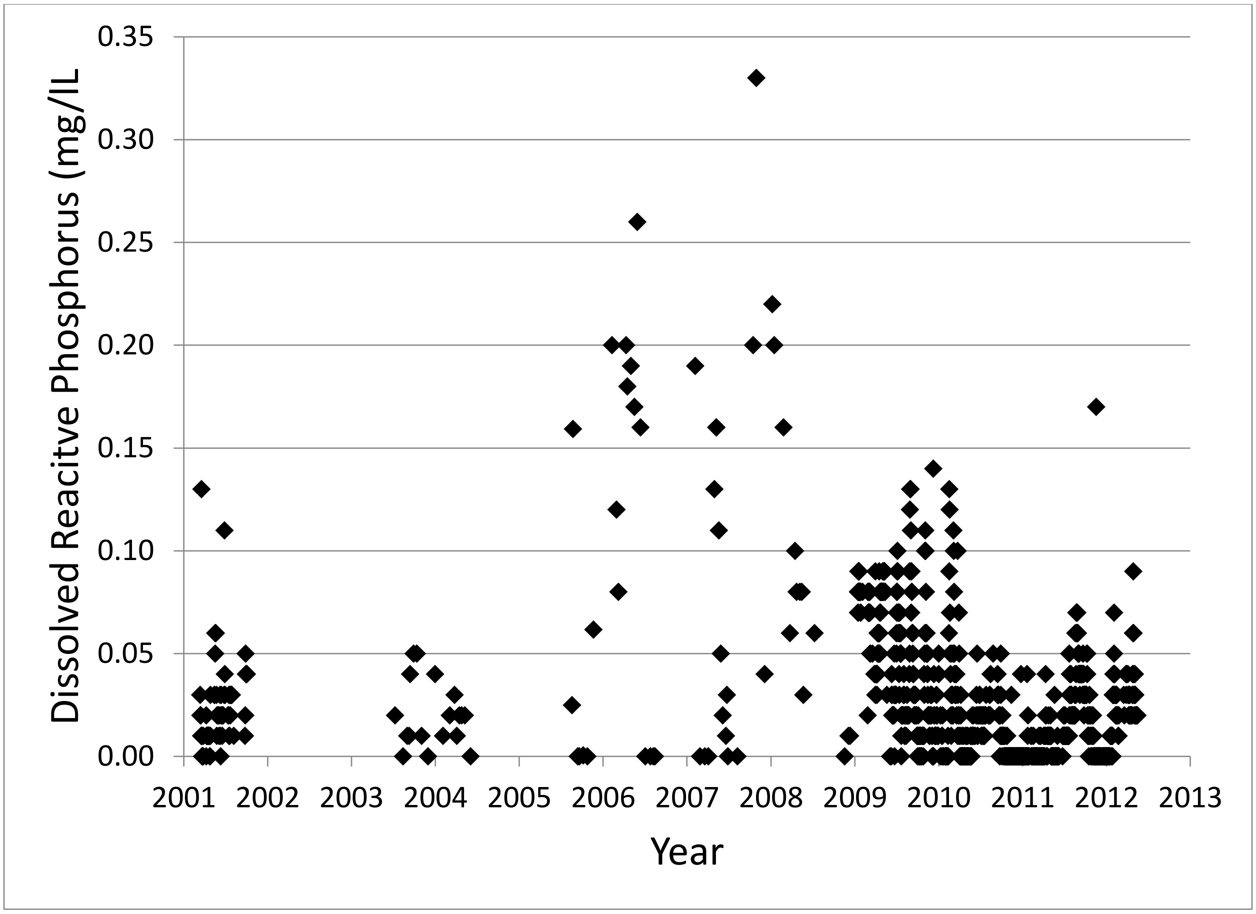

Figure 2. Concentration of DRP at the Juniper Bay outflow over time. The wetland was restored in 2005, after which an increase in DRP at the outflow was observed through approximately 2010. The DRP concentrations declined to pre-restoration levels thereafter. Eutrophication would be expected at 0.10 mg DRP per liter in freshwaters, assuming N is not limiting. Outflow concentrations only exceeded that concentration once after 2010.

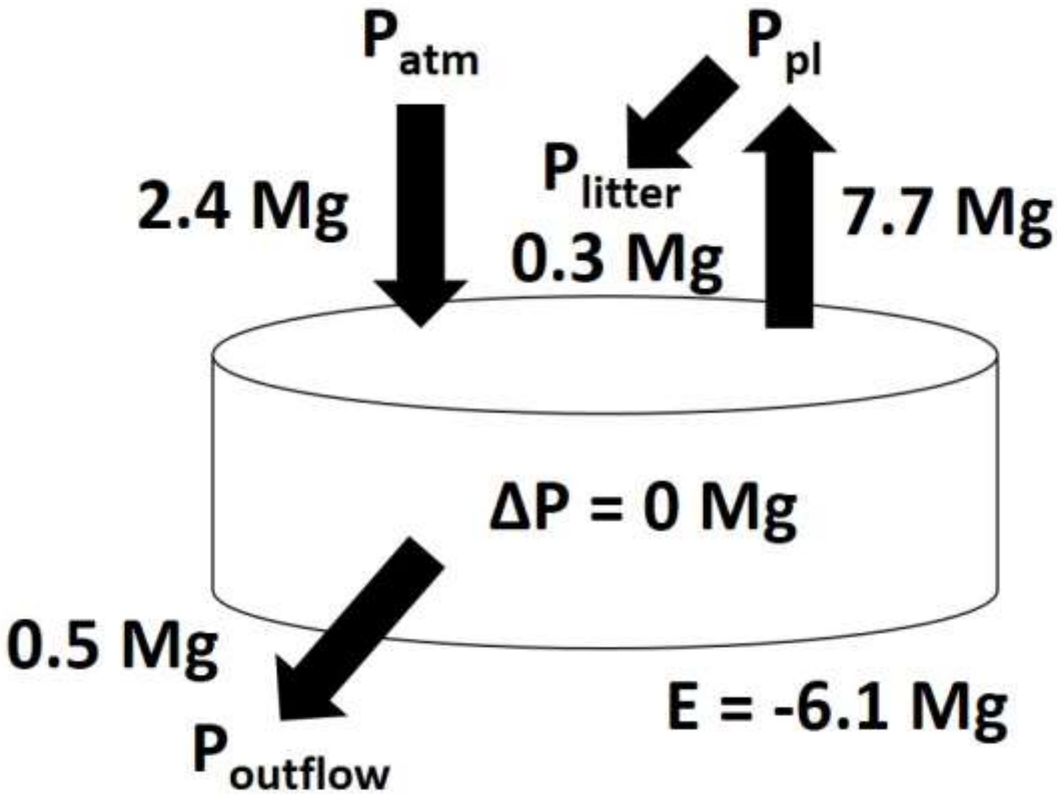

Figure 3. Summary of the P balance for Juniper Bay from 2005-2013. The fluxes include change in total P (ΔPsoil), atmospheric deposition (Patm), plant uptake (Ppl), plant litter (Plitter), surface water outflow (Poutflow), and error (E).

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SI Table 2. Estimations of Flow for Each Transect and Sand Layer. Porewater velocity was estimated from Hydraulic gradients and soil properties for the four piezometer transects at Juniper Bay. The saturated conductivities used were reported by Pati (2006). Porosity was estimated from average bulk densities reported by Ewing (2003). Hydraulic gradients were calculated from measurements made on May 15, 2013. Flow rates were small overall, due to both the small gradients present, and the low conductivities.

SI Table 3. Monthly Rainfall from January 2005 to December 2012.

SI Table 4. Monthly ET between January 2005 and December 2012. Evapotranspiration was measured remotely for 2005-2009, and estimated using the Thornthwaite equation in from 2010 to 2012.

SI Table 5. Monthly runoff between January 2005 and December 2012. Runoff was estimated using a simple water balance for 2005-2010, and measured directly for 2011 and 2012. For estimations of P, months with negative estimated runoff were assumed to have no runoff.

LIST OF SUPPLEMENTAL FIGURES

SI Figure 1. Piezometer Transect Across the Southwest Rim of Juniper Bay.

SI Figure 2. Piezometer Transect Across the Southeast Rim of Juniper Bay.

SI Figure 3. Piezometer Transect Across the Northeast Rim of Juniper Bay.

SI Figure 4. Piezometer Transect Across the Northwest Rim of Juniper Bay.

SI Figure 5. The apparatus used for collection of atmospheric deposition of P, alongside a tipping bucket rain gauge and a traditional rain gauge. The sample collection bottle is not shown.

Figures

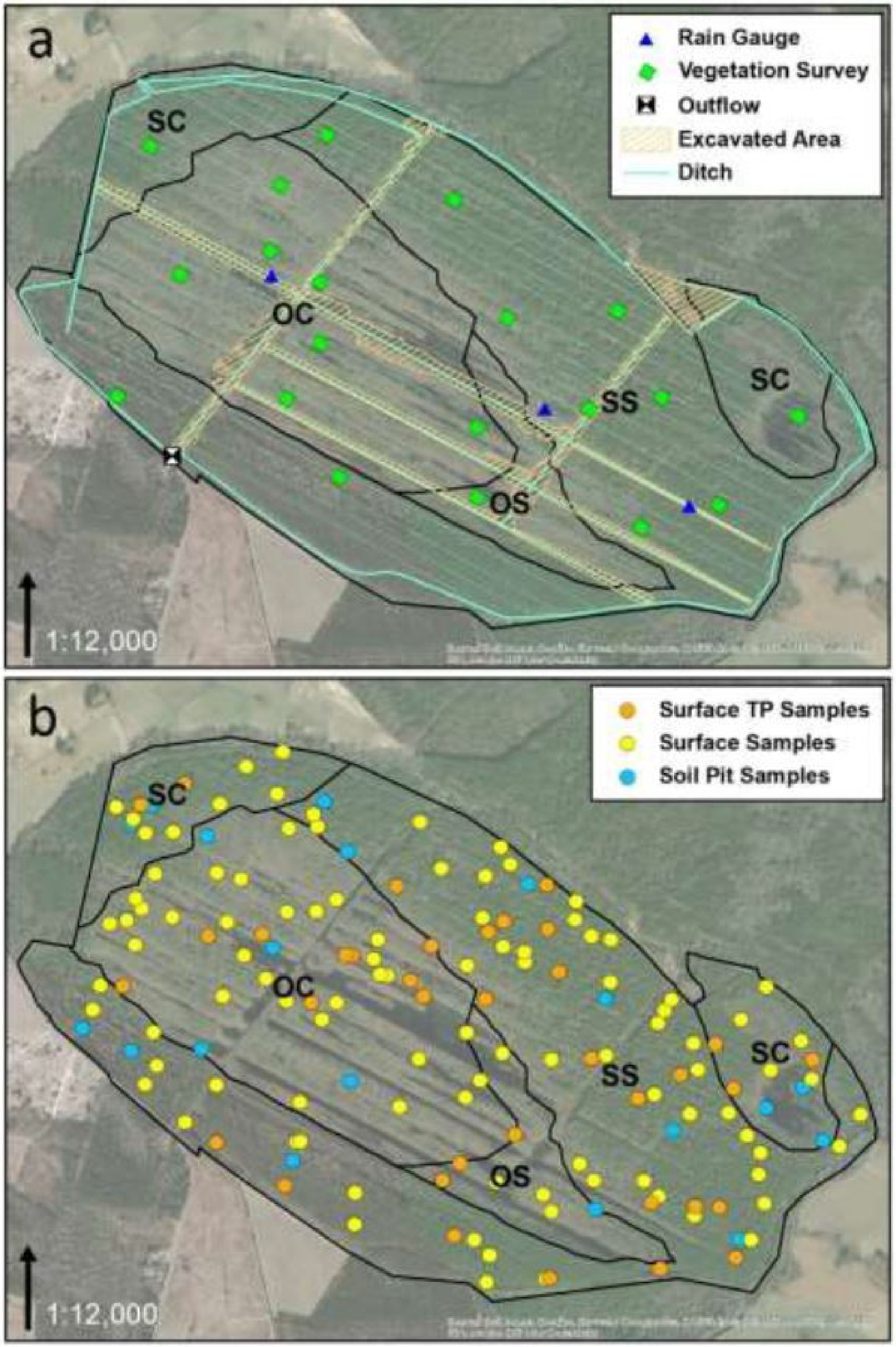
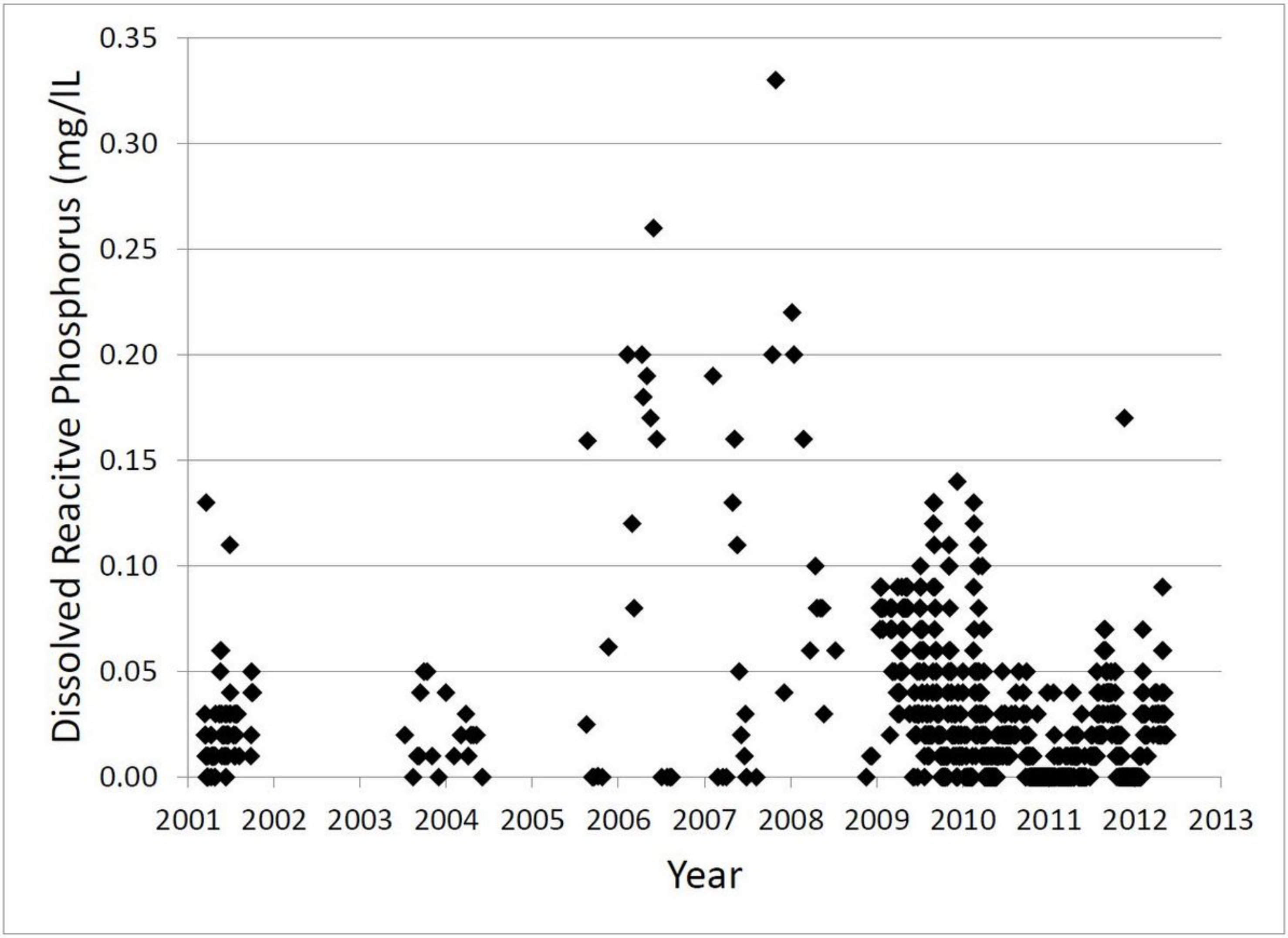


Figure 1

Maps of Juniper Bay depicting locations of a) previous and existing drainage ditches, perimeter ditch outflow, vegetation survey locations (not drawn to scale), rain gauge location, and mineral and organic soil distribution; and b) resampled surface soil locations for extractable and total P, and resampled soil pit locations. The mapping units depict four soil conditions, including sands over clayey subsoil (SC), sands over sandy subsoil (SS), organic soil over clayey subsoil (OC), and organic soil over sandy subsoil (OS). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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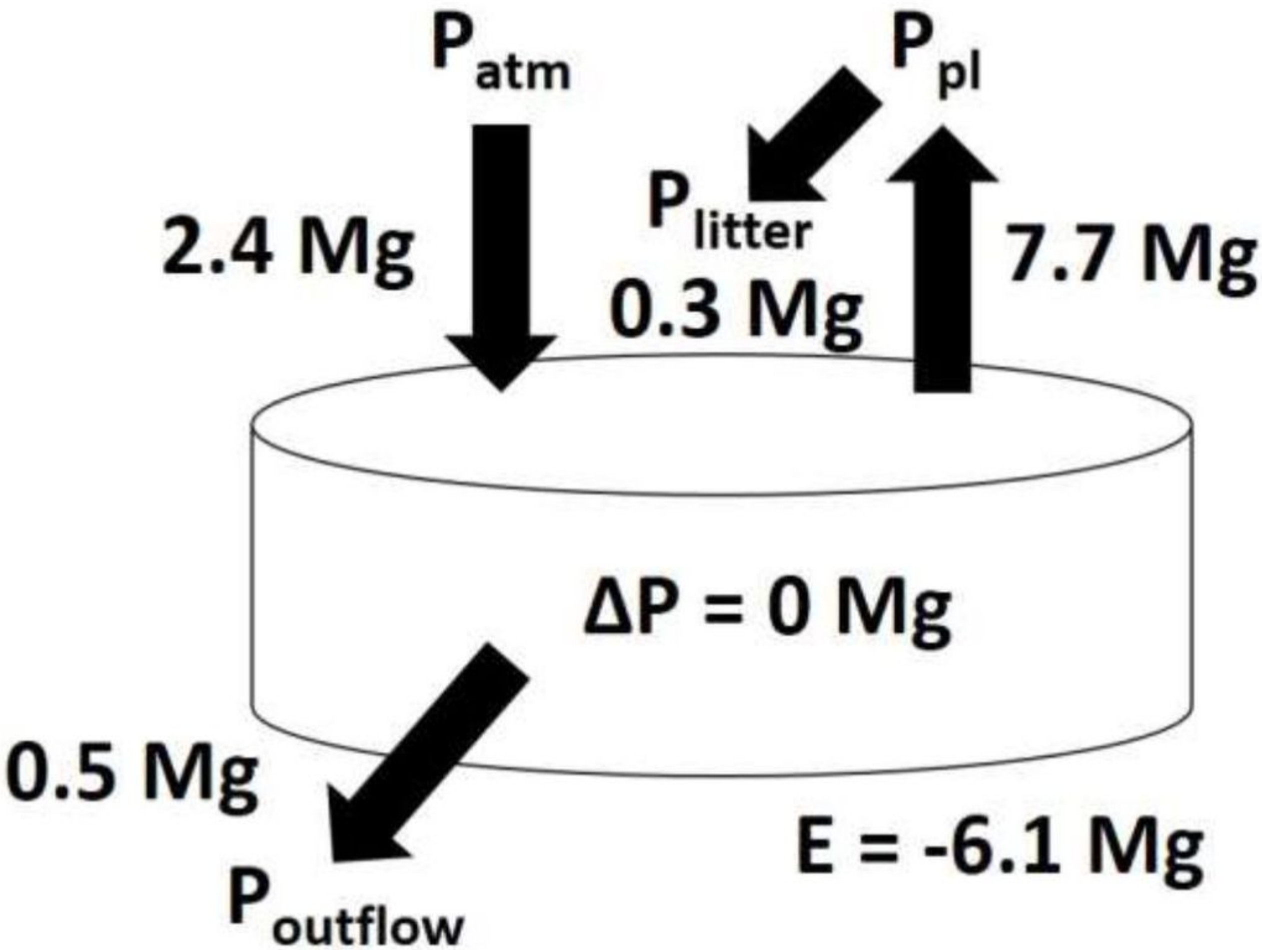

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Summary of the P balance for Juniper Bay from 2005-2013. The fluxes include change in total P (ΔPsoil), atmospheric deposition (Patm), plant uptake (Ppl), plant litter (Plitter), surface water outflow (Poutflow), and error (E).

Supplementary Files

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- PhosphorusBalanceWetlandsSubmissionSI.pdf