FATE OF PHOSPHORUS IN RICHLAND CREEK WMA CONSTRUCTED WETLAND FOR WATER REUSE

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ABSTRACT

The Richland Creek WMA constructed wetland for water reuse, located 40 km southeast of Corsicana, Texas, was designed by Tarrant Regional Water District (TRWD) and is operated jointly with Texas Parks and Wildlife Department (TPWD). TRWD's perspicacity to supply the regions rapidly growing population with an additional secure water source, and the desire of TPWD to enhance migratory and indigenous wildlife habitat, as well as providing outdoor recreational opportunities to the public, led to the joint venture. The constructed wetland operates on water from the Trinity River (TR), from which the wetland reduces water nutrient and metal concentrations and thereby improves water quality. The purpose of this study was to assess the first seven years of operation of the field-scale wetland's nutrient removal efficiency, primarily addressing the fate of phosphorus (P).

For the field study, conducted during a period of moist-soil management (MSM), soil/sediment samples were collected from the sedimentation basin (SB), Cell 1, Cell 3, and a reference wetland (RW) with a similar soil series that is inundated only during overbank flooding from the TR. Soil samples were tested for Mehlich 3 P (M3P), water extractable P (WEP), total P (TP), a P sorption index (PSI), and pH. The field study results indicated that soil P is more

concentrated in the SB and cell 1 of the wetland system than in cell 3 or the RW. M3P concentration was nearly double the threshold for no additional fertilizer recommendations for agriculture of 60 mg kg^{-1} in the SB and cell 1. WEP concentrations are highest in the SB and cell 1. TP concentrations are comparable to other treatment wetland systems that receive high quantities of P from the water column. The PSI identified the SB and cell 1, the areas with consistently higher soil P concentrations, as the areas with the least potential P fixing capacity remaining.

Hydrologic data collected by TRWD from the summer of 2003 through the winter of 2010, was analyzed and provided some insight regarding nutrient loading that has occurred in the constructed wetland. The results indicated that the wetlands efficiency at removing nutrients from the water was linked to the nutrient accumulation in soils of the wetland. The wetland cells with the higher estimated TSS loading, also had a higher soil P concentrations.

An *ex situ* and *in situ* tillage simulation was completed in order to determine a potential solution to prolong the effectiveness of the wetland system and avoid hydrologic burnout. The no-till, 10-cm, and 20-cm tillage groups, underwent a three phase water column study and then the soil was tested for M3P, TP, and a PSI. The water column study indicated the tillage treated soils released less P, were more efficient at removing P from a 2 mg P L^{-1} solution, and just as efficient at removing P from a 75 mg P L^{-1} solution as the no-till soil.

The soil core experiment indicated tillage may provide plants during MSM more readily available P for enhanced growth, while also improving efficiency at removing P from the water column. The *ex situ* soil P data indicated that a deeper tillage depth has potential to distribute P more deeply in the soil column.

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INTRODUCTION

This study focused on one of the efforts made by Tarrant Regional Water District (TRWD) to increase the district's water supply. Historically, the construction of new reservoirs was the usual course of action when additional water supply was needed, but due to economic, political, and environmental constraints on new reservoir development, other options needed to be pursued. After the construction of Richland-Chambers Reservoir, near Corsicana, Texas, was completed in July 1987, TRWD received approval on July 8, 1992 from the Texas Natural Resource Conservation Commission (now Texas Commission on Environmental Quality [TCEQ]) to divert water from the Trinity River to a pilot scale constructed wetland to determine the feasibility of a large-scale water reuse project (TRWD 2010).

After eight years of research using the pilot scale wetland, TRWD determined that the use of a constructed wetland to reduce nutrient, sediment, and other impurities concentration for the purpose of water reuse was practical. In September 2002, the 98 ha (242 ac) field scale phase of The George W. Shannon Wetlands Water Reuse Project on Richland Creed WMA, hereafter called the Richland Creek WMA constructed wetland, became operational as a joint venture between TRWD and Texas Parks and Wildlife Department (TPWD).

This phase of the project consisted of one sedimentation basin and four constructed wetland cells. Water quality testing for the field-scale wetland was based on the same criteria as the pilot scale wetland to determine the efficiency of the entire wetland system upon completion of the 2000-acre project.

The field-scale wetlands, and eventually the full-scale system, were located on the North Unit of TPWD's Richland Creek Wildlife Management Area (WMA). Richland Creek WMA was established for TRWD to fulfill mitigation requirements of the U.S. Army Corps of Engineers in response to the bottomland hardwood and wildlife habitat losses due to the construction of Richland-Chambers Reservoir. Richland Creek WMA is owned and operated by TPWD and Richland Creek WMA constructed wetland is operated jointly between TPWD and TRWD under a memorandum of understanding for moist soil management practices to enhance wetland habitat for wildlife, and to reduce sediment and other impurities from the Trinity River for water quality (Frossard et al. 2006). The construction of the wetland addressed two major goals of TPWD for Richland Creek WMA: (1) enhance habitat for a variety of wildlife species, including indigenous and migratory waterfowl; and (2) provide additional public outdoor recreational opportunities, such as hunting and bird watching (TRWD 2010).

The purpose of this study was to assess the first seven years of operation of the field-scale wetland's nutrient removal efficiency, primarily addressing the fate of removed phosphorus (P). The study will determine the concentration and distribution of P in the wetland soils and sediments, and the potential of soil tillage to improve P and sediment retention.

Objectives

The first objective of this study was to determine the P concentration profile in the top 35-cm of soil in cell 1 and cell 3 of the field scale wetland and compare this data to the reference wetlands P concentration in the top 35-cm of soil. The sedimentation basin was also assessed to determine P concentration in the sediment from the Trinity River.

The next objective of this study was to assess the potential for the wetland soil and sediment to continue P retention. Soil samples from cell 1, cell 3, the sedimentation basin, and reference wetland were used to establish a P sorption index (PSI).

The third objective of this study was to address the potential of soil tillage to disperse the accumulated P throughout the soil column, increasing near surface soil P retention potential. Intact soil cores from cell 1 were collected and returned to the laboratory for a bench tillage simulation study. The depth of tillage will be considered as well as a no-till situation as the control. Select areas in cell 1 tested for P concentrations as indicated in object 1, underwent field tillage to test the effectiveness of TPWD’s tillage equipment.

The final objective of this study was to compare water quality data collected by TRWD with the soils data collected in this study to determine if P loading in the soils relates to total P removed in the water quality data. The incomplete data sets, due to periods of flooding or maintenance, which required the system to be offline, were considered by determining an average P concentration removed.

The objectives of this study were to:

1. Determine the concentration and distribution of P in soils/sediments in two of the constructed wetland cells and the sedimentation basin, and compare to that of a nearby reference wetland not used to treat Trinity River water.
2. Determine the potential for future P fixation of the soil and sediment by establishing a P sorption index.
3. Determine if soil tillage would potentially increase soil P fixation potential using a laboratory bench tillage simulation study.
4. Determine temporal and spatial P retention trends of the constructed wetlands at Richland Creek WMA by analyzing existing data sets from water chemistry monitoring work by TRWD.

LITERATURE REVIEW

Water Supply and Demand Issues for Texas of Region C

Based on the U.S. Census Bureau, the population in Texas Water Development Board (TWDB) Region C, which includes Dallas and Tarrant counties, in 2010 was 6,477,835, which is 25.8% of the State of Texas total population of 25,145,561 (USCB). Labeled as one of the fastest growing areas in the state and country since the 1950s, population growth models show the region to have an estimated population exceeding 13,000,000 by 2060, with the State's population surpassing 46 million by 2060 (TWDB).

With population growth, comes an increase in water use. Table 1 and Table 2 illustrate the 2011 Region C Water Plan, which indicates that in 2006, an estimated 1,732,468 ha-dm [1,404,535 acre-feet (ac-ft)] of water was used with just over 90% of the consumption occurring on the municipal level. With the population expected to nearly double by 2060, water consumption is also expected to nearly double with an estimated demand of 4,036,521 ha-dm year^{-1} (3,272,461 ac-ft year^{-1}) (Region C). Table 3 and Table 4 illustrates this growth in water demand.

Within Region C, it is estimated, as of 2010, that there is 2,880,344 ha-dm year^{-1} (2,335,133 ac-ft year^{-1}) of water available for use of which, 26% is imported from other regions. By 2030, demand is projected to surpass the available water supply (Table 3, Table 4). The supply available from the reservoirs in the region decreases over time due to lost volume to sedimentation and the lack of new reservoirs to add capacity (Morris and Fan 1997, Wetzel 2001).

Table 1. 2011 Region C water plan demand (ha-dm) projections by type of use.

Use	Historical Year 2006 Demand (ha-dm)	Projected Water Demand (ha-dm yr^{-1})					
		2010	2020	2030	2040	2050	2060
Municipal	1,571,473	1,908,159	2,261,800	2,575,013	2,891,423	3,222,072	3,606,895
Manufacturing	65,408	88,843	100,249	111,026	121,481	130,512	136,419
Steam Electric Power	19,732	50,342	79,714	120,990	132,469	143,155	155,947
Irrigation	38,321	50,296	50,531	50,776	51,033	51,308	51,598
Mining	12,788	51,214	48,058	51,350	54,873	58,510	61,921
Livestock	24,747	23,742	23,742	23,742	23,742	23,742	23,742
Region C Total	1,732,468	2,172,597	2,564,093	2,932,897	3,275,020	3,629,300	4,036,521

Table 2. 2011 Region C water plan demand (ac-ft) projections by type of use.

Use	Historical Year 2006 Demand (ac-ft)	Projected Water Demand (ac-ft yr^{-1})					
		2010	2020	2030	2040	2050	2060
Municipal	1,274,014	1,546,970	1,833,671	2,087,597	2,344,115	2,612,176	2,924,157
Manufacturing	53,027	72,026	81,273	90,010	98,486	105,808	110,597
Steam Electric Power	15,997	40,813	64,625	98,088	107,394	116,058	126,428
Irrigation	31,067	40,776	40,966	41,165	41,373	41,596	41,831
Mining	10,367	41,520	38,961	41,630	44,486	47,435	50,200
Livestock	20,063	19,248	19,248	19,248	19,248	19,248	19,248
Region C Total	**1,404,535**	**1,761,353**	**2,078,744**	**2,377,738**	**2,655,102**	**2,942,321**	**3,272,461**

Table 3. 2011 Region C water plan overall water supply availability for Region C (ha-dm yr^{-1}).

Source	Projected Water Supply (ha-dm yr^{-1})					
	2010	2020	2030	2040	2050	2060
Reservoirs in Region C	1,655,735	1,646,975	1,637,838	1,628,545	1,619,252	1,609,957
Local Irrigation	24,923	24,923	24,923	24,923	24,923	24,923
Other Local Supply	29,235	29,235	29,235	29,235	29,235	29,235
Surface Water Imports	738,578	710,634	681,711	677,455	673,212	668,981
Groundwater	180,276	180,276	180,276	180,276	180,276	180,276
Reuse	251,598	304,066	357,704	386,045	396,447	414,551
Region C Total	2,880,344	2,896,107	2,911,686	2,926,479	2,923,345	2,927,922

Table 4. 2011 Region C water plan overall water supply availability for Region C (ac-ft yr^{-1}).

Source	Projected Water Supply (ac-ft yr^{-1})					
	2010	**2020**	**2030**	**2040**	**2050**	**2060**
Reservoirs in Region C	1,342,326	1,335,224	1,327,817	1,320,283	1,312,749	1,305,213
Local Irrigation	20,205	20,205	20,205	20,205	20,205	20,205
Other Local Supply	23,701	23,701	23,701	23,701	23,701	23,701
Surface Water Imports	598,775	576,120	552,672	549,222	545,782	542,352
Groundwater	146,152	146,152	146,152	146,152	146,152	146,152
Reuse	203,974	246,510	289,995	312,972	321,405	336,082
Region C Total	**2,335,133**	**2,347,912**	**2,360,542**	**2,372,535**	**2,369,994**	**2,373,705**

The water reuse projects developed by Region C are the only increase of water supply availability within the region. Current water reuse projects described in the 2011 Region C Water Plan consist of the following:

- City of Fort Worth's Village Creek Reclaimed Water Delivery System
- TRWD Richland Creek WMA Reservoir constructed wetland
- North Texas Municipal Water District (NTMWD) diverting return flow from Wilson Creek Wastewater Treatment Plant to Lake Lavon
- NTMWD East Fork Raw Water Supply Project (John Bunker Sands Wetland)
- An agreement between Dallas Water Utilities and NTMWD to exchange return flows

This list does not include projects by cities to divert effluent from wastewater treatment plants for purposes such as irrigation at golf courses in the region, mining operations, or power plants.

Constructed Treatment Wetlands

The natural nutrient removal capabilities and wildlife habitat potential of wetlands has been recognized throughout history. Mitsch and Gosselink (2000) documented the use of wetlands by the Marsh Arabs around the Tigris and Euphrates Rivers in southern Iraq, and in South East Asia for the production of rice paddies. Researchers in the United States began to develop constructed wetlands for cleansing municipal waste water in the early 1970s in South Florida and in Michigan (Kadlec and Wallace 2009). From research on constructed and natural wetlands, it has been noted that wetlands improve water quality through: (1) retention of surface water associated with floods, which decreases pollution dispersal (Mitchell et al. 1995); (2) filter for pollution, reducing metal and nutrient concentrations (Mitchell et al. 1995, Benyamine et al. 2004); and (3) serve as a site for sediment deposition, which allows for nutrient retention (Almendinger 1999).

Kadlec and Wallace (2009) listed three different types of constructed treatment wetlands. Free water surface (FWS) wetlands, function similar to natural wetlands with open water, floating vegetation, and emergent plants.

Horizontal subsurface flow (HSSF) wetlands are constructed with a gravel bed and planted with wetland vegetation to allow water to flow beneath the surface layer, flowing in and around the roots of the plants. Vertical flow (VF) wetlands are constructed with sand and gravel beds of different fragment sizes, with sand as the surface layer and gravel at the bottom, producing an anaerobic zone in the subsurface layer, treating the wastewater as it moves vertically through the system. Richland Creek WMA constructed wetland is a FWS wetland.

Phosphorus Cycle

The P cycle in constructed wetlands differs among sites based on soil characteristics, seasonal variations, geography, background P concentrations, pH, dissolved oxygen, wind speed, turbidity, and other factors (Blevins 2004). Phosphorus is not just important to plant life, with its involvement in photosynthesis, root development and crop maturation; it is important to animal life as well, being a main component for energy transfer during respiration in adenosine diphosphate and adenosine triphosphate (Gardiner and Miller 2008). Kadlec and Wallace (2009) describe five forms of P that are found in a wetland environment: dissolved P forms, dissolved P plus P associated with suspended solids, P sorbed to the surface of soil particles, P contained in the structure of biomass, and P contained in the structure of soil particles.

The dissolved forms of soil P are defined as those which pass through a 0.45 µm pore size filter paper. This includes the orthophosphates (PO_4-P), condensed phosphates, soluble reactive phosphates (SRP), total dissolved P, and dissolved organic P. An unfiltered sample contains dissolved P plus associated suspended solid forms of P found in a wetland. This includes total reactive P, total acid hyrolyzable P, total P (TP), total organic P, and particulate P. Phosphorus that is sorbed to the surface of soil particles is the fraction of P that is measured using extractants. Water is a common extractant as well as potassium chloride and bicarbonate solutions. Phosphorus that is contained in the structure of biomass in the wetland is expressed as total phosphorus in the biomass. It is typically found by acid digestion of a wet or dry sample analyzed for PO_4-P. The fraction of P contained in the structure of soil particles represents the structural or internal forms of P. It is measured by strong extractants, such as sodium hydroxide or hydrochloric acid. The strong acid or base solutions release the SRP form from the soil particle, which can then be subtracted from the TP form measured by acid digestion to determine the organic P associated with the sample (Kadlec and Wallace 2009).

These five forms of P that Kadlec and Wallace described are either present as inorganic or organic P, but dynamic transformations occur between the two phases of P. These changes in P form occur due to the plant cycle, the microbial cycle, moist-soil management conditions, and changes in soil pH

(Sharpley 1995). Inorganic P consists of labile P, active P, and colloidal or stable P. Labile P consists of soil solution P, which is the P that is readily available to plants. Fertilizer, slow cycling plant decomposition and rapid cycling plant decomposition contribute to soil solution P. Organic P is the P used in cells for energy transfer and respiration. It is classified as active or stable and is found in animal manure and plant tissue. The active inorganic and organic P, classified as moderately labile, undergoes transformation to replenish the labile P as soil solution P. The stable inorganic and organic P contribute to the moderately labile P over time, but are generally considered the chemically and physically protected forms of P (Daroub et al 2003).

Phosphorus in Constructed Treatment Wetlands

Treatment wetlands are constructed to retain sediment, nutrients and other impurities, which improves surface water quality. They have been used for the treatment of industrial and commercial wastewater such as landfill leachate, mine drainage, petroleum refinery wastewater, pulp and paper wastewater, and numerous other applications (Benyamine et. al. 2004, Kadlec and Wallace 2009). The agriculture industry uses constructed wetlands, often as the primary treatment, for livestock wastewater from dairy farms, catfish pond water, runoff from concentrated cattle-feeding operations, milkhouse wash water, swine manure, and runoff after fertilizer application (Kadlec and Wallace 2009, Aldemdinger 1997). Residential, commercial, industrial, or agricultural based, the constructed treatment wetlands are designed to serve as a nutrient trap at the farm-, field- and watershed-scale (Dunne 2005).

The nutrient of primary concern for retention in the constructed wetland is phosphorus. Phosphorus, in natural aquatic settings, is typically present in a limiting amount for primary production by algae and other macrophytes. When an influx of P occurs in an aquatic ecosystem, it can lead to higher rates of primary production. This increase in primary production may lead in turn to higher rates of decomposition and the depletion of dissolved oxygen, resulting in the aquatic state of eutrophication (Correll 1998).

Since P is primarily transported by surface water as dissolved orthophosphate or attached to the suspended particulate matter as particulate P, much is retained in the constructed wetland when the sediment is trapped or utilized in plant growth (Seo et al. 2005). The particulate P trapped with the sediment reaches equilibrium with the dissolved forms of P in the water column. The particulate P still bound to the sediment, P that did not dissolve into the water column, will eventually settle to the bottom of the water column or the surface of the soil. Once on the soil surface, the P will either bind with soil particulates or diffuse into the water column. The P that persists in the water column remains available to plants (Correll 1998).

The removal of P from the constructed wetland is achieved by the removal of the plant matter and the P saturated soil (Seo et al. 2005). The removal of the biomass and P saturated soil from the constructed wetland system as means of P reduction is disruptive to the creation of waterfowl habitat, and is also not cost effective. The removal of biomass has been shown to only remove less than 10% of the annual load of P (Kadlec and Wallace 2009). The most effective method for P removal in a constructed wetland is through particulate settling and the formation of accretions. The accretions occur where the plant matter does not completely decompose, and the permanent organic matter remaining will store 10-20% of the P (Kadlec and Wallace 2009). Without P removal in the constructed wetland system, "hydrologic burnout," as defined by Kadlec in Treatment Wetlands 2nd ed., is the avoidable point "which no further net phosphorus accretion occurs, and the system stores no more phosphorus" (369).

Moist-Soil Management

Moist-soil management (MSM) is a three phase approach used by constructed wetland managers during the summer months to promote seed germination. Phase 1 consist of decreasing the water to expose a mud flat for planting or germination of seeds. Phase 2 is the gradual increase in water depth to allow the emergent plants to flourish. The constructed wetland manager implements phase 3 after the plants are established, and raises the water level of the constructed wetland to the operational depth of the design (Kadlec and Wallace 2009). This management strategy benefits waterfowl habitat and nutrient retention within the constructed wetland. Plant species, which create appropriate waterfowl habitat, are favored (Strader and Stinson 2005). By increasing plant biomass, P is sequestered in the plant mass at greater rates than in wetlands were plants are not allowed to germinate and grow rapidly (Kadlec 2005). However, MSM has also been shown to mobilize P during the water draw down phase, through mineralization of organic matter by decomposition, and the mobilized P is potentially released to the water column after reflooding (Pant and Reddy 2001, Bostic and White 2007).

MATERIALS AND METHODS

Description of Research Area

The Texas Water Development Board (TWDB) divides the State of Texas into sixteen regional water-planning districts. The TWDB monitors population growth in each region, as well as the current and projected water supply and demand. The TWDB develops long-term, sustainable water supply and consumption plans within each region, in conjunction with the regional water development boards, and works to insure that each regional plan does not conflict with the plans of other regions for water management.

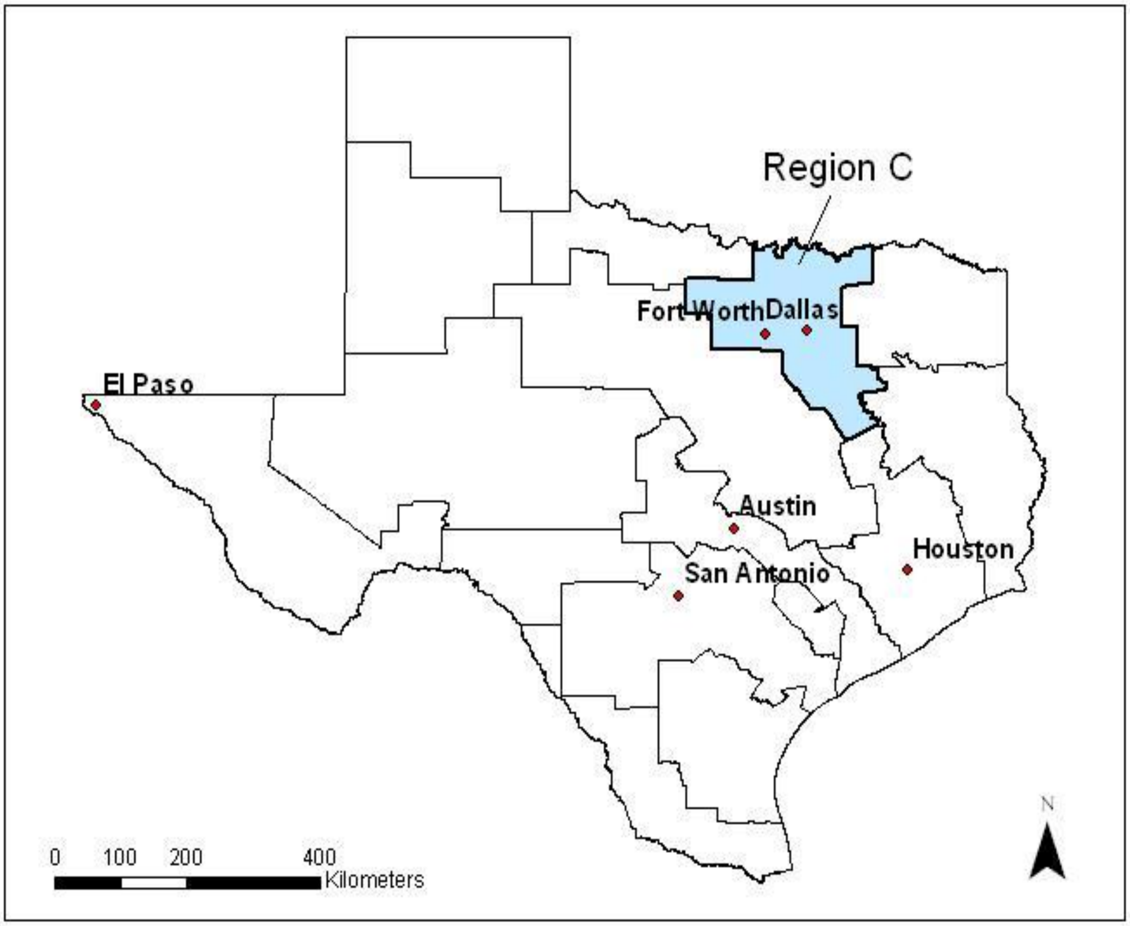

Figure 1. Texas regional water planning districts.

Within Region C, of the TWDB, lies the Tarrant Regional Water District (TRWD). Figure 1 illustrates Region C's boundary spanning from Jack County south to Freestone County, the TRWD serves more than 1.7 million people in an 11 county area. TRWD owns and operates Lake Bridgeport, Eagle Mountain Lake, and the Cedar Creek and Richland-Chambers Reservoirs. It operates over

150 miles of pipeline and sells raw water to over 30 wholesale customers, including Fort Worth, Arlington, and the Trinity River Authority (TRWD 2010).

The study area, depicted in Figure 2, is located approximately 40 km southeast of Corsicana, TX in the North Unit of Richland Creek Wildlife Management Area (WMA). The field-scale constructed wetland, represented in Figure 3, consists of four treatment cells, one sedimentation basin, and covers 98 ha (242 ac). The WMA is owned and operated by Texas Parks and Wildlife Department (TPWD). The Richland Creek WMA constructed wetland is operated jointly between TPWD and Tarrant Regional Water District (TRWD) under a memorandum of understanding for moist soil management practices to enhance wetland habitat for wildlife, and to reduce sediment and other impurities from the Trinity River for water quality (Frossard et al. 2006). Richland Creek WMA is located between the Post Oak Savannah and Blackland Prairie ecological regions in an ecotone located within the Trinity River flood plain. With an average annual rainfall just over 100 cm (39.5 in), the area is prone to periodic and extended flooding from the Trinity River (TPWD 2009).

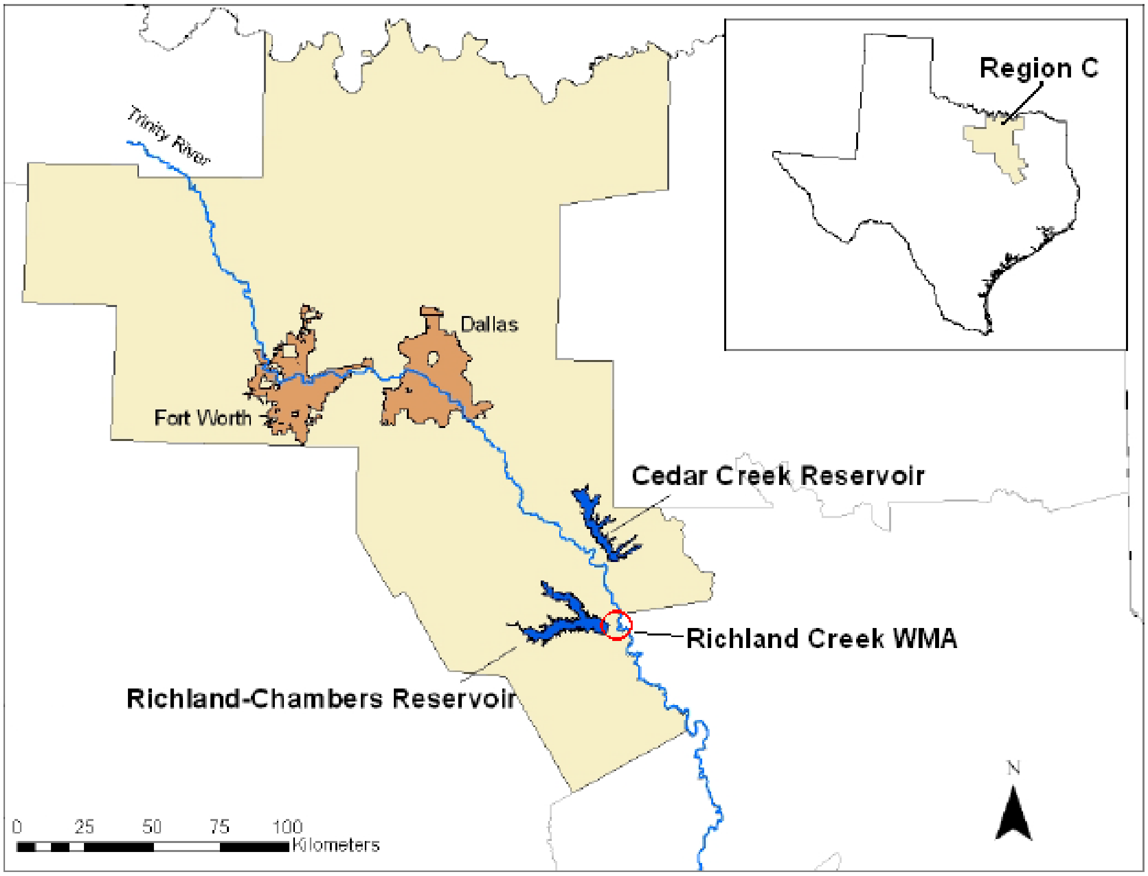

Figure 2. Richland Creek Wildlife Management Area (WMA) location.

The primary soil series within the study area are the Trinity and Kaufman series (Soil 2009). The taxonomic classifications of both soils are very fine, smectitic, thermic Typic Hapluderts. The soils were formed from clayey, alluvium. The Trinity series is calcareous throughout the pedon, whereas the Kaufman series is noncalcareous with a few iron-manganese concretions located throughout the pedon. The alluvium ranges from 2 to 10.7 meter (7 to 35 feet) deep. It is a reasonably well drained, with very slow permeability, and is located on flood plains with a slope typically less than one percent, which makes it ideal for a constructed wetland. Most areas of these soils are cleared and are used for pastureland, row crops such as cotton, corn, or sorghums. Areas of native vegetation consists of hardwood forests of elm, hackberry, oak, and ash species (Soil 2010).

Construction of the field-scale wetland began in 2000 during the summer after 8 years of research on a pilot-scale wetland proved the project viable (TWRD 2002). The field-scale construction phase required a river intake and pump station located directly on the Trinity River to pump raw water through a 107-cm diameter pipe over 1737-m to a sedimentation basin, where removal of nutrients and other impurities from the raw water begins. After a retention time of 7-8 hours in the sedimentation basin, the water enters wetland cell 1 and over the course of a week, it travels through the four wetland cells before exiting to Alligator Creek (AC) and eventually is pumped to Richland-Chambers Reservoir.

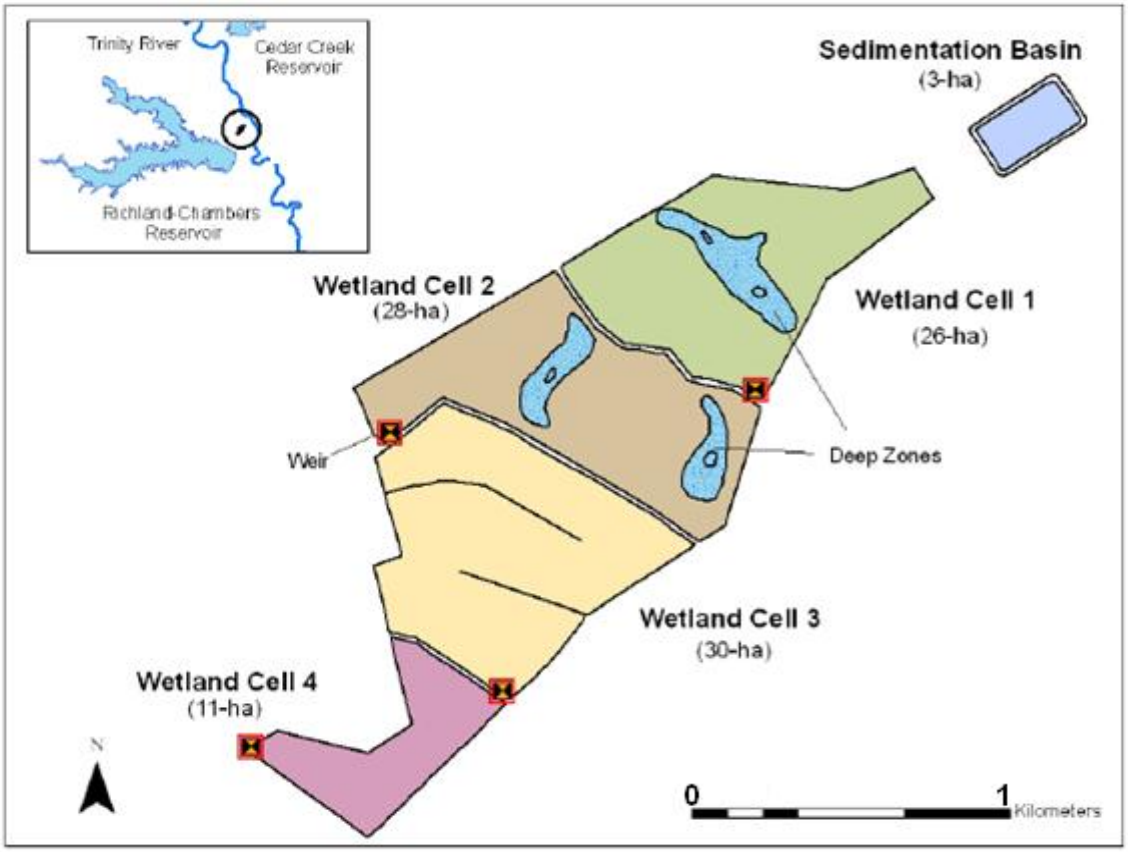

Figure 3. **Field scale wetland cells one through four and sedimentation basin.**

Selection of Research Sites and Soil Pit Locations

Soil/sediment samples were collected from the sedimentation basin, Cell 1, Cell 3, and a reference wetland with a similar soil series that is inundated only during overbank flooding from the Trinity River. Six sample locations were selected in Cell 1, Cell 3, and the reference wetland based on location in the cell and plant community. The established vegetation species at each sampling location was recorded, but was not sampled. In each of the six sampling locations selected, three samples were taken 1 m apart on a transect. In the rectangular sedimentation basin, four samples were taken, 25 m from each side.

The soil/sediment samples were taken during a period of moist-soil management (water draw down), which TPWD initiates to allow the establishment of aquatic vascular plant species for the improvement of waterfowl habitat. Collecting samples during moist-soil management in the wetland cells allowed the soil to become unsaturated, but still moist enough to extract intact cores. A soil core 35-cm in depth was extracted and sliced into increments for analysis. The top 10-cm of the soil core was cut into 2-cm increments, and the remaining 25-cm was cut and bagged in 5-cm increments, totaling ten samples from each intact core.

To extract intact 35-cm soil/sediment cores from the clay textured soils, a "cheater" hole was dug first, with a depth and width exceeding 40-cm using a sharp-nosed spade with a reinforced shaft. With the cheater hole established, a solid metal "sharp shooter" spade was used to cut a U-shape in the wall of the hole to a depth surpassing 35-cm. The U cut was around 10X10-cm to ensure enough soil was available from each sampling depth. With the U-shape cut, the solid metal sharp shooter was used to pry the soil ped into the "cheater" hole and carefully extracted without breaking. The spades were cleaned after each sample to reduce the possibility of cross contamination of phosphorus.

The soil samples were tested for Mehlich-3 P. In addition, one sample core (all 10 depths), from the middle of each transect (6 plots) from each cell tested and reference (18 cores), as well as all samples from the sedimentation basin (4 cores) was tested for water extractable P (WEP), phosphorus sorption index (PSI), total phosphorus (TP), and pH.

Laboratory Analysis Methods of Soil Samples

All laboratory analyses were performed by the Soil, Plant & Water Analysis Laboratory at Stephen F. Austin State University.

Mehlich-3 (M3)

The Mehlich-3 (1984) is a modification of the Mehlich-2 procedure and is designed as a multi-element soil extraction test. The M3 test has the capability to analyze phosphorus (P), potassium (K), calcium, (Ca), magnesium (Mg), sulfur (S), sodium (Na), aluminum (Al), and micronutrients in one test. This broad range of elements tested and the ability to assess a variety of soil types economically and accurately has led to the M3 test to be labeled as a universal soil extractant (Sims 1989).

The M3 extraction was developed as a 1:10 soil-to-solution ratio. For the test, the soil was air-dried to a consistent weight, ground, and passed through a 2 mm sieve. Then, using a standardized M3 scoop of 2.5 cm^3, one scoop of soil was placed into a 50 mL Erlenmeyer extraction flask. Next, 25 mL of the stock extractant 0.2 N acetic acid (CH_3COOH) + 0.25 N ammonium nitrate (NH_4NO_3) + 0.13 N nitric acid (HNO_3) + 0.015 N ammonium fluoride (NH_4F) + 0.001 M ethylenediaminetetraacetic acid (EDTA) were added (Jones 1999). The sample was placed on a rotating or reciprocating shaker for 5 minutes at 200 excursions per minute. Next, the samples were filtered through a Whatman No. 42 filter paper. Finally, the sample was prepared to be measured with an inductively couple plasma (ICP) emission spectroscopy. Results were in mg L^{-1} in the solution and are corrected to mg kg^{-1} in soil by multiplying by a 10X dilution factor.

<u>Phosphorus Sorption Index (PSI)</u>

Sims (2009) modification of Bach and Williams (1971) Phosphorus Sorption Index allows for an inexpensive, less time intensive determination of soil P sorption capacity. Materials needed for the Index are a centrifuge, 50-mL polyethylene centrifuge tubes, end-over end (rotisserie) shaker, and 0.45-µm filter with vacuum flask. The reagent used was a 75 mg P L^{-1} solution made by dissolving 0.3295 g of monobasic potassium phosphate (KH_2PO_4) in 1 L of deionized H_2O, which was refrigerated until used. In order to prevent microbial growth, 1 or 2 drops of toluene was added.

For each sample, 1.00 g of air-dried, sieved (2mm) soil was placed in a screw top, 50-mL centrifuge tube. To the centrifuge tube, 20-mL of the 75 mg P L^{-1} solution and two drops of toluene was added. The tube was then placed in the end-over-end shaker, with lid screwed tightly, and allowed to rotate for 18 hours at 25±2°C. After 18 hours the sample was centrifuged at 2000 rpm for 30 minutes. Using a 0.45-µm filter with vacuum flask the sample was filtered and P concentration measured by ICP emission spectroscopy.

The index is calculated in L kg^{-1}, but it is also acceptable to express PSI directly in mg kg^{-1}. An example of the calculation is as follows: PSI (L kg^{-1}) = X/log C. Where X = P sorbed (mg P kg^{-1}) = [(75 mg P L^{-1} – P_f) x (0.020 L)] / (0.001 kg soil), C = P concentration at equilibrium (mg L^{-1}), and P_f = Final P concentration after 18 h equilibration (mg L^{-1}).

Water Extractable Phosphorus (WEP)

Water extractable P estimates the amount of phosphorus readily available to plants. Self-Davis et al. (2009) standardized the method used in determining WEP levels in soils based on Olsen and Sommers (1982). For each sample, 2.5 cm^3 of air-dried soil, sieved through a 2-mm screen, was placed in a 50 mL Erlenmeyer extraction flask and 25- mL of DI water was added. The flask was then placed on the reciprocating shaker for 60 minutes at 200 excursions per minute. The soil was then filtered through a 0.45-µm filter with vacuum flask and prepared to be measured by ICP emission spectroscopy. The calculation for WEP in mg P kg^{-1} soil is as follows: WEP (mg P kg^{-1} soil) = [Concentration of P in extract (mg L^{-1})] X [Volume of extractant (L) / mass of soil (kg)].

Total Phosphorus (TP)

Total soil P will be measured based on method 3050B, developed by the United States Environmental Protection Agency (USEPA 1996). For this method 1 g of the air-dried, 2-mm sieved soil was measured out to the nearest 0.0001 g and transferred into a digestion vessel. Then 10 mL of 1:1 HNO_3 was added to the sample and heated to 95 ± 5°C without boiling. The sample was allowed to cool to room temperature and then 5 mL of concentrated HNO_3, was added and heated repeatedly until no brown fumes were observed, adding H_2O as necessary to not allow the solution to evaporate. Next, the sample was cooled to room temperate and 2 mL of H_2O and 3 mL of 30% H_2O_2 will be added. The sample was heated to 95 ± 5°C without boiling until effervescence subsides, and then cooled to room temperature. If the effervescence persisted, an additional 1 mL of 30% H_2O_2 was added and heated until effervescence was minimal. The sample was heated, without boiling, and reduced until the approximate volume is 5 mL. Once the volume was achieved, 10 mL of concentrated HCl was added and kept at 95 ± 5°C for 15 minutes. Finally, the sample was filtered through

Whatman No. 41 paper and brought to volume in a 100 mL volumetric flask and then measured for TP using ICP emission spectroscopy.

pH

Soil pH was measured on all samples from the sedimentation basin (4 cores), as well as one sample core (all 10 samples), from the middle of each plot (6 plots) from each cells tested and reference (18 cores). Thomas (1996) standardized the method of soil pH measurement by using 10 g of air-dried soil sieved through a 2-mm screen added to a 100-ml beaker. Then, 10-mL of deionized water was added to the beaker and shaken for 10 minutes on a reciprocating shaker. After it was allowed 10 minutes for the soil particles to settle, the electrode of a calibrated VWR SympHony SB70P or another electrometric measurement device was placed into the suspension in the clear supernatant above the soil, and the pH was recorded. The electrode was rinsed between readings with distilled water. The pH was converted to the hydrogen ion (H^+) concentration by raising 10 the other power of the negative pH ($H^+ = 10^{-pH}$).

Tillage Simulation

Ex Situ

For the purpose of the simulated tillage experiment, eighteen intact soil cores were collected from cell 1 randomly throughout the cell. Soil cores were collected in a thin walled 10-cm diameter PVC pipe, 45-cm in length and a minimum of 25-cm of soil was collected in each tube. The cores were capped to prevent moisture from escaping the tubes. The eighteen cores were divided into three groups of six, with one group being the control (no-till), a group for 10-cm simulated tillage, and the final group representing 20-cm simulated tillage. In order to determine initial P concentration's, a 40 g sample from each tube was taken from 1 cm below the soil surface, air-dried to a constant weight, sieved through a 2 mm screen, and tested for M3P, PSI, TP, and WEP. The soil in the tubes was excavated to the appropriate depth (0, 10, or 20 cm), weighed, and allowed to air-dry until a constant weight was achieved. The excavated soil was ground and sieved through a 5.66 mm screen, mixing the sieved sample thoroughly. A 40 g subsample of the homogenized soil was sieved though a 2 mm screen and tested for M3P, PSI, TP, and WEP. The remaining ground soil was returned to the appropriate tube and compacted in layers to achieve original soil depth (Lewis and Sjöstrom 2010). Based on Peifang and Chao (2007), equilibrium should occur within five days.

Soil saturation was reached using deionized (DI) water (NANOpure Infinity), by applying 500 mL at a time until standing water was maintained. At this point, an additional 1000 mL was added, to bring the water level to 12.75 cm from the surface of the soil. With a water depth of 12.75 cm, and a tube radius of 5 cm, the volume of water, above the soil, was approximately 1000 mL ($V=\pi r^2 h$). The depth of water was returned to 12.75 cm above the soil surface after each 50.0 mL water sample was extracted on day 3, 6, 9, 12 and 15 (Bostic and White 2007). Each extracted sample was analyzed for P concentration by ICP. After day 15, the surface water was removed by siphoning, as to not disturb the soil column.

To represent field P concentration from Trinity River water, 1000 mL solution of 2.0 mg P L^{-1} was added to the cores and returned to a depth of 12.75 cm above the soil surface after each sampling period with the 2.0 mg P L^{-1} water solution. The water was sampled and measured for P concentration (mg kg^{-1}) by ICP on days 3, 6, 9, 12 and 15. After day 15, the surface water was removed by siphoning to maintain the integrity of the soil column.

After day 15 with the 2.0 mg P L^{-1} concentration, the soil core was spiked with 1000 mL of 83.0 mg P L^{-1}. This high concentration of P is used to determine the phosphorus sorption index (PSI). The P concentration was determined by

ICP on days 3, 6, 9, 12 and 15. The concentrated P water was returned to a depth of 12.75 cm above the soil surface after each sample was extracted with the 83.0 mg P L^{-1} water solution. After day 15, the surface water was removed by siphoning, as to not disturb the soil column.

The soil core was then drained and frozen. Once frozen solid, the soil core was secured in a bench-vise and extracted from the PVC using a reciprocating saw. This allowed the soil core to be secured in the bench-vise and sliced, using the reciprocating saw, into 2-cm samples for the top 10-cm and 5-cm increments for the remainder of the soil in the cores. These samples were air-dried until constant weight was reached, then sieved through a 2-mm screen. They were tested for M3P, PSI and TP soil P tests.

In situ

Within cell 1, three areas were marked with a T-post to indicate where soil samples were collected. After extraction of soil samples, TPWD disked the area with the best available equipment. Tillage occurred until the employee was satisfied that the tillage equipment had completely homogenized the near surface soil to the limitations of the equipment. The soil was undisturbed until one rainfall occurred which caused the loose soil to settle. This enabled an intact soil core to be extracted. Three soil cores were extracted from each area tilled and divided into sections to be tested as previously described. These soil samples were tested for M3P, PSI, and TP soil P tests.

Statistical Analysis

All data were analyzed using SAS® software, Version 9.2 of the SAS System for am XP PRO platform. Copyright © 2007 SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA. Soil sample data grouped by cell and location were analyzed for significant variance (ANOVA) using a Within-Subjects (Repeated Measures) experimental design to identify significant differences between sample means and a Tukey's Studentized Range (Tukey's) analysis to determine where the difference in depth occurred. Water samples from the *ex situ* tillage simulation grouped by treatment and sample day after saturation were analyzed for significant difference using a Within-Subjects experimental design and a Tukey's analysis performed to determine where significant differences in treatment occurred. The soil samples from the *ex situ* and *in situ* tillage simulation were analyzed for significant variance using a Within-Subjects experimental design and a Tukey's analysis performed to determine where significant differences in depth or treatment occurred.

FIELD STUDY

Results

Mehlich 3 Phosphorus

The average Mehlich 3 phosphorus (M3P) concentrations (mg kg^{-1}) from 18 soil cores collected from each of the different wetland cells and reference wetland (RW), and 4 soil cores from the sedimentation basin (SB) ranged from a high of 119 mg kg^{-1} in the 0-2 cm depth in cell 1 to a low of 26 mg kg^{-1} in the RW. The mean M3P concentration generally decreased with depth, with the range in mean high value, at the bottom of the soil core (30-35 cm), of 64 mg kg^{-1} in the SB to 5 mg kg^{-1} in the RW (Table 5). All areas tested had a reducing trend in mean M3P concentration, with an increase in depth (Figure 4).

Table 5. Mean Mehlich 3 phosphorus (M3P) concentration (mg kg^{-1}) by depth (cm) intervals for Richland Creek WMA constructed wetland (All Cells), the sedimentation basin (SB), cell 1, cell 3, and the reference wetland (RW). Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Test.

Depth (cm)	All Cells Mean (n=58)	SB Mean (n=4)	Cell 1 Mean (n=18)	Cell 3 Mean (n=18)	RW Mean (n=18)
	mg kg^{-1}				
0-2	72a	107	119	63	26
2-4	63b	93	108	54	20
4-6	49c	78	82	41	19
6-8	40d	62	63	33	20
8-10	37de	57	55	30	21
10-15	29ef	51	41	24	19
15-20	22fg	49	27	18	13
20-25	16gh	51	18	12	9
25-30	13gh	61	13	10	6
30-35	12h	64	10	8	5

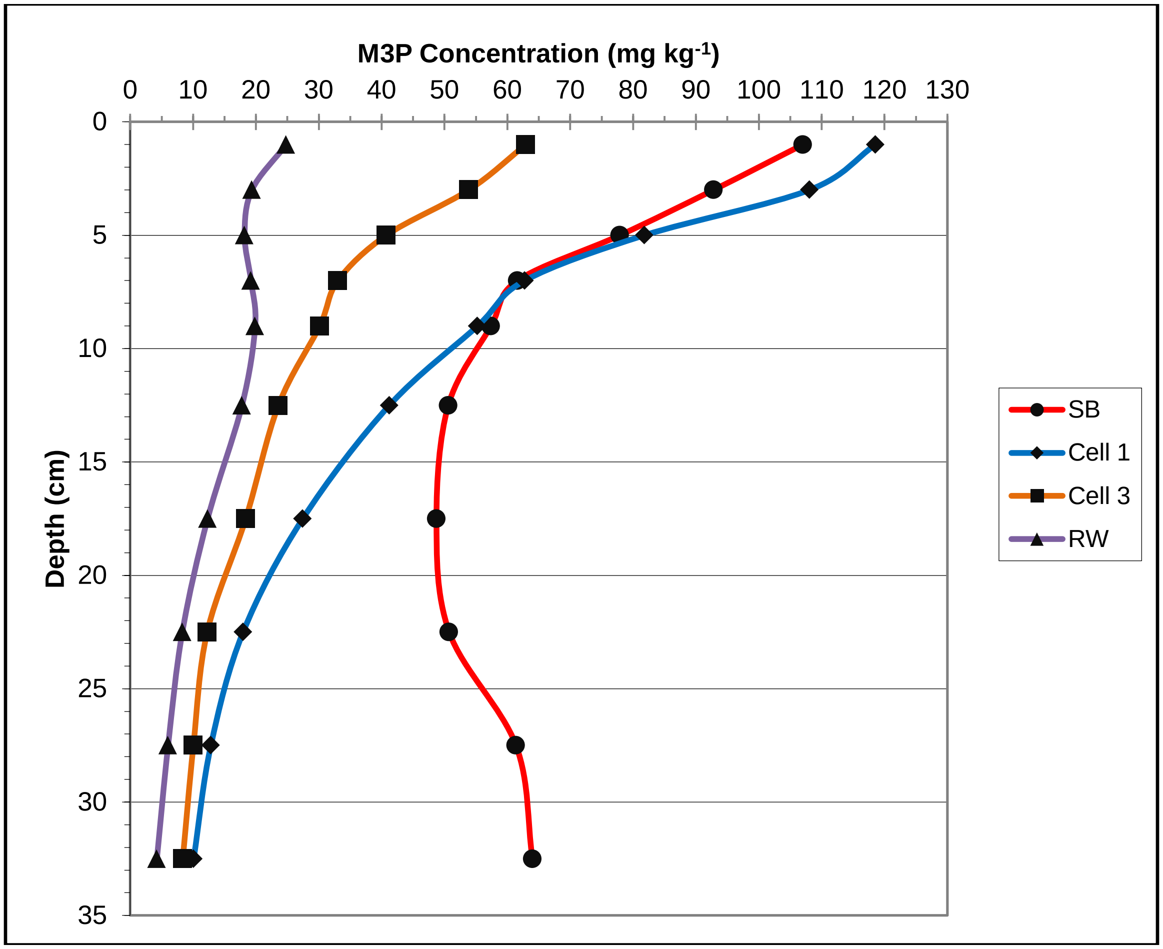

Figure 4. Mean (Cell 1, Cell 3, Reference Wetland (RW) n=18; Sedimentation Basin (SB) n=4) Mehlich 3 phosphorus (M3P) concentration (mg kg^{-1}) by depth (cm) increments at Richland Creek WMA constructed wetland.

The mean M3P concentration was significantly different ($P<0.05$) among the cells ($P<0.0001$), at depth ($P<0.0001$), and among the cells and depth ($P<0.0001$) (Appendix B). The mean M3P concentration among the cells, compared using Tukey's Studentized Range (Tukey's) test, was significant at $\alpha<0.05$ level between cells, except the SB and cell 1 (Table 6).

Table 6. Mean Mehlich 3 phosphorus (M3P) concentration (mg kg^{-1}) among cells compared using Tukey's Studentized Range (HSD) Test. Comparisons significant at α<0.05 are indicated by Yes.

Cell Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		Significance (α=0.05)
	mg kg^{-1}			
SB - Cell 1	14	-3	30	----
SB - Cell 3	38	22	54	Yes
SB - RW	52	35	68	Yes
Cell 1 - RW	38	28	48	Yes
Cell 1 - Cell 3	24	14	34	Yes
Cell 3-RW	14	4	23	Yes

Water Extractable Phosphorus

The average water extractable phosphorus (WEP) concentrations (mg kg^{-1}) from 6 soil cores collected from each of the wetland cells and reference wetland (RW), and 4 soil cores from the sedimentation basin (SB) ranged from a high of 19.0 mg kg^{-1} in the 0-2 cm depth in the SB to a low of 4.3 mg kg^{-1} in Cell 3. The mean WEP concentration generally decreased with depth, with a range at the bottom of the soil core (30-35 cm) from 0.3 mg kg^{-1} in Cell 3 to 2.2 mg kg^{-1} in the SB (Table 7). Cell 1 and Cell 3 both had an increase in WEP concentration from depth 4-6 cm to depth 6-8 cm. The RW and the SB had an increase in WEP concentration from depth 8-10 cm to depth 10-15 cm. In general, as depth increases in all of the areas tested, there is a reduction trend from depth 0-2 cm to depth 30-35 cm in WEP concentration (Figure 5).

Table 7. Mean water extractable phosphorus (WEP) concentration (mg kg^{-1}) by depth (cm) intervals for Richland Creek WMA constructed wetland (All Cells), the sedimentation basin (SB), cell 1, cell 3, and the reference wetland (RW). Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Test.

Depth (cm)	All Cells Mean (n=22)	SB Mean (n=4)	Cell 1 Mean (n=6)	Cell 3 Mean (n=6)	RW Mean (n=6)
	mg kg^{-1}				
0-2	9.4a	19.0	10.2	4.3	7.9
2-4	4.7b	8.4	8.7	1.3	1.8
4-6	2.5bcd	4.4	4.3	0.9	1.1
6-8	3.9bc	3.2	9.4	2.4	0.9
8-10	1.8bcd	2.2	3.6	0.5	1.2
10-15	1.7cd	2.8	2.2	0.4	2.0
15-20	1.2cd	1.8	2.0	0.3	0.9
20-25	1.2cd	2.1	1.3	0.2	0.9
25-30	1.0cd	2.1	1.8	0.3	0.8
30-35	1.0d	2.2	1.0	0.3	0.8

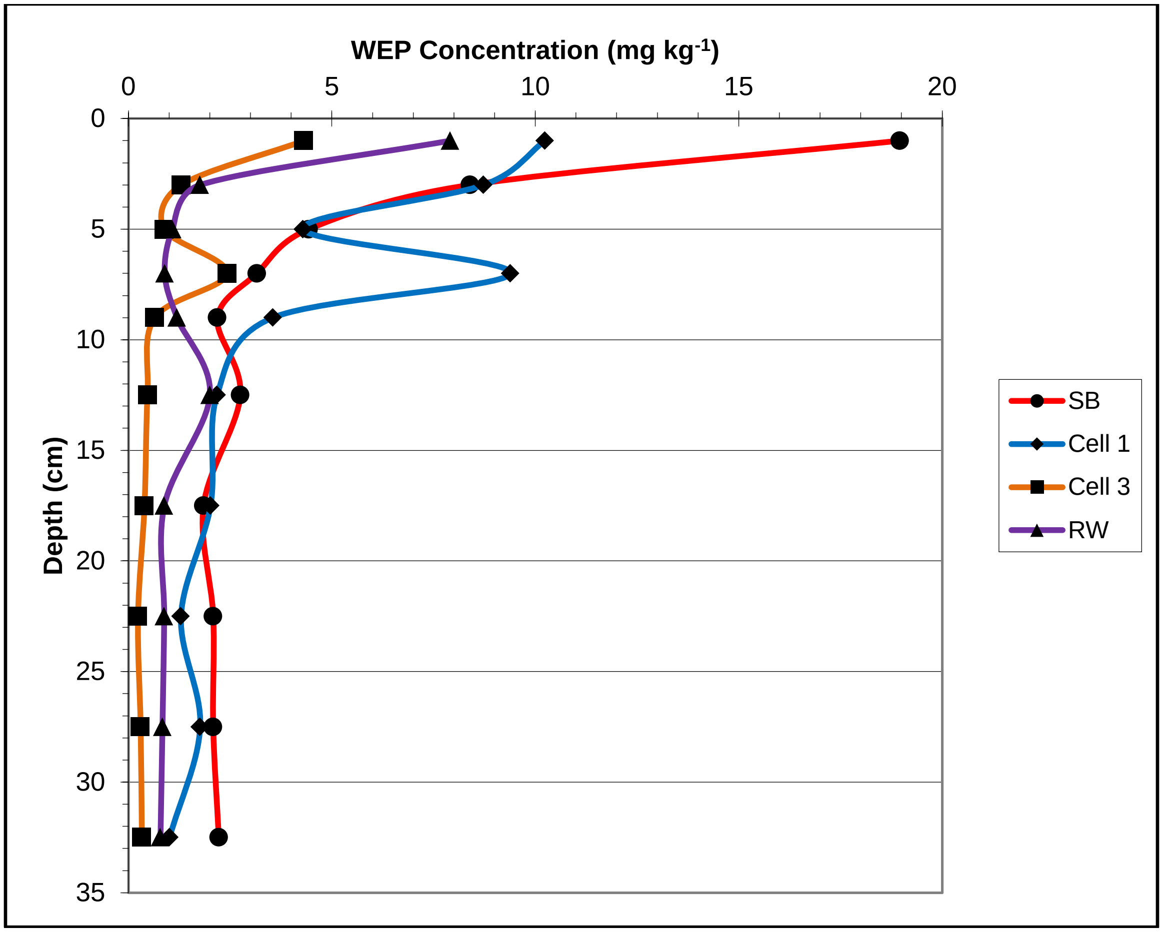

Figure 5. Mean (Cell 1, Cell 3, Reference Wetland (RW) n=6; Sedimentation Basin (SB) n=4) water extractable phosphorus (WEP) concentration (mg kg^{-1}) by depth (cm) increments at Richland Creek WMA constructed wetland.

The WEP concentration was significantly different (P<0.05) among the cells (P=0.0007), at depth (P<0.0001) and among the cells and depth (P<0.0001) (Appendix B). The mean WEP concentration between the cells, compared using Tukey's Studentized Range (Tukey's) test, is significant at α<0.05 level among cells, except the SB and Cell 1, and Cell 3 and the RW (Table 8).

Table 8. Mean water extractable phosphorus (WEP) concentration (mg kg^{-1}) among cells compared using Tukey's Studentized Range (HSD) Test. Comparisons significant at α<0.05 are indicated by Yes.

Cell Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		Significance (α=0.05)
	mg kg^{-1}			
SB - Cell 1	0.4	-2.3	3.0	----
SB - Cell 3	3.9	1.2	6.5	Yes
SB - RW	3.0	0.3	5.7	Yes
Cell 1 - RW	2.6	0.2	5.0	Yes
Cell 1 - Cell 3	3.5	1.1	5.9	Yes
RW - Cell 3	0.9	-1.5	3.3	----

Total Phosphorus

The mean total phosphorus (TP) concentration (mg kg^{-1}) from 6 soil cores collected from each of the wetland cells and reference wetland (RW), and 4 soil cores from the sedimentation basin (SB) ranged from a high of 1372 mg kg^{-1} in the 0-2 cm depth in cell 1 to a low of 719 mg kg^{-1} in the RW. The mean TP concentration generally decreased with depth, with a range at the bottom of the tested soil core (20-25 cm) from 867 mg kg^{-1} in the SB to 397 mg kg^{-1} in cell 3 (Table 9). Generally, with increase in depth, in all of the areas tested, a reduction trend in the TP concentration occurred (Figure 6).

Table 9. Mean total phosphorus (TP) concentration (mg kg^{-1}) by depth (cm) intervals for Richland Creek WMA constructed wetland (All Cells), the sedimentation basin (SB), cell 1, cell 3, and the reference wetland (RW). Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Test.

Depth (cm)	Wetland Mean (n=22)	SB Mean (n=4)	Cell 1 Mean (n=6)	Cell 3 Mean (n=6)	RW Mean (n=6)
			mg kg^{-1}		
0-2	1057a	1017	1372	1106	719
2-4	888b	982	1151	827	623
4-6	762bc	950	875	730	558
6-8	694cd	906	789	628	526
8-10	691cd	918	802	595	523
10-15	601de	868	613	528	483
15-20	546e	826	511	496	444
20-25	515e	867	426	463	422

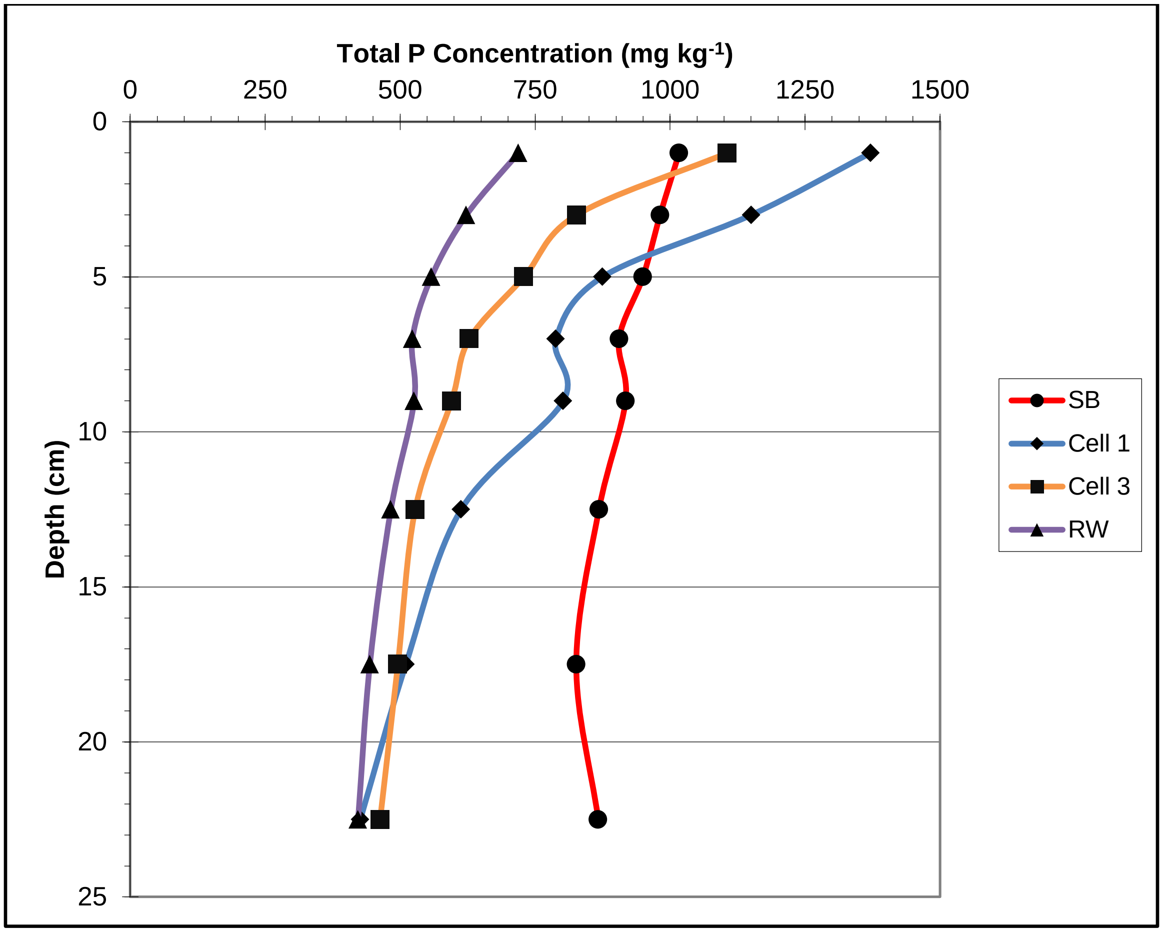

Figure 6. Mean (Cell 1, Cell 3, Reference Wetland (RW) n=6; Sedimentation Basin (SB) n=4) total phosphorus (TP) concentration (mg kg^{-1}) by depth (cm) increments at Richland Creek WMA constructed wetland.

The TP concentration was significantly different (P<0.05) among the cells (P=0.0006), by depth (P<0.0001) and among the cells and depth (P<0.0001) (Appendix B). The mean TP concentration among the cells, compared using Tukey's Studentized Range (Tukey's) test, was significant at α<0.05 level between cell 1 and the RW, cell 3 and the SB, and the RW and the SB (Table 10).

Table 10. Mean total phosphorus (TP) concentration (mg kg^{-1}) among cells compared using Tukey's Studentized Range (HSD) Test. Comparisons significant at α<0.05 are indicated by Yes.

Cell Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		Significance (α=0.05)
	mg kg^{-1}			
SB - Cell 1	99	-127	326	----
SB - Cell 3	379	19	471	Yes
SB - RW	245	153	606	Yes
Cell 1 - RW	280	78	483	Yes
Cell 1 - Cell 3	146	-57	348	----
Cell 3 - RW	135	-68	337	----

<u>Phosphorus Sorption Index</u>

The mean phosphorus sorption index (PSI) value (mg kg^{-1}) from 6 soil cores collected from each of the wetland cells and reference wetland (RW), and 4 soil cores from the sedimentation basin (SB) ranged from a high of 611 mg kg^{-1} in the 0-2 cm depth in cell 3 to a low of 281 mg kg^{-1} in the SB. The mean PSI value generally increased somewhat with depth, with the highest value in the 30-35 cm depth occurring in cell 3 at 645 mg kg^{-1} and the lowest at this depth is 408 mg kg^{-1} in the SB (Table 11). Generally, with increase in depth, the mean

PSI value showed minimal change, except for an increase in concentration in the SB (Figure 7).

Table 11. Mean phosphorus sorption index (PSI) value (mg kg^{-1}) by depth (cm) intervals for Richland Creek WMA constructed wetland (All Cells), the sedimentation basin (SB), cell 1, cell 3, and the reference wetland (RW).

Depth (cm)	All Cells Mean (n=22)	SB Mean (n=4)	Cell 1 Mean (n=6)	Cell 3 Mean (n=6)	RW Mean (n=6)
	mg kg^{-1}				
0-2	498	281	515	611	513
2-4	513	323	488	613	565
4-6	505	316	483	602	555
6-8	521	368	486	622	558
8-10	520	399	450	632	557
10-15	532	458	489	594	561
15-20	527	409	474	610	576
20-25	538	415	497	624	576
25-30	547	454	501	645	556
30-35	529	408	488	645	533

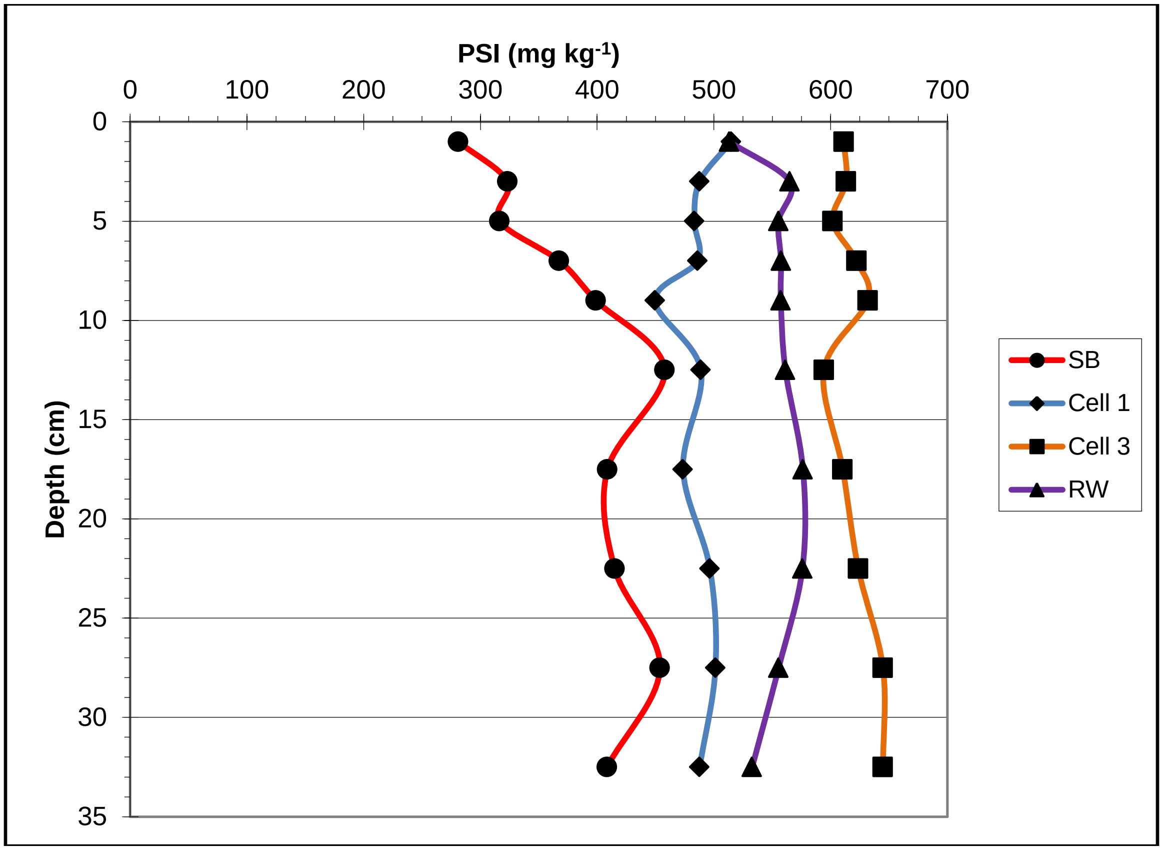

Figure 7. Mean (Cell 1, Cell 3, Reference Wetland (RW) n=6; Sedimentation Basin (SB) n=4) phosphorus sorption index (PSI) value (mg kg^{-1}) by depth (cm) increments at Richland Creek WMA constructed wetland.

The PSI value was significantly different ($P<0.05$) among the cells ($P<0.0001$), but it was not significantly different among depths and among the cells and depth (Appendix B). The mean PSI value between the cells, compared using Tukey's Studentized Range (Tukey's) test, was significant at $\alpha<0.05$ level between the SB and cell 3, the SB and the RW, and between the RW and cell 1 (Table 12).

Table 12. Mean phosphorus sorption index (PSI) value (mg kg^{-1}) among cells compared using Tukey's Studentized Range (HSD) Test. Comparisons significant at α<0.05 are indicated by Yes.

Cell Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		Significance (α=0.05)
	mg kg^{-1}			
Cell 1 - SB	104	215	8	----
Cell 3 - SB	237	348	125	Yes
RW - SB	172	284	60	Yes
RW - Cell 1	68	169	32	----
Cell 3 - Cell 1	133	233	33	Yes
Cell 3 - RW	65	164	-35	----

pH

The mean hydrogen ion (H^+) concentration (moles) from 6 soil cores collected from each of the wetland cells and reference wetland (RW), and 4 soil cores from the sedimentation basin (SB), was used to calculate pH. The pH value ranged from 7.9 in the 0-2 cm depth in the SB to a low value in the 0-2 cm depth of 6.3 in the RW. The pH generally increased slightly with depth, with the highest value in the 30-35 cm depth occurring in cell 1 at 8.0 and the lowest value of 7.4 in the RW (Table 13). The pH value generally increased somewhat with depth throughout all cells, but not in the SB, which showed little change with depth (Figure 8).

Table 13. Mean (Cell 1, Cell 3, Reference Wetland (RW) n=6; Sedimentation Basin (SB) n=4) pH value, calculated from hydrogen ion (H^+) concentration (moles), by depth (cm) intervals at Richland Creek WMA constructed wetland.

Depth (cm)	SB	Cell 1	Cell 3	RW
0-2	7.9	7.2	6.4	6.3
2-4	7.9	7.3	6.4	6.3
4-6	7.9	7.2	6.8	6.5
6-8	8.0	7.6	7.4	6.3
8-10	7.9	7.4	7.2	6.9
10-15	7.9	7.6	7.5	7.0
15-20	7.9	7.4	7.3	7.3
20-25	7.9	8.0	7.4	7.2
25-30	7.9	7.8	7.5	7.4
30-35	8.0	8.0	7.5	7.4

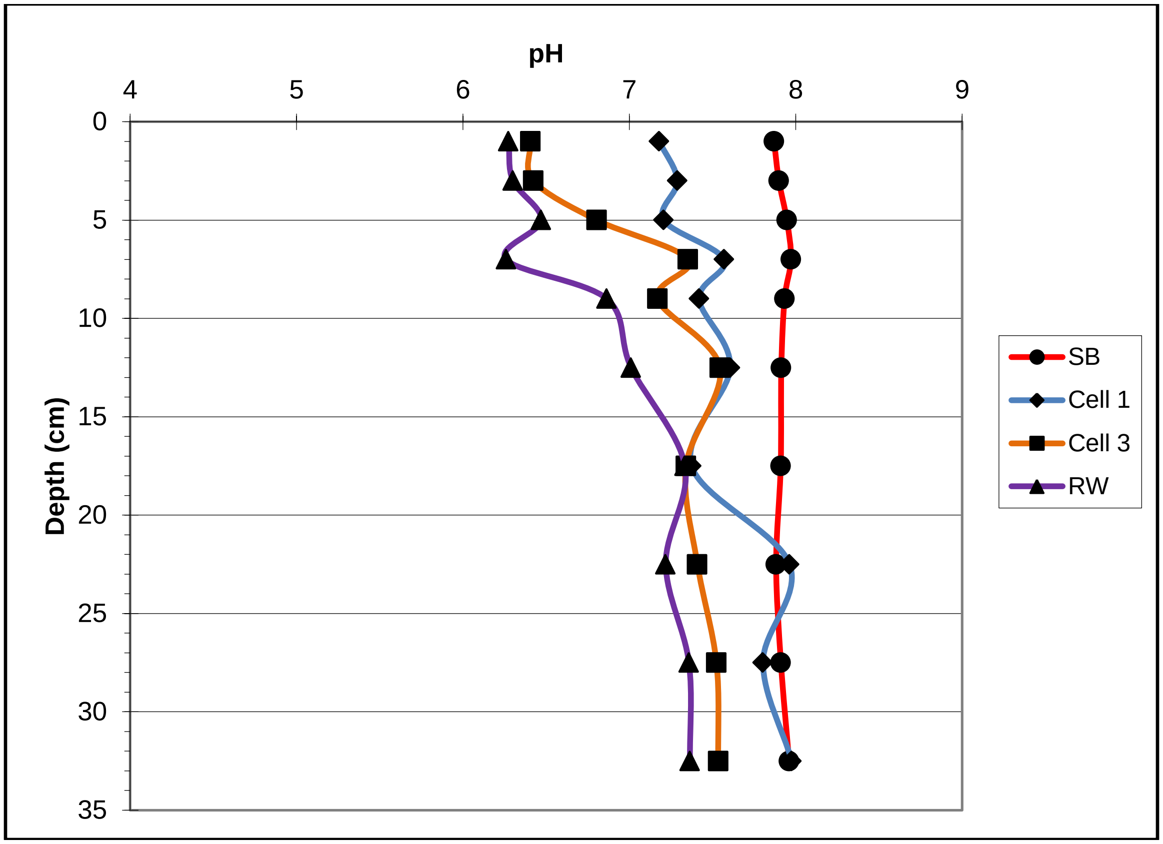

Figure 8. Mean (Cell 1, Cell 3, Reference Wetland (RW) n=6; Sedimentation Basin (SB) n=4) pH value, calculated from H+ ion concentration (moles), by depth (cm) intervals at Richland Creek WMA constructed wetland.

The mean H^+ ion concentration (moles) was significantly different (P<0.05) among the depths (P<0.001), but it was not significantly different among the cells and among cells and depth (Appendix B). The Tukey's Studentized Range (Tukey's) test for depth (All Cells) indicated a comparison significant at α <0.05 among sample depths by grouping depths by letters, and those with the same letter are not significantly different (Table 14).

Table 14. Mean hydrogen ion (H+) concentration (moles) by depth (cm) intervals for Richland Creek WMA constructed wetland (All Cells), the sedimentation basin (SB), cell 1, cell 3, and the reference wetland (RW). Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Test.

Depth (cm)	All Cells Mean (n=22)	SB Mean (n=4)	Cell 1 Mean (n=6)	Cell 3 Mean (n=6)	RW Mean (n=6)
			moles		
0-2	2.7E-07a	1.4E-08	6.1E-08	3.9E-07	5.3E-07
2-4	2.6E-07ab	1.3E-08	5.1E-08	3.8E-07	5.0E-07
4-6	1.5E-07abc	1.1E-08	6.2E-08	1.6E-07	3.4E-07
6-8	1.7E-07abc	1.1E-08	2.7E-08	4.4E-08	5.5E-07
8-10	6.8E-08abc	1.2E-08	3.8E-08	6.8E-08	1.4E-07
10-15	4.3E-08bc	1.2E-08	2.5E-08	2.9E-08	9.8E-08
15-20	3.9E-08c	1.2E-08	4.2E-08	4.6E-08	4.6E-08
20-25	3.2E-08c	1.3E-08	1.1E-08	3.9E-08	6.0E-08
25-30	2.7E-08c	1.2E-08	1.6E-08	3.0E-08	4.4E-08
30-35	2.5E-08c	1.1E-08	1.1E-08	2.9E-08	4.3E-08

Discussion

Mehlich 3 P (M3P) measures plant available P, which is called labile P. It is commonly used in agriculture to determine fertilizer recommendations. When M3P concentrations (mg kg^{-1}) exceed 60 mg kg^{-1}, it is recommended that no additional fertilizer be applied (Appendix C). M3P exceeded 60 mg kg^{-1} at the Richland Creek WMA constructed wetland on the soil surface in the sedimentation basin (SB), cell 1 and cell 3. In the SB, the no additional fertilizer threshold was exceeded throughout the sampling depths. Whereas, in cell 1, the threshold was exceeded to depth 8-10 cm, and then the concentration decreased to single digits with increase in depth, just as it does in cell 3 and the reference wetland (RW) (Table 5, Figure 4).

Water extractable phosphorus (WEP) measures the amount of P that is readily water soluble. This fraction of P is also measured in the M3 test, but the WEP test indicates highly mobile P. Mobile P has the potential to be transported from the soil by runoff or moved down in the soil where permeable (Fisher 2001). The mobile P that is transported has been associated with the increased eutrophication of natural waters (Sharpley 1982). P is potentially released during the rewetting period of moist-soil management (MSM) (Meissner et al. 2008, Novak et al. 2004). The trend for WEP concentration is similar to the trend for M3P concentration. The SB and cell 1 have the highest concentration on the surface horizon. The SB maintains a WEP over 2.0 mg kg^{-1} throughout the sampling depths. Cell 1, cell 3, and the RW WEP concentrations trend towards ≤1.0 mg kg^{-1} as sampling depth increased (Table 7, Figure 5).

Total P (TP) measures labile and non-labile P. The removal of labile P (M3P and WEP) from the TP concentration indicates the amount of non-labile P that is available to undergo transformation, due to P mineralization, changes in soil chemistry or weathering (Compton et al 2000). In constructed treatment wetlands that receive over 3 mg L^{-1} TP from the water, it is typical to measure 1000-2000 mg kg^{-1} TP in the top 10 cm of the soil column. The Houghton Lake wetland in Michigan reported 1268 mg kg^{-1} TP in the 0-5 cm depth and 1180 mg kg^{-1} TP in the 5-10 cm depth and the Tres Rios wetland in Arizona reported a range of 968-1365 mg kg^{-1} TP in the 0-5 cm depth in all four of its wetland systems (Kadlec and Wallace 2009). The TR water enters the wetland system at the SB around 1 mg L^{-1} TP. TP concentrations in the soil exceed 1000 mg kg^{-1} in surface horizon in the SB, cell 1, and cell 3. The SB has a higher concentration at the 20-25 cm depth than the RW does at the surface horizon. This further identifies that the SB is nutrient rich throughout the sampling depth, but field observations of soil texture consistencies throughout depth indicate that the antecedent soil was not reached. With an increase in depth, all cells follow a reduction trend in concentration (Table 9, Figure 6).

Soil P loading within the Richland Creek WMA constructed wetland from TR water was evident. The SB had a significant difference ($P<0.05$) in M3P, WEP, TP, and PSI concentration with cell 3 and the RW, but it had no significant difference with cell 1 in any of the soil P test. Cell 1 was significantly different in all soil P tests from cell 3. Cell 1 was significantly different in M3P and WEP concentrations with the RW. Cell 3 was significantly different with the RW only in M3P concentration (Table 6, Table 8, Table 10, Table 12).

The SB and cell 1 had generally higher concentrations of M3P, WEP, and TP than cell 3 and the RW (Table 5, Table 7, Table 9). The SB and cell 1 also had lower PSI values than cell 3 and the RW (Table 11). This indicates that the area of the wetland that received water from the TR first, the SB and cell 1, are more highly concentrated in soil P than areas further into the wetland system, cell 3.

The lower PSI values in the SB and cell 1 further indicates that these cells have higher concentrations of soil P than cell 3 and the RW. The lower the PSI value, the lower the continued P-sorbing, or fixing, capacity for that site (Nair 2004). The P-sorbing capacity for a site is a product of soil type (chemical and physical properties), existing soil P concentration, and P loading rate from fertilizer or in this case, from TR water (Bache 1971). It is interesting to note that even though the RW had significantly lower M3P and TP concentrations than the SB and cell 1, it did not have a significant difference from cell 1 in PSI concentration (Table 12).

Conclusion

P loading in the soil at Richland Creek WMA constructed wetland was more concentrated in the sedimentation basin (SB) and cell 1 of the wetland system than in cell 3 or the reference wetland (RW). Mehlich 3 P (M3P), P that is readily available for plant use, concentration was nearly double the threshold for no additional fertilizer recommendations for agriculture of 60 mg kg^{-1} in the SB and cell 1 (Table 5, Appendix C). Water extractable P (WEP), the highly mobile P, concentrations were highest in the SB and cell 1 and were significantly different than cell 3 and the RW (Table 7, Table 8). Total P (TP) concentrations were comparable to other treatment wetland systems, such as the Tres Rios, Arizona or Houghton Lake, Michigan wetland systems (Kadlec and Wallace 2009), that receive high quantities of P from the water column and the highest concentrations were found in the SB, cell 1 and cell 3 (Table 9). The P sorption index (PSI), a measure of the soil's potential P fixing capacity, identified the SB and cell 1, the areas with consistently higher soil P concentrations, as the areas with the least potential P fixing capacity remaining (Table 12).

The soil P concentrations at Richland Creek WMA constructed wetland were representative of roughly ten years of nutrient loading from Trinity River (TR) water. Throughout the completion of Phase I, sporadic TR flow data into the wetland system from downtime caused by construction, maintenance, moist-soil management, and over bank flooding from the TR, resulted in an unquantifiable amount of P entering the wetland system. The P concentrations in the SB and cell 1 illustrate that the effectiveness and longevity of the treatment wetland system is an area of concern, but without a quantifiable P loading rate from TR water, the time frame for Kadlec and Wallace's (2009) "hydrologic burnout" is difficult to determine.

TARRANT REGIONAL WATER DISTRICT DATA INTERPRETATION

Hydrologic data (quantity and quality) collected by Tarrant Regional Water District (TRWD) during phase I of the Richland Creek WMA constructed wetland project, from the summer of 2003 through the winter of 2010, provides some insight regarding nutrient loading that has occurred in the constructed wetland. TRWD collected hydrologic data from the Trinity River (TR) at the inflow to the wetland and again at the outflow from the sedimentation basin (SB) and at the outflow of each wetland cell. The parameters of importance included flow, total suspended solids (TSS), total phosphorus (TP), and orthophosphate (OP) concentrations.

In order to estimate the quantity of a nutrient retained within a wetland cell, the amount of the nutrient entering the cell is first quantified and then the amount of nutrient exiting the cell is subtracted. To quantify the estimated maximum nutrient loading rate, the following formula was used:

Estimated Maximum Potential Loading Rate = $\text{Area}_{\text{input}}$ [Nutrient Concentration * Flow Rate * Time] – $\text{Area}_{\text{output}}$ [Nutrient Concentration * Flow Rate * Time]

The nutrient concentration and flow rates were average values calculated from the TRWD data set, and time is based on an annual basis. The flow between cells rate was considered constant at the indicated rate for the entire year and was converted from its recorded unit of million gallons per day (MGD). Due to incomplete data on flow rate and nutrient loading, the resulting data was only an assumptive estimate of potential nutrient loading. In addition, by maintaining the flow rate for the entire year and not accounting for any system maintenance or other down time, the result is an estimated maximum loading rate.

Results

Estimated Maximum Loading Potential Rate

Inflow from the TR averaged 212 mg L^{-1} TSS before entering the low flow, deep-water SB. When exiting the SB, the TSS was reduced to an average of 76 mg L^{-1}. This equates to an estimated 68% reduction in TSS occurring in the SB. The TR water was reduced in TSS throughout each wetland cell, and when exiting cell 4, the TSS of 9 mg L^{-1} equates to a 97% cumulative estimated reduction of TSS (Table 15, Table 161)

Table 15. Estimated maximum (kg ha^{-1} yr^{-1}) total suspended solids (TSS) loading in Richland Creek WMA constructed wetland from the Trinity River (TR) using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TSS (mg L^{-1})	Flow (L s^{-1})	Area (ha)	Estimated Maximum Loading (kg ha^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	212	589			
SB	72	560	3	888000	68 %
Cell 1	38	535	26	24200	84 %
Cell 2	16	542	28	13200	93 %
Cell 3	10	499	30	4000	96 %
Cell 4	9	407	11	4300	97 %

Table 16. Estimated maximum (lb ac^{-1} yr^{-1}) total suspended solids (TSS) loading in Richland Creek WMA constructed wetland from the Trinity River (TR) using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TSS (mg L^{-1})	Flow (gal s^{-1})	Area (ac)	Estimated Maximum Loading (lb ac^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	212	156			
SB	72	148	7	791900	68 %
Cell 1	38	141	64	21600	84 %
Cell 2	16	143	69	11800	93 %
Cell 3	10	132	74	3600	96 %
Cell 4	9	107	27	3800	97 %

The average TP concentration in the TR water when entering the SB was 0.97 mg L^{-1}. The SB reduced the TP concentration to 0.92 mg L^{-1}, which was an estimated 10% reduction. The wetland cells further reduced the TP concentration to an average value of 0.56 mg L^{-1} when exiting cell 4. This equates to an estimated cumulative reduction of 61% (Table 17, Table 18).

Table 17. Estimated maximum (kg ha^{-1} yr^{-1}) total phosphorus (TP) loading in Richland Creek WMA constructed wetland from the Trinity River (TR) using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TP (mg L^{-1})	Flow (L s^{-1})	Area (ha)	Estimated Maximum Loading (kg ha^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.97	589			
SB	0.92	560	3	620	10 %
Cell 1	0.81	535	26	100	24 %
Cell 2	0.67	542	28	80	37 %
Cell 3	0.56	499	30	90	51 %
Cell 4	0.56	407	11	160	61 %

Table 18. Estimated maximum (lb ac^{-1} yr^{-1}) total phosphorus (TP) loading in Richland Creek WMA constructed wetland from the Trinity River (TR) using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TP (mg L^{-1})	Flow (gal s^{-1})	Area (ac)	Estimated Maximum Loading (lb ac^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.97	156			
SB	0.92	148	7	550	10 %
Cell 1	0.81	141	64	90	24 %
Cell 2	0.67	143	69	70	37 %
Cell 3	0.56	132	74	80	51 %
Cell 4	0.56	107	27	140	61 %

The average OP concentration in the TR water when entering the SB was 0.89 mg L^{-1}. The OP concentration when exiting the SB was about the same at 0.90 mg L^{-1}, but is still an estimated 5% reduction due to the decreased volume of water. The wetland cells further reduced the OP concentration to an average value of 0.53 mg L^{-1} when exiting cell 4. This equates to an estimated cumulative reduction of 59% (Table 19, Table 20).

Table 19. Estimated maximum (kg ha^{-1} yr^{-1}) orthophosphate (OP) loading in Richland Creek WMA constructed wetland from the Trinity River (TR) using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	OP (mg L^{-1})	Flow (L s^{-1})	Area (ha)	Estimated Maximum Loading (kg ha^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.89	589			
SB	0.90	560	3	250	5 %
Cell 1	0.76	535	26	120	23 %
Cell 2	0.63	542	28	70	35 %
Cell 3	0.53	499	30	80	50 %
Cell 4	0.53	407	11	140	59 %

Table 20. Estimated maximum (lb ac^{-1} yr^{-1}) orthophosphate (OP) loading in Richland Creek WMA constructed wetland from the Trinity River (TR) using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	OP (mg L^{-1})	Flow (gal s^{-1})	Area (ac)	Estimated Maximum Loading (lb ac^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.89	156			
SB	0.90	148	7	220	5 %
Cell 1	0.76	141	64	100	23 %
Cell 2	0.63	143	69	70	35 %
Cell 3	0.53	132	74	70	50 %
Cell 4	0.53	107	27	130	59 %

This estimated nutrient loading indicates that TSS is reduced effectively in the SB. The accumulation of TSS is not distributed evenly throughout all the wetland cells. Variations in plant communities, deep water zones, wildlife disturbance, and weather are known to alter the distribution of TSS accumulation (Mitsch et al 2012, Nahlik and Mitsch 2008). TSS data has been shown to typically under estimate potential sediment load (USGS 2000).

The SB alone does not appear to be an effective measure at reducing the TP or OP, but the wetland system, in its entirety, is an effective measure at reducing P concentrations. It is interesting to note that the TP concentration in the TR of 0.97 mg L^{-1} is comprised of 92% OP (0.89 mg OP L^{-1} / 0.97 mg TP L^{-1}). An OP is any generic inorganic P, which is found in a dissolved form in the water column, making it readily available for plant and other macrophytes use (Kadlec and Wallace 2009). The OP concentration was reduced in the shallower vegetated wetland cells.

Phase III Extrapolated Potential Loading Rate

Upon completion of phase III construction in 2013, the wetland area will be 809 ha (2000 ac) and have a maximum water output capacity of 2463 L s^{-1} (651 gal s^{-1}) (Mokry and McDonald 2010). Following the trends established for nutrient (TSS, TP, OP) removal, flow rate loss, and land area utilization (total wetland area, roads, functioning wetland) an extrapolated loading potential for the completed wetland was established. This extrapolated loading potential is only a presumptive estimation. It is important to note that after phase I data analysis completion by TPWD and TRWD, it was determined additional SB area was needed and this extrapolated data reflects the additional land allocation.

With the TSS removal rate maintained at the same level of efficiency, the cumulative estimated reduction percentage remained at 68% for the SB and 97% for the completed wetland system. The larger area allocated to sedimentation basins will disperse TSS accumulation, resulting in a net reduction in estimated annual TSS loading from 888000 kg ha^{-1} (791900 lb ac^{-1}) (Table 15, Table 16) to 310000 kg ha^{-1} (279400 lb ac^{-1}) (Table 21, Table 22).

Table 21. Extrapolated potential (kg ha^{-1} yr^{-1}) total suspended solids (TSS) loading in Richland Creek WMA constructed wetland, upon phase III completion in 2013, from the Trinity River (TR), using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TSS (mg L^{-1})	Flow (L s^{-1})	Area (ha)	Extrapolated Loading Potential (kg ha^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	212	3226			
SB	72	3071	47	310000	68 %
Area 1	38	2955	202	17000	84 %
Area 2	16	2987	218	9400	93 %
Area 3	10	2798	234	2800	96 %
Area 4	9	2463	86	2500	97 %

Table 22. Extrapolated potential (lb ac^{-1} yr^{-1}) total suspended solids (TSS) loading in Richland Creek WMA constructed wetland, upon phase III completion in 2013, from the Trinity River (TR), using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TSS (mg L^{-1})	Flow (gal s^{-1})	Area (ac)	Extrapolated Loading Potential (lb ac^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	212	852			
SB	72	812	115	279400	68 %
Area 1	38	781	500	15200	84 %
Area 2	16	789	539	8400	93 %
Area 3	10	739	577	2500	96 %
Area 4	9	651	212	2300	97 %

With the TP removal rate maintained at the same level of efficiency, the cumulative estimated reduction percentage remained at 10% for the SB and 56% for the completed wetland system. The extrapolated data set (Table 23, Table

24) identifies the TP loading rate in the wetland areas will not exceed estimated maximum loading potential from phase I data (Table 17, Table 18).

Table 23. Extrapolated potential (kg ha^{-1} yr^{-1}) total phosphorus (TP) loading in Richland Creek WMA constructed wetland, upon phase III completion in 2013, from the Trinity River (TR), using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TP (mg L^{-1})	Flow (L s^{-1})	Area (ha)	Extrapolated Loading Potential (kg ha^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.97	3226			
SB	0.92	3071	47	210	10 %
Area 1	0.81	2955	202	70	24 %
Area 2	0.67	2987	218	60	36 %
Area 3	0.56	2798	234	60	50 %
Area 4	0.56	2463	86	80	56 %

Table 24. Extrapolated potential (lb ac^{-1} yr^{-1}) total phosphorus (TP) loading in Richland Creek WMA constructed wetland, upon phase III completion in 2013, from the Trinity River (TR), using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	TP (mg L^{-1})	Flow (gal s^{-1})	Area (ac)	Extrapolated Loading Potential (lb ac^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.97	852			
SB	0.92	812	115	190	10 %
Area 1	0.81	781	500	60	24 %
Area 2	0.67	789	539	50	36 %
Area 3	0.56	739	577	50	50 %
Area 4	0.56	651	212	70	56 %

With the OP removal rate maintained at the same level of efficiency, the cumulative estimated reduction percentage remained at 4% for the SB and 55% for the completed wetland system. The extrapolated data set (Table 25, Table 26) identifies the OP loading rate in the wetland areas will not exceed estimated maximum loading potential from phase I data (Table 19, Table 20).

Table 25. Extrapolated potential (kg ha^{-1} yr^{-1}) orthophosphate (OP) loading in Richland Creek WMA constructed wetland, upon phase III completion in 2013, from the Trinity River (TR), using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	OP (mg L^{-1})	Flow (L s^{-1})	Area (ha)	Extrapolated Loading Potential (kg ha^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.89	3226			
SB	0.90	3071	47	80	4 %
Area 1	0.76	2955	202	80	22 %
Area 2	0.63	2987	218	50	35 %
Area 3	0.53	2798	234	50	48 %
Area 4	0.53	2463	86	70	55 %

Table 26. Extrapolated potential (lb ac^{-1} yr^{-1}) orthophosphate (OP) loading in Richland Creek WMA constructed wetland, upon phase III completion in 2013, from the Trinity River (TR), using Tarrant Regional Water District hydrologic data from 2003-2010.

Location	OP (mg L^{-1})	Flow (gal s^{-1})	Area (ac)	Extrapolated Loading Potential (lb ac^{-1} yr^{-1})	Cumulative Estimated Reduction
TR	0.89	852			
SB	0.90	812	115	70	4 %
Area 1	0.76	781	500	70	22 %
Area 2	0.63	789	539	50	35 %
Area 3	0.53	739	577	50	48 %
Area 4	0.53	651	212	60	55 %

Discussion

The accretion rates of TSS in the SB and wetland cell 1, is a primary factor for the increased P loading within those same areas. The TSS transports P primarily as detrital and particulate P (Kadlec and Wallace 2009, Seo et al. 2005). Detrital P is the P that is sorbed to the surface of particles and is not readily available for plant uptake until it undergoes chemical weathering. It is a semi-labile P and contributes to the total phosphorus (TP) concentration (Compton et al 2000). Particulate P is dissolved form of P that is readily available to plants. Particulate P is the labile P that is represented as Mehlich 3 P (M3P) and water extractable P (WEP) (Surridge et al. 2007).

Nutrient loading associated with TSS and the accumulated sediment is typically much higher than in the antecedent soil, and the ability of the sediment to sequester P from the water column is well documented (Liikanen et al. 2004, Mayer et al. 2005, Poach and Faulkner 2007). Nutrient loading from sediment is apparent when comparing data collected from the SB, the wetland cells, and the RW. The SB, which accounts for approximately twice the estimated TSS removal compared to the wetland cells, and cell 1, which accounts for approximately twice the estimated TSS removal than from the remaining wetland cells (Table 20, Table 21) , are not significantly different in M3P (Table 7), WEP (Table 10) , TP (Table 13), or PSI (Table 16) concentration. The SB is significantly different (α=0.05) from cell 3 and the RW in M3P, WEP, TP, and PSI concentration. Cell 1 is significantly different from cell 3 and the RW in M3P and WEP, and it is significantly different from the RW in TP concentration (Table 7, Table 10, Table 13, Table 16). This indicates that the areas with the higher estimated TSS loading, also have higher soil P concentrations.

TSS accumulation is not the only factor for nutrient loading within the wetland. The retention of particulate P in the sediment promotes the development of aquatic vascular plants and other macrophytes, especially during a period of moist-soil management (MSM), which allows seeds to germinate and emergent species to flourish (Kadlec and Wallace 2009). The emerging plants utilize labile P in the soil, and when the plant communities are established, the wetland system is reflooded to complete the MSM cycle, which allows the plants to utilize OP, dissolved particulate P and other forms of labile P in the water column. The accelerated rate of primary production causes a net reduction in TP concentration, in this case by reducing OP in the water column, and the net reduction will continue until the primary production growth rate is exceeded by the rate of plant decay (Almendinger 1997, Fisher and Reddy 2001).

When compared to the estimated maximum loading from data collected by TRWD (Tables 20-25), the extrapolated data (Tables 26-31) identifies that projected loading potential of TSS, TP, and OP is reduced on an annual basis per hectare (acre). With the completion of the expansion of the wetland system area from 98 ha (242 ac) to 809 ha (2000 ac), the land area is roughly 9 times larger. The increased annual flow output from 407 L s^{-1} (107 gal s^{-1}) to 2463 L s^{-1} (651 gal s^{-1}), is approximately 6 times greater. As noted above, this higher ratio of surface area to flow rate will result in an overall decrease in nutrient loading per unit surface area annually. With soil M3P levels in Cell 1 and Cell 3 (Table 5) already exceeding the 60 mg L^{-1} M3P threshold for no additional fertilizer recommendations (Appendix C) management applications to extend the effectiveness of the wetland in capturing P should be developed.

Conclusion

The wetlands efficiency at removing nutrients from the water is linked to the nutrient accumulation in the wetland's soils. The wetland cells with the highest estimated TSS loading, also had higher soil P concentrations. The establishment of plant species through MSM, has the potential to remove nutrients from the water column efficiently, but also has the potential to re-release P previously sequestered in the soil column. Even though the annual expected nutrient loading per unit area for the wetland after completion of phase III is projected to be less than during phase I, solutions to prolong the effectiveness of the wetland should be considered.

The soil P concentrations at Richland Creek WMA constructed wetland were representative of roughly eight years of nutrient loading from Trinity River (TR) water. Throughout the completion of Phase I, sporadic TR flow data into the wetland system from downtime caused by construction, maintenance, moist-soil management, and over bank flooding from the TR, resulted in an unquantifiable amount of P entering the wetland system. The P concentrations in the SB and cell 1 illustrate that the effectiveness and longevity of the treatment wetland system was an area of concern, but without a quantifiable P loading rate from TR water, the time frame for Kadlec and Wallace's (2009) "hydrologic burnout" was difficult to determine.

EX SITU TILLAGE SIMULATION

Water Phosphorus Results

Soluble Reactive Phosphorus

The average soluble reactive phosphorus (SRP) concentrations (mg L^{-1}), collected every third day after saturation with deionized water, from three *ex situ* tillage depth (cm) groups (no-till, 10-cm, 20-cm), with each tillage group represented by six soil cores collected from cell 1 of Richland Creek WMA constructed wetland, ranged from 0.23 to 0.34 mg L^{-1} on day 3 in the no-till and 10-cm tillage group, respectfully. The mean concentration increased each sampling period in the no-till group until water SRP reach 0.67 mg L^{-1} on day 12. The mean SRP concentration decreased somewhat in the 20-cm tillage group to 0.17 mg L^{-1} on day 12, and it remained nearly unchanged in the 10-cm tillage group at 0.34 mg L^{-1} on day 12 (Table 27). Day 15 data was excluded from this stage of the simulation due to unavailability of the ICP due to equipment maintenance. The 10-cm and 20-cm tillage groups had a reducing trend in mean SRP concentration and the no-till group had an increase in mean SRP (Figure 10).

Table 27. ***Ex Situ*** **tillage simulation mean soluble reactive phosphorus (SRP) concentration (mg L^{-1}) from cell 1 of Richland Creek WMA constructed wetland by sampling day. Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Tests.**

Tillage Depth (cm)	Sampling Day Mean 3	6	9	12	All
	-----(n=6)-----				(n=24)
	-----mg L^{-1}-----				
No Till	0.23	0.56	0.58	0.67	0.52a
10-cm Till	0.34	0.36	0.34	0.32	0.34ab
20-cm Till	0.24	0.19	0.16	0.17	0.19b

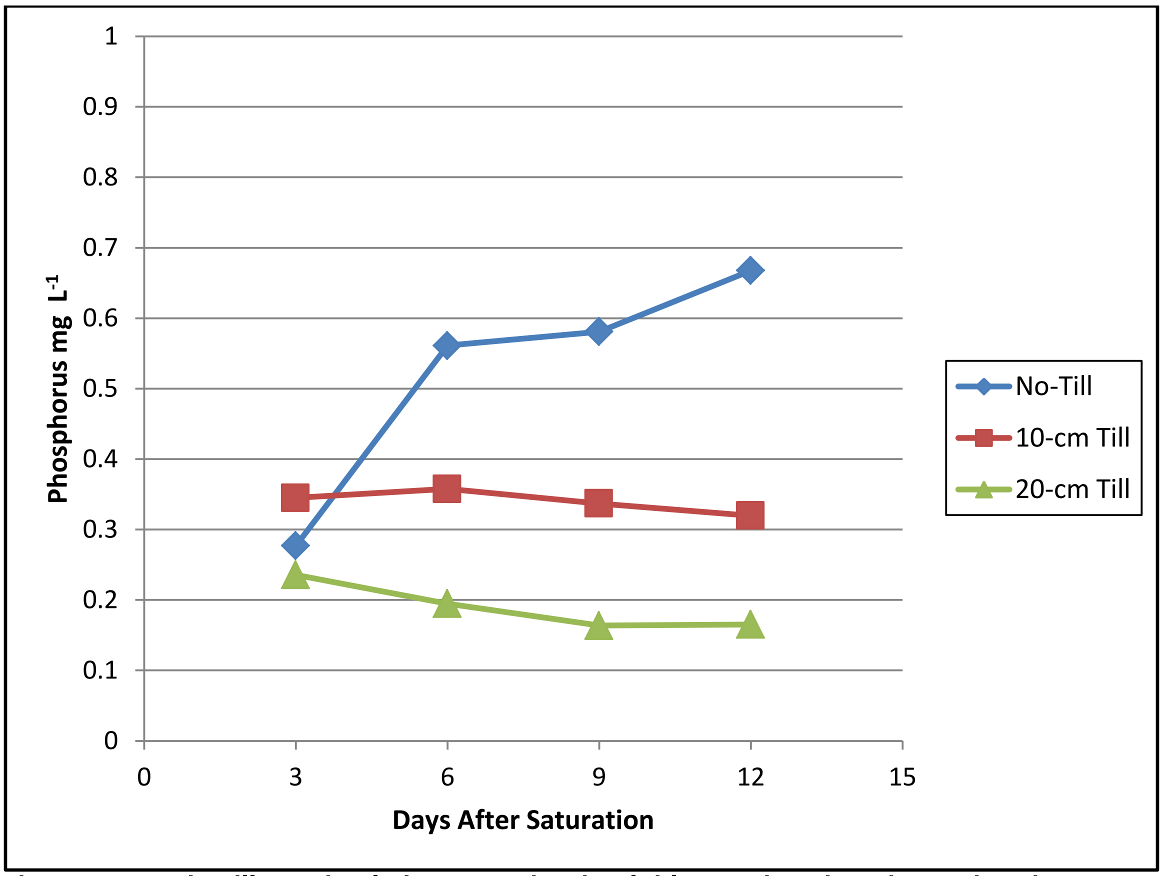

Figure 9. ***Ex Situ*** **tillage simulation mean (n=6) soluble reactive phosphorus (SRP) concentration (mg L^{-1}) versus days after saturation for Richland Creek WMA constructed wetland.**

The mean SRP concentration was significantly different ($P<0.05$) among the tillage treatments ($P=0.0073$), and among the tillage treatment and day ($P<0.0001$) (Appendix D).

Saturation with 2 mg P L^{-1}

The average water phosphorus (WP) concentrations (mg L^{-1}), collected every third day after saturation with 2 mg P L^{-1} water from three *ex situ* tillage depth (cm) groups (no-till, 10-cm, 20-cm), with each tillage group represented by six soil cores collected from cell 1 of Richland Creek WMA constructed wetland, ranged from 0.96 to 1.84 mg L^{-1} on day 3 in the 20-cm and no-till groups, respectfully. Fifteen days after the 2 mg P L^{-1} saturation, the WP concentration was reduced to 1.42 mg L^{-1} in the no-till, 0.72 mg L^{-1} in the 10-cm till, and 0.50 mg L^{-1} in the 20-cm tillage group (Table 28). The mean WP concentration generally decreased with each sampling day after saturation with the no-till, 10-cm till, and 20-cm till, respectively, showing a 29.1, 63.8, and a 74.8 percent added P removal from the water column at day 15 (Figure 10).

Table 28. ***Ex Situ*** **tillage simulation mean water phosphorus (WP) concentration (mg L^{-1}) from cell 1 of Richland Creek WMA constructed wetland by sampling day after the addition of 2 mg P L^{-1}. Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Tests.**

Tillage Depth (cm)	Sampling Day Mean 3	6	9	12	15	All
	----------(n=6)----------					(n=24)
	----------mg L^{-1}----------					
No Till	1.84	1.56	1.48	1.56	1.42	1.57a
10-cm Till	1.23	0.82	0.85	0.79	0.72	0.88b
20-cm Till	0.96	0.62	0.54	0.50	0.50	0.63b

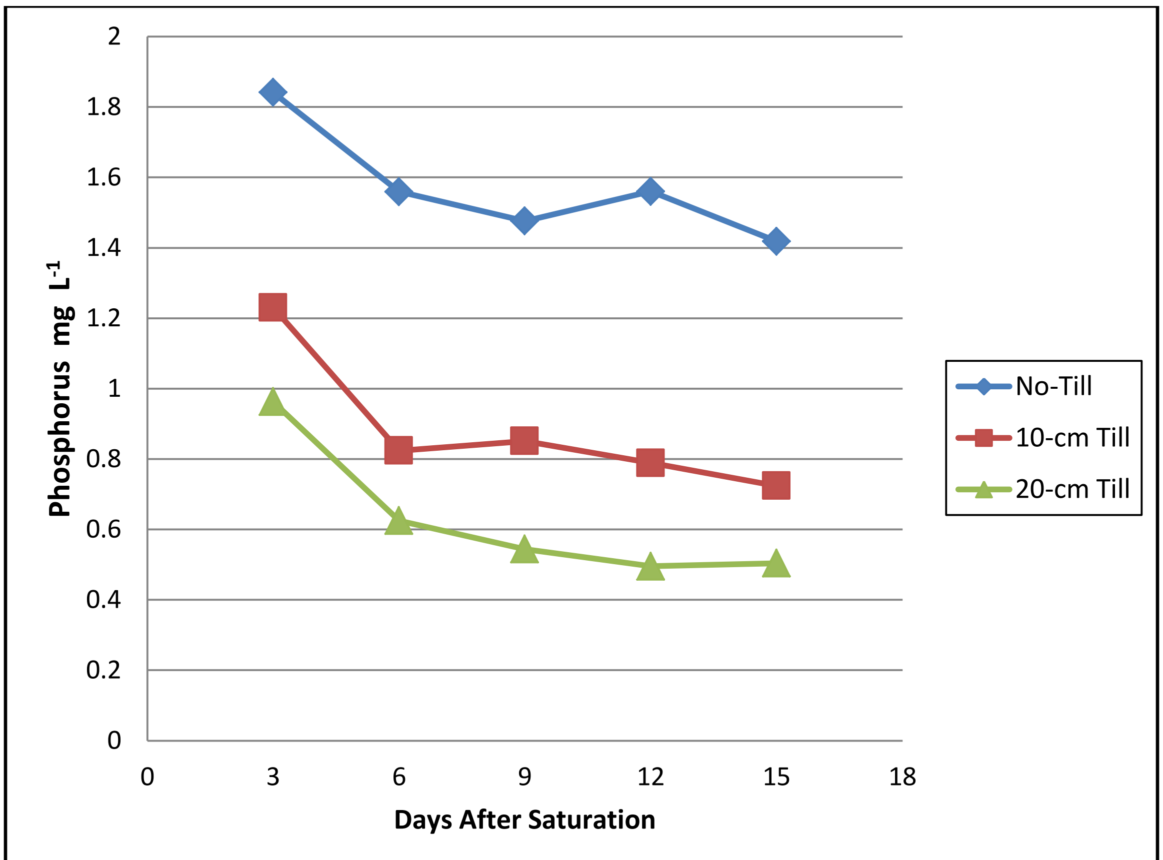

Figure 10. ***Ex Situ*** **tillage simulation mean (n=6) phosphorus concentration (mg L^{-1}) with 2 mg P L^{-1} versus days after saturation for Richland Creek WMA constructed wetland.**

The mean WP concentration after the 2 mg P L^{-1} addition was significantly different ($P<0.05$) among the tillage treatments ($P<0.0001$), and among the days after saturation ($P<0.0001$) (Appendix D).

Saturation with 75 mg P L^{-1}

The average water phosphorus (WP) concentrations (mg L^{-1}), collected every third day after saturation with 75 mg P L^{-1} water from three *ex situ* tillage depth (cm) groups (no-till, 10-cm, 20-cm), with each tillage group represented by six soil cores collected from cell 1 of Richland Creek WMA constructed wetland, ranged from 66.5 mg L^{-1} in the no-till group to 71.1 mg L^{-1} in the 10-cm tillage group. Fifteen days after the 75 mg P L^{-1} addition, the WP concentration decreased to 41.4 mg L^{-1} in the no-till group, 47.4 mg L^{-1} in the 10-cm tillage group and 49.1 mg L^{-1} in the 20-cm tillage treatment (Table 29). The mean WP concentration decreased with each sampling day after saturation with the no-till, 10-cm till, and 20-cm till, respectively, showed a 50.1, 42.9, 40.8 percent removal of added P from the water column at day 15 (Table 11).

Table 29. *Ex Situ* tillage simulation mean water phosphorus (WP) concentration (mg L^{-1}) from cell 1 of Richland Creek WMA constructed wetland by sampling day after the addition of 75 mg P L^{-1}.

Tillage Depth (cm)	Sampling Day Mean 3	6	9	12	15	All
	(n=6)					(n=24)
	mg L^{-1}					
No Till	66.5	57.8	53.2	51.2	41.4	54.0
10-cm Till	71.1	65.6	59.4	56.3	47.4	60.0
20-cm Till	69.8	68.3	60.4	59.7	49.1	61.5

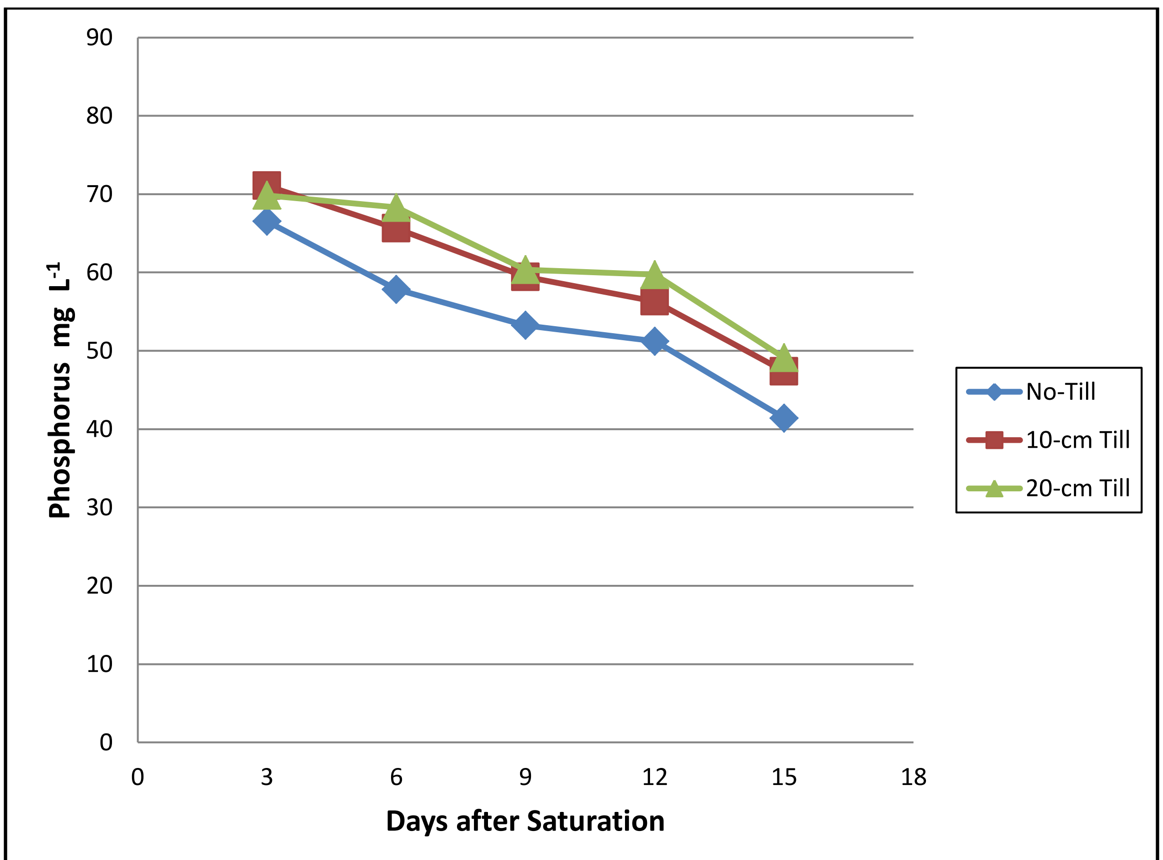

Figure 11. ***Ex Situ*** **tillage simulation mean (n=6) phosphorus concentration (mg L^{-1}) with 75 mg P L^{-1} versus days after saturation for Richland Creek WMA constructed wetland.**

The mean WP concentration after the 75 mg P L^{-1} addition was significantly different (P<0.05) among the days after saturation (P<0.0001) and among the tillage treatment and day (P=0.0042) (Appendix D).

Soil Phosphorus Results

Mehlich 3 Phosphorus

The average Mehlich 3 phosphorus (M3P) concentration (mg kg^{-1}) from 18 soil cores collected from cell 1 of Richland Creek WMA constructed wetland, that were divided equally into three tillage groups (no-till, 10-cm, 20-cm), ranged from 154 mg kg^{-1} in the 0-2 cm depth in the 20-cm tillage group to 248 mg kg^{-1} in the 10-cm tillage group. The mean M3P concentration generally decreased with depth, with a range in the 20-25 cm depth from 9 mg kg^{-1} in the no-till group to 25 mg kg^{-1} in the 20-cm tillage group (Table 30). With an increase in depth, all areas tested had a reducing trend in mean M3P concentration (Figure 12).

Table 30. *Ex Situ* tillage simulation mean Mehlich 3 phosphorus (M3P) concentration (mg kg^{-1}) from cell 1 of Richland Creek WMA constructed wetland by depth (cm) intervals. Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Test.

Depth (cm)	Total Mean (n=18)	No-till Mean (n=6)	10-cm Till Mean (n=6)	20-cm Till Mean (n=6)
	----------------------------------	--------------mg kg^{-1}	----------------------------------	
0-2	195a	182	248	154
2-4	127b	129	124	129
4-6	94bc	91	118	73
6-8	83c	69	106	74
8-10	74c	51	80	90
10-15	60cd	38	55	86
15-20	32de	19	43	34
20-25	18e	9	19	25

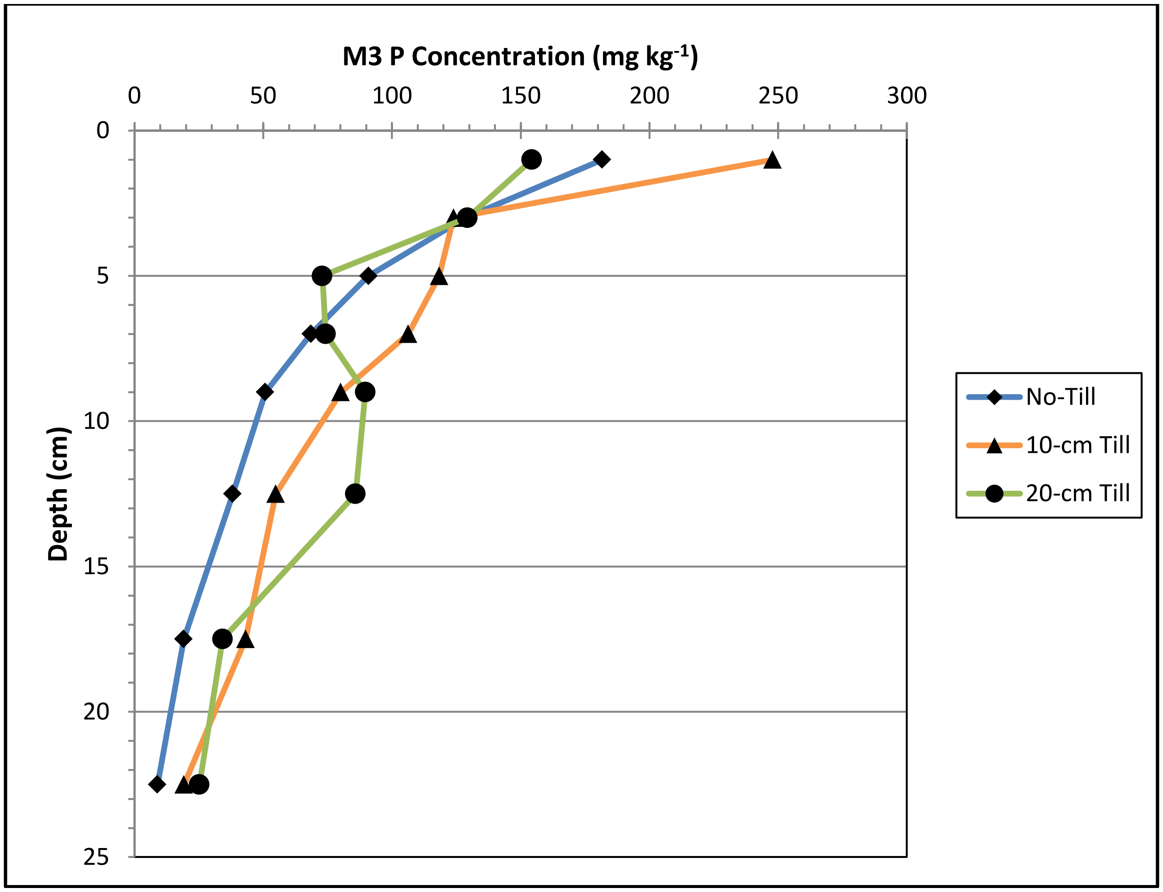

Figure 12. ***Ex situ* tillage simulation mean (n=6) Mechlich-3 phosphorus (M3 P) concentration (mg kg^{-1}) versus depth (cm) at Richland Creek WMA constructed wetland.**

The mean M3P concentration was significantly different (P<0.05) among the depths (P<0.0001) and among the tillage treatment and depth (P=0.0097) (Appendix D).

Total Phosphorus

The average total phosphorus (TP) concentration (mg kg^{-1}) from 18 soil cores collected from cell 1 of Richland Creek WMA constructed wetland, that were divided equally into three tillage groups (no-till, 10-cm, 20-cm), ranged from 950 mg kg^{-1} in the 0-2 cm depth in the 20-cm tillage group to 2103 mg kg^{-1} in the 10-cm tillage group. The mean TP concentration generally decreased with depth, with a range in the 20-25 cm depth from 451 mg kg^{-1} in the 20-cm tillage group to 630 mg kg^{-1} in the 10-cm tillage group (Table 31). With an increase in depth, all areas tested had a reducing trend in mean TP concentration (Figure 13).

Table 31. *Ex Situ* tillage simulation mean total phosphorus (TP) concentration (mg kg^{-1}) from cell 1 of Richland Creek WMA constructed wetland by depth (cm) intervals. Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Test.

Depth (cm)	Total Mean (n=18)	No-till Mean (n=6)	10-cm Till Mean (n=6)	20-cm Till Mean (n=6)
	------------------------------------mg kg^{-1}---------------------------------			
0-2	1499a	1444	2103	950
2-4	1098b	1172	1384	738
4-6	907bc	981	1059	680
6-8	933bc	897	1239	663
8-10	835bcd	914	847	743
10-15	755dec	696	880	688
15-20	568de	497	649	557
20-25	522e	485	630	451

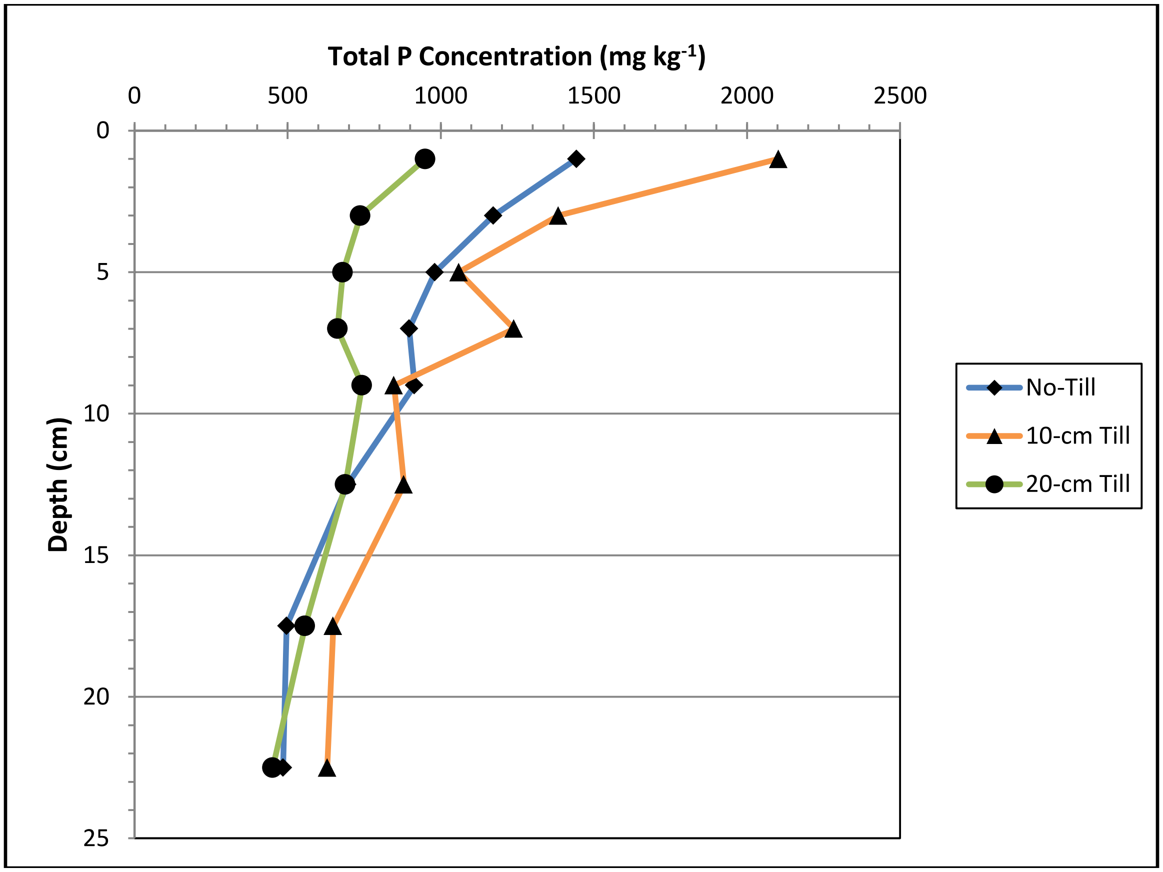

Figure 13. ***Ex situ*** **tillage simulation mean (n=6) total phosphorus (TP) concentration (mg kg^{-1}) versus depth (cm) at Richland Creek WMA constructed wetland.**

The mean TP concentration was significantly different (P<0.05) among the tillage treatments (P=0.0266), depths (P<0.0001) and among the tillage treatment and depth (P=0.0003). The mean TP concentration among the tillage treatments, compared using Tukey's Studentized Range (Tukey's) test, was significant at α<0.05 level between the 10-cm and 20-cm tillage groups, but neither is significantly different than the no-till treatment (Appendix D).

Phosphorus Sorption Index

The average phosphorus sorption index (PSI) concentration (mg kg^{-1}) from 18 soil cores collected from cell 1 of Richland Creek WMA constructed wetland, that were divided equally into three tillage groups (no-till, 10-cm, 20-cm), ranged from 416 mg kg^{-1} in the 0-2 cm depth in the 20-cm tillage group to 674 mg kg^{-1} in the no-till group. The mean PSI concentration did not increase significantly with depth, with a range in the 20-25 cm depth from 382 mg kg^{-1} in the 20-cm tillage group to 746 mg kg^{-1} in the no-till group (Table 32). With an increase in depth, all areas tested had a minimal change in mean PSI concentration (Figure 13).

Table 32. *Ex Situ* tillage simulation mean phosphorus sorption index (PSI) concentration (mg kg^{-1}) from cell 1 of Richland Creek WMA constructed wetland by depth (cm) intervals. Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Tests.

Depth (cm)	Total Mean (n=18)	No-till Mean (n=6)	10-cm Till Mean (n=6)	20-cm Till Mean (n=6)
	---------------mg kg^{-1}---------------			
0-2	544b	674	542	416
2-4	586ab	728	569	461
4-6	628ab	778	587	518
6-8	631a	792	594	509
8-10	634a	799	594	508
10-15	629a	802	553	533
15-20	571ab	746	544	422
20-25	565ab	746	565	382

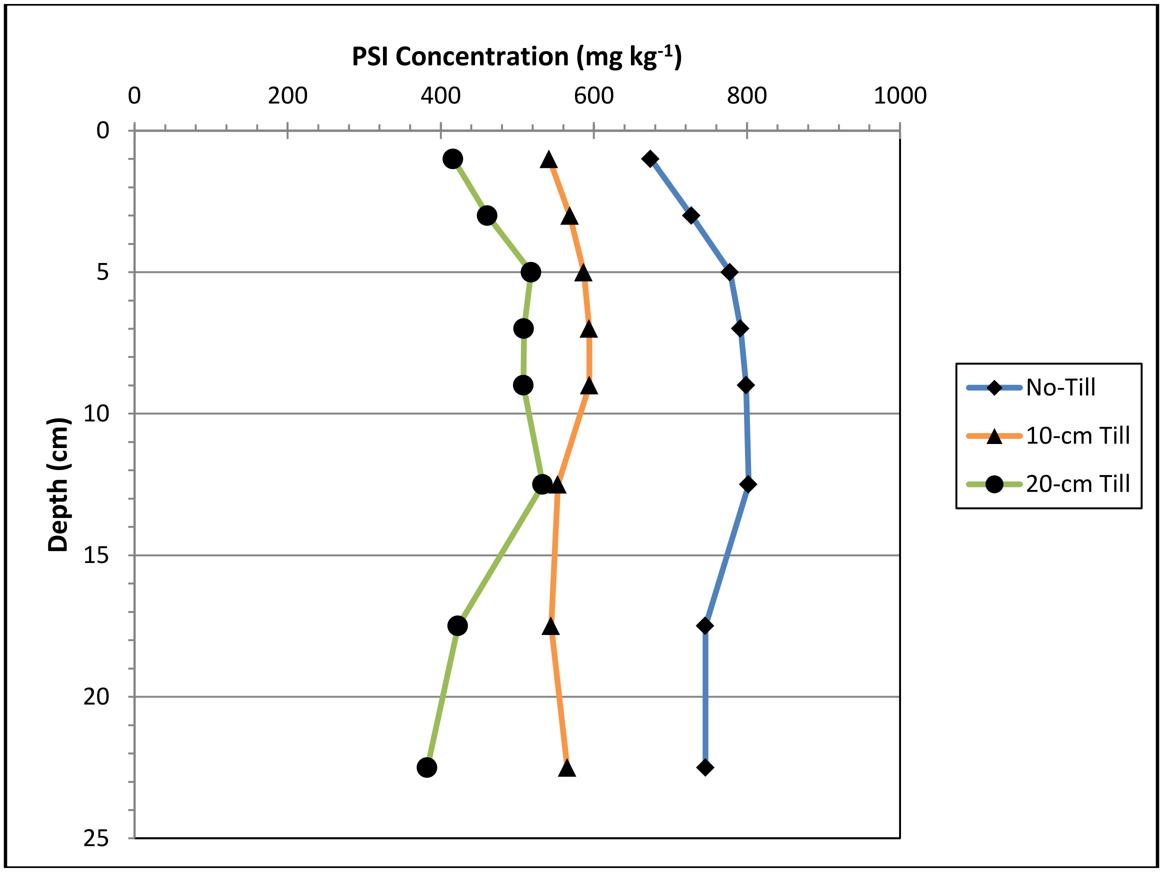

Figure 14. ***Ex situ*** **tillage simulation mean (n=6) phosphorus sorption index (PSI) concentration (mg kg^{-1}) versus depth (cm) for Richland Creek WMA constructed wetland**

The mean PSI concentration was significantly different (P<0.05) among the tillage treatments (P=0.0211) and depths (P=0.0018). The mean PSI concentration among the tillage treatments, compared using Tukey's Studentized Range (Tukey's) test, was significant at α<0.05 level between the no-till and 20-cm tillage groups, but neither is significantly different than the 10-cm tillage treatment (Appendix D).

Discussion

The first phase of the tillage simulation yielded soluble reactive P (SRP). SRP includes water extractable P (WEP) and is readily available for plant uptake (Bostic and White 2007). SRP has the potential to be released into the overlying floodwater, such as during the flooding phase of moist soil management (MSM) or the DI water used in this simulation, when concentrations of P in the soil pore water exceed concentrations of P in the floodwater (Dunne et al. 2005). SRP concentrations were highest in the no-till group, where it reached a mean of 0.67 mg L^{-1} twelve days after saturation, which is more than double the SRP concentration of 0.32 mg L^{-1} in the 10-cm tillage group, and more than triple the 0.17 mg L^{-1} for the 20-cm tillage group (Table 27).

The second phase of the tillage simulation yielded a reduction in the 2 mg P L^{-1} solution that was added to the soil column after the DI was siphoned and discarded. The 2 mg P L^{-1} concentration was chosen in order to replicate the P concentration in the Trinity R. water, which is approximately 1 mg L^{-1}, but it was doubled, in order to detect change over a broader range. The 20-cm tillage group proved to be the most efficient at reducing the water P (WP) concentration with 74.8% removal and the no-till proved to be the least efficient by removing only 29.1% of the WP. The WP was reduced to concentrations similar to those reported by Tarrant Regional Water District (TRWD) for the efficiency of the wetland system to remove total P (TP) and orthophosphates (OP) (Tables 17-20). The Tukey's test did not identify a significant difference (α=0.05) between the 10- and 20-cm tillage groups, but both tillage groups are significantly different from the no-till group (Table 28).

The third phase of the tillage simulation represented an extreme saturation of the soil column with a 75 mg P L^{-1} solution that was added after the 2 mg P L^{-1} was siphoned and discarded. Each group was efficient at removing P from the water column and no significant difference (α=0.05) among treatments was determined (Appendix D). The no-till was most efficient with 44.8% removal and the 20-cm tillage least efficient with 34.5% removal of P from the water column (Table 11).

The soil's P removal efficiency of the extreme saturation with 75 mg P L^{-1}, is evident in the Mehlich 3 P (M3P) concentrations (mg kg^{-1}) near the surface horizon. The mean M3P was 119 mg kg^{-1} at 0-2 cm and 108 mg kg^{-1} at 2-4 cm (Table 5). Post-tillage simulation produced a mean in the no-till group of 182 mg kg^{-1} at 0-2 cm and 129 mg kg^{-1} at 2-4 cm (Table 30) and then trends to similar concentrations found with an increase in depth (Table 5). The 10-cm tillage group had a mean M3P of 248 mg kg^{-1} at 0-2 cm and maintained a concentration great than 100 mg kg^{-1} until the 80 mg kg^{-1} at 8-10 cm (Table 30). The 20-cm tillage group had a mean M3P of 154 mg kg^{-1} at 0-2 cm and experienced a sharp decline from 86 mg kg^{-1} at 10-15 cm to 34 mg kg^{-1} at 15-20 cm (Table 30). The increased concentrations in the 10- and 20-cm tillage groups with an increase in depth indicated more vertical flow of P than in the no-till group. The increased vertical distribution of labile P enhances plant growth productivity, especially during the water draw down phase of moist-soil management (Malecki et al. 2004). An upward movement of nutrients should be expected through repetition of the plant cycle, unless the plant biomass is removed or a tillage cycle continued (Jobbágy and Jackson 2001).

Total P (TP) concentrations from the no-till group nearly replicate TP concentrations throughout depth of cell 1 from the field study (Table 9, Table 31). The Tukey's test indicated that the no-till TP concentration had no significant difference (α=0.05) among the tillage groups, but that the tillage groups had a significant difference from each other (Appendix D). Throughout depth, the 10-cm tillage group had the highest mean TP concentration of 1099 mg kg^{-1}, whereas the 20-cm tillage group had the lowest mean TP concentration of 681 mg kg^{-1} (Appendix D).

The P sorption index (PSI) values are not valid due to the extreme saturation event with 75 mg P L^{-1} during the tillage simulation, but they still have relevancy. The PSI values are highest in the no-till group, with a mean value from all depths of 758 mg kg^{-1}. The no-till group, using a Tukey's test, is significantly different from the 20-cm tillage group but not the 10-cm tillage group, which respectively have a PSI value of 469 mg kg^{-1} and 569 mg kg^{-1} (Appendix

D). The PSI values indicate that the 20-cm tillage group is the closest to potential saturation, but with an increase in depth, it has more plant available P than the other two tillage groups (Table 30). The higher PSI values in the no-tillage group indicate that it is further from potential saturation, and also that it had less readily available P for plant uptake (Table 30) (Horáček et al. 2008).

Conclusion

The *ex situ* tillage simulation water column study indicated that the soluble reactive P (SRP), which has potential to be released during moist-soil management (MSM), was highest in the no-till group (Table 27). The no-till group was also least efficient (29.1%) and significantly different (α=0.05) from the 10- and 20-cm tillage groups (Appendix D) at removing P from the water column when spiked with a 2 mg P L^{-1} solution (Table 28). The extreme saturation with 75 mg P L^{-1} identified the no-till group as the most efficient (44.8%) removal efficiency but there was no significant difference among the groups (Appendix D). Therefore, the water column study indicated the tillage treated soil released less SRP (Table 27), were more efficient at removing P from a 2 mg P L^{-1} solution (Table 28), and just as efficient at removing P from a 75 mg P L^{-1} solution (Table 29) as the no-till group.

The *ex situ* tillage simulation soil core analysis indicated higher Mehlich 3 P (M3P) in the 0-2 and 2-4 cm depths than those found in cell 1 from the field study, and with an increase in depth, the tillage groups maintained a higher M3P than the no-till group (Table 5, Table 30). The increased M3P in the 0-2 and 2-4 cm depths was presumably linked to the removal efficiencies of the soil columns during the extreme saturation with 75 mg P L^{-1} solution during the water column study. Even though there was a significant difference (α=0.05) between the 10- and 20-cm tillage groups in total P (TP) concentration, neither group was significantly different than the no-till group (Appendix D), which nearly replicated TP concentrations found in cell 1 from the field study (Table 9, Table 31). The P sorption index (PSI) values, which may not be accurate, still provided information in the extreme saturation during the water column study, and indicated that the no-till group was furthest from a potential saturation, but that it also had less readily available P at depth (Table 32). Therefore, tillage may provide plants during MSM more readily available P for enhanced growth, while also improving efficiency at removing P from the water column.

IN SITU TILLAGE SIMULATION

Results

The average soil phosphorus (P) concentrations (mg kg^{-1}), from 3 soil cores collected pre- and post-tillage from each of 3 locations within cell 1 of Richland Creek WMA constructed wetland showed minimal change in concentration pre- and post-tillage. Mehlich 3 P (M3P) concentration increased slightly post-tillage at all depth intervals compared to pre-tillage concentrations. Water extractable P (WEP) concentration decreased somewhat post-tillage in the 0-2 cm depth interval from 12.3 mg kg^{-1} pre-tillage to 9.4 mg kg^{-1} post-tillage, but overall, it remained relatively unchanged post-tillage from pre-tillage concentrations. Total P (TP) concentration decreased somewhat post-tillage in the 0-2 cm depth interval from 1330 mg kg^{-1} pre-tillage to 977 mg kg^{-1} post-tillage, but overall, it remained relatively unchanged post-tillage from pre-tillage concentrations. The P sorption index (PSI) value increased slightly post tillage at all depth intervals compared to pre-tillage values, but overall, it remained relatively unchanged (Table 33). None of the soil P tests had a significant difference between concentration pre- and post-tillage (Appendix F).

Table 27. ***In*** **Situ pre-tillage (Pre-) and post-tillage (Post-) mean Mehlich 3 phosphorus (M3P), water extractable P (WEP), total P (TP), and P sorption index (PSI) concentrations (mg kg^{-1}) by depth (cm) intervals, for Richland Creek WMA constructed wetland.**

Depth (cm)	M3P Mean		WEP Mean		TP Mean		PSI Mean	
	Pre- (n=9)	Post- (n=9)	Pre- (n=3)	Post- (n=9)	Pre- (n=3)	Post- (n=9)	Pre- (n=3)	Post- (n=9)
	---------------------------------------mg kg^{-1}---							
0-2	102	107	12.3	9.4	1330	977	486	643
2-4	81	95	6.3	6.2	856	857	507	658
4-6	71	77	5.0	5.3	805	774	519	642
6-8	51	68	8.2	3.9	717	677	530	675
8-10	49	59	3.3	3.6	699	641	484	634
10-15	36	45	2.4	3.3	575	538	420	623
15-20	29	31	2.2	2.5	506	433	467	630
20-25	16	25	1.6	2.3	413	406	545	660
25-30	12	16	1.3	1.9	---	---	540	620
30-35	10	11	1.0	1.4	---	---	528	628

Discussion

Post-tillage soil P concentrations revealed minimal change compared to pre-tillage soil P concentrations. Field observations of tillage depth generated from the tillage equipment used by TPWD penetrated to no deeper than 5 cm. The lack of tillage depth does not compare well to the 10- and 20-cm tillage depths in the *ex situ* tillage simulation experiment.

Conclusion

In order to achieve results similar to those generated from the *ex situ* tillage simulation study (Appendix D), similar field tillage depth needs to be reached. With no significant differences between the *in situ* pre- and post-tillage soil P concentrations generated (Appendix F), and significant differences occurring among tillage depth treatments of the *ex situ* soil P concentrations (Appendix D), it was evident that a deeper tillage depth has potential to distribute P more evenly throughout depth in the soil column. The field tillage study should be repeated with a plow that cuts deeper than the disc harrow used in this work.

CONCLUSIONS AND RECOMMENDATIONS

Phosphorus (P) loading in the soil at Richland Creek WMA constructed wetland was more concentrated in the sedimentation basin (SB) and cell 1 of the wetland system than in cell 3 or the reference wetland (RW). Mehlich 3 P (M3P), P that is readily available for plant use, concentration was nearly double the threshold for no additional fertilizer recommendations for agriculture of 60 mg kg^{-1} in the SB and cell 1 (Table 5, Appendix C). Water extractable P (WEP), the highly mobile P, concentrations were highest in the SB and cell 1 and were significantly different than cell 3 and the RW (Table 7, Table 8). Total P (TP) concentrations were comparable to other treatment wetland systems, such as the Tres Rios, Arizona or Houghton Lake, Michigan wetland systems (Kadlec and Wallace 2009), that receive high quantities of P from the water column and the highest concentrations were found in the SB, cell 1 and cell 3 (Table 9). The P sorption index (PSI), a measure of the soil's potential P fixing capacity, identified the SB and cell 1, the areas with consistently higher soil P concentrations, as the areas with the least potential P fixing capacity remaining (Table 12).

The wetlands efficiency at removing nutrients from the water is linked to the nutrient accumulation in the wetland's soils. The wetland cells with the highest estimated total suspended solids (TSS) loading, based on Tarrant Regional Water District (TWRD) data, also had higher soil P concentrations. The establishment of plant species through moist-soil management (MSM), has the potential to remove nutrients from the water column efficiently, but also has the potential to re-release P previously sequestered in the soil column. Even though the annual expected nutrient loading per unit area for the wetland after completion of phase III is projected to be less than during phase I, solutions to prolong the effectiveness of the wetland, such as tillage or biomass removal, should be considered.

The soil P concentrations were representative of roughly ten years of nutrient loading from Trinity River (TR) water. Throughout the completion of Phase I, sporadic TR flow data into the wetland system from downtime caused by construction, maintenance, MSM, and over bank flooding from the TR, resulted in an unquantifiable amount of P entering the wetland system. The P concentrations in the SB and cell 1 illustrate that the effectiveness and longevity of the treatment wetland system is an area of concern, but without a quantifiable P loading rate from TR water, the time frame for Kadlec and Wallace's (2009) "hydrologic burnout" is difficult to determine. Sediment traps throughout the wetland cells and better flow records would aid in determining P loading rates. Hydrologic burnout could also be delayed by remediating, possibly with tillage, any hot spots or areas of high soil P concentration, after establishing a soil P grid.

The *ex situ* tillage simulation water column study indicated that the soluble reactive P (SRP), which has potential to be released during MSM, was highest in the no-till group (Table 27). The no-till group was also least efficient (29.1%) and significantly different (α=0.05) from the 10- and 20-cm tillage groups (Appendix D) at removing P from the water column when spiked with a 2 mg P L^{-1} solution (Table 28). The extreme saturation with 75 mg P L^{-1} identified the no-till group as the most efficient (44.8%) removal efficiency but there was no significant difference among the groups (Appendix D). Therefore, the water column study indicated the tillage groups released less SRP (Table 27), were more efficient at removing P from a 2 mg P L^{-1} solution (Table 28), and just as efficient at removing P from a 75 mg P L^{-1} solution (Table 29) as the no-till group.

The *ex situ* tillage simulation soil core analysis indicated higher M3P in the 0-2 and 2-4 cm depths than those found in cell 1 from the field study, and with an increase in depth, the tillage groups maintained a higher M3P than the no-till group (Table 5, Table 30). The increased M3P in the 0-2 and 2-4 cm depths was presumably linked to the removal efficiencies of the soil columns during the extreme saturation with 75 mg P L^{-1} solution during the water column study. Even though there was a significant difference (α=0.05) between the 10- and 20-cm tillage groups in TP concentration, neither group was significantly different than the no-till group (Appendix D), which nearly replicated TP concentrations found in cell 1 from the field study (Table 9, Table 31). The PSI values, which may not be accurate, still provided information in the extreme saturation during the water column study, and indicated that the no-till group was furthest from a potential saturation, but that it also had less readily available P at depth (Table 32). Therefore, tillage may provide plants during MSM more readily available P for enhanced growth, while also improving efficiency at removing P from the water column.

In order to achieve results similar to those generated from the *ex situ* tillage simulation study (Appendix D), similar field tillage depth needs to be reached. With no significant differences between the *in situ* pre- and post-tillage soil P concentrations generated (Appendix F), and significant differences occurring among tillage depth treatments of the *ex situ* soil P concentrations (Appendix D), it is evident that a deeper tillage depth has potential to distribute P more evenly throughout depth in the soil column. The field tillage study should be repeated with a plow that cuts deeper than the disc harrow used in this work.

LITERATURE CITED

Almendinger, J.E. 1999. A Method to Prioritize and Monitor Wetland Restoration for Water-Quality Improvement. Wetlands Ecology and Management 6:241-251.

Bache, B.W., and E.G. Williams. 1971. A Phosphate Sorption Index for Soils. Journal of Soil Science of America. 22:289-301.

Benyamine, M., M. Bäckström, and P. Sandén. 2004. Multi-Objective Environmental Management in Constructed Wetlands. Environmental Monitoring and Assessment 90:171-185.

Blevins, D.W., 2004. Hydrology and Cycling of Nitrogen and Phosphorus in Little Bean Marsh: A Remnant Riparian Wetland Along the Missouri River in Platte County, Missouri, 1996-1997: U.S. Geological Survey Scientific Investigations Report 2004-5171, 80 p.

Bostic, E. M., and J. R. White. 2007. Soil Phosphorus and Vegetation Influence on Wetland Phosphorus Release after Simulated Drought. Soil Science Society of America Journal 71:238-244.

Compton, J., D. Mallinson, C.R. Glenn, G. Filippelli, K. Föllmi, G. Shields, and Y. Zann. 2000. Variations in the Global Phosphorus Cycle. Society for Sedimentary Geology 66:21-33.

Correll, David L. 1998. The Role of Phosphorus in the Eutrophication of Receiving Waters: A Review. Journal of Environmental Quality 27:261-266.

Daroub, Samira H., Argyrios Gerakis, Joe T. Ritchie, Dennis K. Friesen, and John Ryan. 2003. Development of a Soil-Plant Phosphorus Simulation Model for Calcareous and Weathered Tropical Soils. Agriculture Systems 76:1157-1181.

Dunne, E.J., N. Culleton, G. O'Donovan, R. Harrington, and K. Daly. 2005. Phosphorus Retention and Sorption by Constructed Wetland Soils in Southeast Ireland. Water Research 39:4355-4362.

Fisher, M.M., and K. R. Reddy. 2001. Phosphorus Flux from Wetland Soils Affected by Long-Term Nutrient Loading. Journal of Environmental Quality. 30:261-271.

Frossard, Woody, Darrel Andrews, Alan H. Plummer, and Loretta Mokry. 2006. "Over The River and Through The Plants To Richland Chambers We Go." WEFTEC: 4714-4726.

Gardiner, Duane T., and Raymond W. Miller. 2008. *Soils in our Environment*. 11th ed. New Jersey: Pearson Education.

Horáček, J., L. Kolář, V. Ćechová, and J. Hŕebečková. 2008. Phosphorus and Carbon Fraction Concentrations in a Cambisol Soil as Affected by Tillage. Communications in Soil Science and Plant Analysis 39: 2032-2045.

Jobbágy, Esteban G., and Robert B. Jackson. 2001. The Distribution of Soil Nutrients with Depth: Global patterns and the imprint of Plants. Biogeochemistry 53: 51-77.

Jones, J. Benton, Jr., ed. 1999. *Soil Analysis Handbook of Reference Methods.* Soil and Plant Analysis Council, INC.

Kadlec, Robert H. 2005. Phosphorus Removal in Emergent Free Surface Wetlands. Journal of Environmental Science and Health 40:1293-1306.

Kadlec, Robert H., Scott D. Wallace. 2009. *Treatment Wetlands.* 2nd ed. Boca Raton, FL: CRC Press.

Lewis, Jeffrey, Jan Sjöstrom. 2010. Optimizing the Experimental Design of soil Columns in Saturated and Unsaturated Transport Experiments. Journal of Contaminant Hydrology 115: 1-13.

Liikanen, Anu, Markku Puustinen, Jari Koskiaho, Tero Väisnen, Pertti Martikainen, and Helin Hartikainen. 2004. Phosphorus Removal in a Wetland Constructed on Former Arable Land. Journal of Environmental Quality 33:1124-1132.

Malecki, Lynette M., John R. White, and K. R. Reddy. 2004. Nitrogen and Phosphorus Flux Rates from Sediment in the Lower St. Johns River Estuary. Journal of Environmental Quality 33:1545-1555.

Mayer, T., F. Rosa, and M. Charlton. 2005. Effect of Sediment Geochemistry on the Nutrient Release Rates in Cootes Paradise Marsh, Ontario, Canada. Aquatic Ecosystem Health & Management 8(2):133-145.

Mehlich, A.1984. Mehlich-3 soil test extractant: A modification of Mehlich-2 extractant. Communications in Soil Science and Plant Analysis 15:1409–1416.

Meissner, R., P. Leinweber, H. Rupp, M. Shenker, M. Litaor, S. Robinson, A. Schlichting, and J. Koehn. 2008. Mitigation of Diffuse Phophorus Pollution during Rewetting of Fen Peat Soils: A Trans-European Case Study. Water, Air, Soil Pollution 188:111-126.

Mitchell, D. S., A. J. Chick, and G. W. Raisin. 1995. The Use of Wetlands for Water Pollution Control in Australia: an ecological perspective. Water Science and Technology 32:365-373.

Mitsch, W.J. and Gosselink, J.G. 2000. *Wetlands,* 3rd ed. New York: John Wiley & Sons.

Mitsch, William J., Li Zhang, Kay C. Stefanik, Amanda M. Nahlik, Christopher J. Anderson, Blanca Bernal, Maria Hernandez, and Keunyea Song. 2012. Creating Wetlands: Primary Succession, Water Quality Changes, and Self-Design over 15 years. BioScience 62:237-250.

Mokry, Loretta E., and Ellen T. McDonald. 2010. Constructed Wetlands, Water Reuse, and Water Supply. Arizona Hydrologic Society 2010 symposium.

Morris, Gregory L. and Jiahua Fan. 1997. *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use.* McGraw-Hill.

Nahlik, Amanda M., and William J. Mitsch. 2008. The Effect of River Pulsing on Sedimentation and Nutrients in Created Riparian Wetlands. Journal of Environmental Quality 37: 1634-1643.

Nair, V. D., and W. G. Harris. 2004. A Capacity Factor as an Alternative to Soil Test Phosphorus in Phosphorus Risk Assessment. New Zealand Journal of Agricultural Research47:491-497.

Novak, J.M., K.C. Stone, A.A. Szogi, D.W. Watts, and M.H. Johnson. 2004. Dissolved Phosphorus Retention and Relase from a Coastal Plain In-Stream Wetland. Journal of Environmental Quality 33:394-401.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. P. 403-430 *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agronomy Monogr. 9. ASA and SSSA, Madison, WI.

Pant, H.K., K.R. Reddy. 2001. Hydrologic Influence on Stability of Organic Phosphorus in Wetland Detritus. Journal of Environmental Quality 30:668-674.

Peifang, W. and W. Chao. 2007. Nutrients Removing by Arrowheads in Different Growing Periods in the Transition Zone between Lands and Rivers. Water Resources 34:471-477.

Poach, M. E. and S. P. Faulkner. 2007. Effect of River Sediment on Phosphorus Chemistry of Similarly Aged Natural and Created Wetland sin the Atchafalaya Delta, Louisiana, USA. Journal of Environmental Quality 36:1217-1223.

Region C Water Planning Group. 2011 Region C Water Plan. 2010. http://www.regioncwater.org/Documents/index.cfm?Category=2011+Region+C+Water+Plan. Accessed: 19 October 2010.

Self-Davis, M.L., P.A. Moore, Jr., and B.C. Joern. 2009. Water-or Dilute Salt-Extractable Phosphorus in Soil. Southern Cooperative Series Bulletin, 408: 22-24.

Seo, Dong Cheol, Ju Sik Cho, Hong Jae Lee, and Jong Soo Heo. 2005. Phosphorus Retention Capacity of filter Media for Estimating the Longevity of Constructed Wetland. Water Research 39:2445-2457.

Sharpley, A. N. 1982. Prediction of Water-Extractable Phosphorus Content of Soil Following a Phosphorus Addition. Journal of Environmental Quality 11(2):166-170.

Sharpley, Andrew N. 1995. Soil Phosphorus Dynamics: Agronomic and Environmental Impacts. Ecological Engineering 5:261-279.

Sims, J. T. 1989. Comparison of Mehlich-1 and Mehlich-3 extractants for P, K, Ca, Mg, Mn, Cu and Zn in Atlantic Coastal plain soils. Communications in Soil Science and Plant Analysis 20:1707–1726.

Sims, J. Thomas. 2009. A Phosphorus Sorption Index. Southern Cooperative Series Bulletin, 408:20-21.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. 2009. Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/. Accessed: 22 July 2010. .

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Official Soil Series Descriptions. 2010. http://soils.usda.gov/technical/classification/osd/index.html. Accessed: 22 May 2010. USDA-NRCS, Lincoln, NE.

Strader, Robert W. and Pat H. Stinson. 2005. Moist-Soil Management Guidelines for the U.S. Fish and Wildlife Service Southeast Region. http://www.fws.gov/columbiawildlife/MoistSoilReport.pdf. Accessed: 21 October 2010. USFWS, Jackson, MS.

Surridge, Ben W.J., A.L. Heathwaite, and A. J. Baird. 2007. The Release of Phosphorus to Porewater and Surface Water from River Riparian Sediments. Journal of Environmental Quality 36:1534-1544.

Thomas, G.W. 1996. Soil pH and Soil Acidity. In J.M. Bigham (Ed.), Methods of Soil analysis: Part 3 Chemical Methods. p. 475-490. Madison, WI: Soil Science Society of America.

TPWD (Texas Parks and Wildlife Department). 2009. Richland Creek WMA. http://www.tpwd.state.tx.us/huntwild/hunt/wma/find_a_wma/list/?id=23. Accessed: 23 August 2010.

TRWD (Tarrant Regional Water District) 2002. Richland-Chambers Wetlands Water Reuse Project: Integrated Water Supply and Wildlife Habitat Project. Tarrant Regional Water District, Fort Worth, TX, USA.

TRWD (Tarrant Regional Water District) 2010. http://www.trwd.com/home.aspx. Accessed: 6 September 2010.

TWDB (Texas Water Development Board). 2010. Water Resources Planning and Information. http://www.twdb.state.tx.us/wrpi/. Accessed: 3 September 2010.

USCB (United States Census Bureau) Census 2010 Data for the State of Texas; Population by County, Population by Place. http://factfinder2.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=DEC_10_PL_GCTPL1.ST05&prodType=table . Accessed: 10 May 2011.

USEPA (United States Environmental Protection Agency) 1996. Method 3050B-Acid Digestion of Sediments, Sludges, and Soils. http://www.epa.gov/osw/hazard/testmethods/sw846/pdfs/3050b.pdf. Accessed: 8 April 2011.

USGS (United States Geological Survey) 2000. Comparability of Suspended-Sediment Concentration and Total Suspended Solids. Water Resources Investigations Report 00-4191.

Wetzel, R.G. 2001. Limnology: Lake and River Ecosystems, 3rd ed. Academic Press.

Zar, Gerrold H., 2010, Biostatistical Analysis, 5th Ed., Prentice Education Inc., New Jersey, pp. 226- 287.

APPENDIX A

The following data correlates to the field study section. The sample ID's four digits respectfully identifies the cell, location, transect repetition, and depth. For example, sample ID 1230, the first digit identifies the cell as cell 1 (5 = reference wetland, 9 = sedimentation basin). The second digit identifies that it was the second sample location in cell 1. The third digit labels it as the third or final sample on the transect. The fourth digit identifies depth of sample, with 0 being the surface horizon and 9 being the 30-35 cm sample from the soil core. All values are mg kg^{-1}.

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
1110	78.3				
1111	70.6				
1112	79.3				
1113	36.7				
1114	39.0				
1115	31.9				
1116	19.2				
1117	17.5				
1118	14.0				
1119	13.5				
1120	107.3	22.0	1828.5	748.9	6.9
1121	37.3	5.2	666.7	624.5	6.9
1122	33.9	3.1	584.1	622.9	7.2
1123	28.7	2.8	581.4	564.4	7.3
1124	29.9	4.0	576.8	591.7	7.2
1125	20.9	2.3	511.7	516.4	7.2
1126	17.5	2.0	506.6	436.9	7.9
1127	14.1	2.1	466.2	470.4	8.0
1128	14.8	2.1		450.4	7.9
1129	10.2	1.7		444.8	8.0

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
1130	95.5				
1131	51.3				
1132	42.5				
1133	43.1				
1134	33.2				
1135	26.2				
1136	16.2				
1137	8.7				
1138	6.4				
1139	5.5				
1210	156.8				
1211	146.3				
1212	109.1				
1213	92.9				
1214	81.3				
1215	66.3				
1216	46.4				
1217	30.6				
1218	13.9				
1219	6.7				
1220	107.9	9.4	1487.0	528.2	7.7
1221	87.6	5.9	1145.5	465.7	8.2
1222	68.1	2.7	747.9	381.7	8.1
1223	63.4	13.4	811.9	319.0	8.2
1224	62.8	4.9	1003.0	320.7	8.0
1225	46.6	2.7	729.6	793.2	8.0
1226	29.4	3.0	540.5	473.0	8.0
1227	11.1	1.4	449.7	419.3	8.2
1228	7.2	1.4		391.4	8.1
1229	7.2	1.5		401.6	8.2
1230	147.8				
1231	109.3				
1232	105.4				
1233	108.4				
1234	113.0				
1235	83.0				
1236	44.1				
1237	41.3				
1238	36.8				
1239	27.6				
1310	92.1				
1311	128.7				

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
1312	111.4				
1313	70.6				
1314	40.6				
1315	27.1				
1316	28.7				
1317	21.6				
1318	13.7				
1319	19.4				
1320	102.2	2.3	801.7	460.9	7.6
1321	92.1	2.1	739.2	503.9	7.8
1322	72.3	2.0	645.9	502.8	7.7
1323	20.8	10.8	486.2	598.5	7.8
1324	18.5	1.8	470.6	467.5	7.9
1325	11.8	1.2	448.7	564.5	7.7
1326	10.7	1.1	427.7	582.4	6.8
1327	11.6	1.0	417.8	574.5	8.2
1328	12.9	1.2		572.5	8.0
1329	13.9	0.8		582.0	7.9
1330	109.0				
1331	100.4				
1332	74.4				
1333	55.4				
1334	79.9				
1335	24.0				
1336	7.3				
1337	6.1				
1338	6.1				
1339	6.5				
1410	117.0				
1411	96.3				
1412	85.3				
1413	77.3				
1414	82.7				
1415	87.3				
1416	74.6				
1417	33.7				
1418	25.3				
1419	14.9				
1420	139.2	12.7	1361.0	248.1	7.3
1421	82.3	11.7	1162.0	391.8	7.4
1422	83.0	9.7	1186.0	430.7	7.6
1423	58.9	11.2	1082.0	426.9	7.7

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
1424	59.0	4.1	1051.0	393.9	8.8
1425	67.5	3.7	766.1	177.7	7.9
1426	64.3	3.5	584.5	380.8	7.9
1427	21.1	1.8	353.7	590.4	7.7
1428	3.7	0.5		598.3	7.4
1429	3.3	0.5		556.1	7.8
1430	76.5				
1431	73.2				
1432	60.5				
1433	65.0				
1434	60.8				
1435	26.5				
1436	20.2				
1437	10.3				
1438	7.3				
1439	6.2				
1510	90.0				
1511	78.2				
1512	62.7				
1513	53.6				
1514	46.2				
1515	38.0				
1516	25.7				
1517	17.8				
1518	19.0				
1519	13.8				
1520	98.4	10.1	1427.5	601.0	7.1
1521	133.5	20.4	1801.5	460.2	7.2
1522	64.1	5.0	904.4	451.7	6.7
1523	48.1	11.2	743.2	471.3	7.4
1524	52.5	5.3	891.0	462.8	6.9
1525	36.1	2.3	534.8	449.6	7.7
1526	17.0	1.6	428.2	493.2	7.5
1527	10.2	1.1	360.3	511.1	8.0
1528	12.2	1.6		521.3	7.9
1529	7.2	1.1		515.9	8.1
1530	58.7				
1531	96.1				
1532	60.7				
1533	63.3				
1534	36.6				
1535	30.8				

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
1536	12.2				
1537	10.0				
1538	10.3				
1539	5.3				
1610	159.9				
1611	148.3				
1612	84.5				
1613	30.2				
1614	20.1				
1615	17.3				
1616	12.3				
1617	11.1				
1618	10.3				
1619	8.0				
1620	176.5	5.0	1325.0	501.6	7.1
1621	238.8	7.1	1389.5	480.5	7.2
1622	128.7	3.2	1181.5	509.8	7.4
1623	97.1	7.0	1028.0	537.0	7.6
1624	52.7	1.2	821.4	461.1	7.8
1625	25.0	0.9	688.1	431.9	7.9
1626	11.7	1.0	575.9	475.2	7.9
1627	5.8	0.4	510.0	414.0	7.9
1628	7.3	3.7		474.3	7.9
1629	7.1	0.5		426.7	8.0
1630	221.4				
1631	175.3				
1632	146.9				
1633	116.3				
1634	86.1				
1635	75.9				
1636	36.7				
1637	40.6				
1638	9.9				
1639	5.4				
3110	117.9				
3111	98.9				
3112	44.6				
3113	25.2				
3114	30.3				
3115	34.7				
3116	33.1				
3117	15.3				

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
3118	4.8				
3119	0.1				
3120	38.9	17.4	1365.0	600.8	6.0
3121	45.8	5.2	845.1	627.7	6.8
3122	44.0	3.9	767.2	647.4	7.2
3123	36.6	3.0	665.4	634.9	7.8
3124	26.3	2.3	660.7	631.7	7.5
3125	11.6	1.5	495.6	524.0	7.9
3126	10.1	1.4	508.9	466.7	7.8
3127	4.2	0.9	468.0	523.2	8.0
3128	5.9	1.2		656.3	7.9
3129	3.8	1.3		634.4	7.1
3130	35.4				
3131	28.2				
3132	19.9				
3133	7.3				
3134	16.4				
3135	34.4				
3136	30.0				
3137	19.5				
3138	10.0				
3139	5.4				
3210	56.7				
3211	54.4				
3212	37.0				
3213	28.8				
3214	12.9				
3215	20.6				
3216	23.2				
3217	17.7				
3218	8.5				
3219	6.1				
3220	55.8	1.9	1124.0	730.6	6.3
3221	52.0	0.1	925.8	659.6	5.9
3222	41.4	0.1	985.2	624.2	6.4
3223	32.1	0.1	781.7	642.8	7.1
3224	37.9	0.1	814.9	668.1	7.1
3225	48.0	0.1	772.7	719.6	7.2
3226	37.6	0.1	621.6	694.9	6.9
3227	29.2	0.1	553.7	662.1	7.0
3228	26.6	0.1		632.2	7.0
3229	21.8	0.1		633.2	7.6

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
3230	61.3				
3231	47.1				
3232	38.6				
3233	36.3				
3234	32.4				
3235	16.7				
3236	15.3				
3237	9.9				
3238	5.4				
3239	3.3				
3310	71.8				
3311	63.5				
3312	44.0				
3313	36.7				
3314	40.3				
3315	36.7				
3316	26.0				
3317	8.6				
3318	6.6				
3319	8.8				
3320	55.8	0.1	1512.5	526.4	6.3
3321	38.2	0.1	1058.0	602.6	6.2
3322	35.1	0.1	683.6	566.5	7.0
3323	41.9	0.1	611.5	589.3	7.4
3324	30.3	0.1	554.3	601.5	7.6
3325	13.9	0.1	488.2	537.7	7.8
3326	10.5	0.1	466.1	607.7	8.0
3327	7.2	0.1	441.5	621.0	8.0
3328	6.4	0.1		624.7	8.0
3329	7.8	0.1		657.5	7.8
3330	80.1				
3331	54.3				
3332	30.7				
3333	34.2				
3334	33.7				
3335	26.9				
3336	16.6				
3337	15.6				
3338	11.6				
3339	9.4				
3410	75.8				
3411	69.3				

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
3412	69.0				
3413	49.5				
3414	47.7				
3415	25.9				
3416	9.6				
3417	4.6				
3418	9.0				
3419	11.6				
3420	71.6	0.1	999.7	649.9	7.6
3421	61.8	0.1	762.5	642.1	7.1
3422	42.0	0.1	607.0	603.6	7.2
3423	35.8	0.1	582.4	617.9	7.4
3424	23.5	0.1	489.8	635.5	7.1
3425	13.6	0.1	444.5	638.5	7.4
3426	11.5	0.1	423.7	659.2	7.5
3427	13.5	0.1	418.6	632.8	7.3
3428	12.1	0.1		674.2	7.9
3429	15.0	0.1		640.3	7.8
3430	85.3				
3431	72.0				
3432	66.0				
3433	54.2				
3434	51.9				
3435	29.6				
3436	27.1				
3437	10.7				
3438	10.7				
3439	7.5				
3510	56.4				
3511	39.6				
3512	29.4				
3513	21.5				
3514	18.4				
3515	15.2				
3516	12.3				
3517	8.6				
3518	6.3				
3519	4.6				
3520	49.4	0.1	757.9	616.5	6.8
3521	48.2	0.1	721.7	594.3	7.1
3522	56.8	0.1	832.3	588.7	6.5
3523	41.1	0.1	641.9	676.4	7.2

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
3524	42.1	0.1	604.3	668.6	6.8
3525	29.7	0.1	519.6	569.0	7.6
3526	20.9	0.1	506.3	665.0	7.2
3527	16.1	0.1	462.3	709.6	7.3
3528	14.2	0.1		706.4	7.5
3529	10.1	0.1		705.8	7.7
3530	54.2				
3531	49.9				
3532	42.3				
3533	44.1				
3534	41.6				
3535	36.0				
3536	19.5				
3537	18.6				
3538	18.8				
3539	12.4				
3610	35.4				
3611	44.3				
3612	39.6				
3613	30.5				
3614	26.8				
3615	15.8				
3616	13.7				
3617	8.7				
3618	12.1				
3619	7.2				
3620	66.8	2.2	879.3	544.2	7.5
3621	43.4	1.1	650.6	553.3	7.7
3622	17.1	0.4	502.1	580.8	7.8
3623	11.2	9.0	487.7	572.0	7.6
3624	8.1	0.8	448.5	585.8	7.9
3625	7.4	0.7	447.0	576.7	8.0
3626	6.7	0.4	448.3	568.9	7.8
3627	5.0	0.1	433.4	593.3	7.7
3628	5.4	0.2		575.2	7.9
3629	10.7	0.2		598.0	7.8
3630	64.6				
3631	59.0				
3632	36.0				
3633	27.8				
3634	22.3				
3635	7.5				

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
3636	7.1				
3637	7.4				
3638	6.7				
3639	7.2				
5110	21.1				
5111	12.8				
5112	14.1				
5113	14.7				
5114	17.3				
5115	20.3				
5116	15.8				
5117	15.8				
5118	10.7				
5119	7.5				
5120	14.1	10.6	431.7	720.8	5.7
5121	13.6	2.8	393.8	606.2	6.0
5122	14.9	1.5	299.4	571.1	6.1
5123	16.0	1.0	313.0	542.7	6.1
5124	14.7	2.2	334.7	536.3	6.2
5125	15.7	0.9	399.2	558.9	6.3
5126	12.4	1.3	401.6	562.0	6.7
5127	11.6	0.9	384.1	565.0	6.5
5128	8.8	2.6		580.2	6.7
5129	7.1	0.7		550.1	6.8
5130	17.8				
5131	15.5				
5132	12.8				
5133	18.3				
5134	22.9				
5135	20.9				
5136	20.4				
5137	20.6				
5138	13.8				
5139	7.3				
5210	11.3				
5211	24.4				
5212	13.7				
5213	15.8				
5214	20.6				
5215	28.8				
5216	29.5				
5217	18.9				

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
5218	11.2				
5219	6.1				
5220	19.5	0.1	566.6	560.4	6.4
5221	17.4	0.1	494.2	478.1	7.0
5222	20.1	0.1	491.0	487.3	7.1
5223	25.4	0.1	463.1	573.4	7.4
5224	30.0	0.1	434.4	545.6	7.4
5225	22.7	0.1	408.9	549.4	7.3
5226	12.7	0.1	420.8	557.5	8.0
5227	8.2	0.1	437.5	578.1	7.6
5228	7.5	0.1		538.7	8.0
5229	5.4	0.1		474.8	7.5
5230	20.5				
5231	13.4				
5232	21.0				
5233	23.6				
5234	24.0				
5235	24.8				
5236	12.8				
5237	7.6				
5238	6.9				
5239	6.3				
5310	28.6				
5311	13.7				
5312	19.4				
5313	16.2				
5314	17.0				
5315	13.1				
5316	6.9				
5317	2.6				
5318	0.2				
5319	1.1				
5320	18.7	0.1	704.5	466.2	6.7
5321	18.9	0.1	505.6	329.1	6.7
5322	18.6	0.1	454.9	340.4	7.1
5323	17.0	0.1	437.4	376.9	7.2
5324	15.6	0.1	467.6	405.4	7.5
5325	14.2	0.1	452.7	453.1	7.8
5326	8.6	0.1	418.2	549.3	7.9
5327	5.0	0.1	370.6	505.1	8.0
5328	3.4	0.1		468.2	8.0
5329	3.0	0.1		436.3	8.0

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
5330	22.0				
5331	19.0				
5332	12.6				
5333	15.0				
5334	16.9				
5335	17.1				
5336	15.8				
5337	7.6				
5338	2.6				
5339	0.9				
5410	13.0				
5411	9.3				
5412	14.5				
5413	17.6				
5414	17.3				
5415	14.5				
5416	8.1				
5417	8.3				
5418	4.7				
5419	3.3				
5420	51.7	32.1	1035.5	115.4	6.3
5421	14.7	3.8	920.3	682.1	5.8
5422	12.1	1.4	802.5	615.3	6.0
5423	19.4	1.0	610.6	532.1	5.7
5424	25.9	1.6	599.3	572.8	7.0
5425	19.8	1.5	522.0	590.1	7.8
5426	11.1	0.9	444.4	574.4	7.9
5427	12.5	2.7	462.5	607.2	7.8
5428	6.2	0.7		563.9	8.1
5429	8.0	0.8		559.4	7.9
5430	14.4				
5431	9.4				
5432	11.3				
5433	8.0				
5434	11.8				
5435	16.8				
5436	13.2				
5437	8.6				
5438	9.1				
5439	8.2				
5510	33.1				
5511	28.7				

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
5512	27.8				
5513	24.0				
5514	22.2				
5515	18.3				
5516	5.0				
5517	5.2				
5518	6.4				
5519	2.2				
5520	42.9	2.1	844.6	588.5	7.4
5521	32.9	2.4	693.3	643.4	8.0
5522	29.0	2.2	657.9	665.9	7.6
5523	25.7	2.0	642.2	659.7	7.9
5524	21.4	1.7	625.1	667.3	8.0
5525	20.3	8.5	601.8	653.4	7.9
5526	10.4	1.8	456.2	601.1	7.8
5527	9.9	0.7	417.6	626.2	7.9
5528	8.8	0.8		586.4	7.9
5529	4.4	2.2		572.4	7.7
5530	31.8				
5531	32.7				
5532	28.7				
5533	27.8				
5534	24.9				
5535	19.2				
5536	11.8				
5537	1.7				
5538	0.1				
5539	1.6				
5610	36.4				
5611	32.8				
5612	21.5				
5613	22.4				
5614	23.1				
5615	23.0				
5616	12.2				
5617	1.4				
5618	0.1				
5619	0.1				
5620	32.5	2.6	732.2	627.9	7.1
5621	29.0	1.5	729.7	650.9	7.5
5622	26.2	1.2	642.5	652.4	7.7
5623	30.7	1.2	670.2	660.3	7.3

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
5624	27.6	1.6	695.0	616.8	7.8
5625	13.8	1.0	512.8	562.7	7.9
5626	17.4	1.1	522.7	613.5	7.8
5627	15.0	0.9	460.4	573.7	7.9
5628	12.0	0.8		595.7	8.0
5629	9.4	1.0		603.8	8.0
5630	30.7				
5631	20.6				
5632	19.7				
5633	20.6				
5634	18.6				
5635	11.5				
5636	9.6				
5637	0.8				
5638	4.2				
5639	0.1				
9110	109.8	21.4	1123.5	369.8	7.6
9111	109.6	10.1	1103.0	346.0	7.7
9112	98.2	5.3	1094.0	333.2	8.0
9113	77.2	4.0	1013.5	430.3	7.7
9114	52.2	2.4	969.8	444.4	7.7
9115	47.2	3.7	954.3	528.8	7.9
9116	44.1	1.7	892.1	472.0	7.8
9117	49.9	3.0	978.2	499.6	7.9
9118	62.3	2.5		591.0	8.0
9119	61.9	2.0		465.0	7.9
9120	104.9	15.8	1079.5	339.0	7.9
9121	107.7	7.2	1114.5	319.6	7.9
9122	93.5	5.1	1138.0	328.1	7.8
9123	67.8	4.2	1024.0	387.4	8.0
9124	58.2	2.4	898.5	410.5	7.9
9125	39.7	1.7	866.9	466.6	8.0
9126	43.8	2.4	821.4	427.9	8.0
9127	65.9	2.0	898.7	432.1	7.9
9128	71.5	2.8		395.3	8.1
9129	78.4	2.5		384.7	8.1
9130	115.9	21.9	872.8	156.3	8.2
9131	97.5	6.9	835.1	206.0	8.4
9132	74.4	5.1	734.3	196.9	8.3
9133	56.4	2.5	698.7	225.1	8.3
9134	71.4	2.1	889.2	307.2	8.3
9135	40.6	1.6	722.7	321.1	8.0

Sample ID	M3P	WEP	TP	PSI	pH
	--------------mg kg^{-1}------------				
9136	46.6	1.4	675.7	250.2	8.0
9137	49.7	1.5	727.2	253.9	8.0
9138	60.9	1.8		370.1	7.9
9139	58.4	3.0		297.7	8.0
9140	97.5	16.7	992.2	259.0	8.0
9141	56.4	9.4	874.2	421.1	7.9
9142	45.6	2.2	833.4	407.4	7.9
9143	45.1	2.0	886.5	427.2	8.0
9144	47.8	1.8	913.1	433.9	8.0
9145	74.9	4.0	929.5	514.9	7.8
9146	60.5	1.9	916.0	485.3	7.9
9147	37.6	1.8	864.2	474.2	7.8
9148	50.8	1.2		458.9	7.8
9149	57.3	1.3		486.2	7.9

APPENDIX B

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for Mehlich 3 phosphorus (M3P).

Source	DF	Type III SS	F Value	Pr > F
Cell	3	177067.2863	48.32	<0.0001
Depth	9	159322.7316	88.55	<0.0001
Cell*Depth	27	95798.7167	17.75	<0.0001

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for water extractable phosphorus (WEP).

Source	DF	Type III SS	F Value	Pr > F
Cell	3	587.0778	9.12	0.0007
Depth	9	1517.2301	18.49	<0.0001
Cell*Depth	27	690.5927	2.81	<0.0001

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for total phosphorus (TP).

Source	DF	Type III SS	F Value	Pr > F
Cell	3	34083354.683	9.23	0.0006
Depth	7	4550826.698	34.67	<0.0001
Cell*Depth	21	1605047.956	4.08	<0.0001

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for phosphorus sorption index (PSI).

Source	DF	Type III SS	F Value	Pr > F
Cell	3	1485175.423	13.26	<0.0001
Depth	9	59904.689	1.20	0.2981
Cell*Depth	27	135579.163	0.91	0.6034

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for H+ concentration (moles) (pH).

Source	DF	Type III SS	F Value	Pr > F
Cell	3	1.667E-12	2.09	0.1378
Depth	9	1.592E-12	3.60	0.0004
Cell*Depth	27	1.899E-12	1.43	0.0909

APPENDIX C

The following table was provided by Stephen f. Austin State University – Soil, Plant, and Water Analysis Laboratory. It classifies the relative phosphorus class of the soil. The very low class indicates the soil has low P availability to plans and the addition of P fertilizer, at a high rate, is needed to improved plant growth. As the class level moves towards the very high class, the rate of P is reduced and at the very high level, no additional P is needed.

Mehlich 3 Phosphorus Levels	
mg kg^{-1} P in soil	**Class Level**
0 - 10	Very Low
11 - 20	Low
21 - 40	Medium
41 - 60	High
> 60	Very High

APPENDIX D

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *ex situ* tillage simulation water diffused phosphorus (WDP).

Source	DF	Type III SS	F Value	Pr > F
Treatment	2	1.01525664	6.96	0.0073
Day	4	0.13397712	1.92	0.1182
Treatment*Day	8	0.76984336	5.53	<0.0001

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *ex situ* tillage simulation water phosphorus (WP) after an addition of 2 mg P L^{-1}.

Source	DF	Type III SS	F Value	Pr > F
Treatment	2	14.31228126	23.86	<0.0001
Day	4	2.40657959	76.97	<0.0001
Treatment*Day	8	0.09515571	1.52	0.1689

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *ex situ* tillage simulation water phosphorus (WP) after an addition of 75 mg P L^{-1}.

Source	DF	Type III SS	F Value	Pr > F
Treatment	2	922.682287	2.00	0.1693
Day	4	5546.942185	382.19	<0.0001
Treatment*Day	8	93.081068	3.21	0.0042

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *ex situ* tillage simulation Mehlich 3 phosphorus (M3P).

Source	DF	Type III SS	F Value	Pr > F
Treatment	2	16390.5269	0.92	0.4216
Depth	7	395901.0184	48.09	<0.0001
Treatment*Depth	14	37314.3128	2.27	0.0097

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *ex situ* tillage simulation total phosphorus (TP).

Source	DF	Type III SS	F Value	Pr > F
Treatment	2	4138480.55	4.66	0.0266
Depth	7	12179263.66	25.31	<0.0001
Treatment*Depth	14	3080823.76	3.20	0.0003

***Ex Situ* tillage simulation mean total phosphorus (TP) and phosphorus sorption index (PSI) concentration (mg kg^{-1}) from cell 1 of Richland Creek WMA constructed wetland by tillage treatment. Means followed by the same letter in a column are not significantly different (α=0.05) using Tukey's Studentized Range (Tukey's) Test.**

Treatment	TP Mean (n=48)	PSI Mean (n=48)
	-------------------mg kg^{-1}	------------
No-Till	885ab	758a
10-cm Till	1099a	569ab
20-cm Till	684b	469b

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *ex situ* tillage simulation phosphorus sorption index (PSI).

Source	DF	Type III SS	F Value	Pr > F
Treatment	2	2072098.852	5.04	0.0211
Depth	7	165072.019	3.57	0.0018
Treatment*Depth	14	67297.077	0.73	0.7430

APPENDIX E

The following data correlates to the *ex situ* tillage simulation study. The first digit of the sample ID identifies the tillage group, with 0=no-till, 1=10-cm till, and 2=20-cm till. The third digit identifies the sample number from within the tillage group. The fourth digit on the soil data identifies depth with 0=0-2cm and 7=20-25cm. All water P concentrations are measured in mg L^{-1}, and all soil P concentrations are measured in mg kg^{-1}.

Sample ID	SRP Days after Saturation			
	3	6	9	12
	---------------------mg L^{-1}--------------------			
001	0.248	0.677	0.563	0.902
002	0.681	0.958	0.859	0.901
003	0.259	0.574	0.659	0.716
004	0.248	0.477	0.533	0.544
005	0.065	0.225	0.296	0.318
006	0.159	0.457	0.575	0.624
101	0.358	0.353	0.327	0.308
102	0.370	0.370	0.348	0.358
103	0.422	0.528	0.471	0.453
104	0.349	0.320	0.303	0.307
105	0.327	0.323	0.307	0.426
106	0.243	0.252	0.265	0.065
201	0.231	0.159	0.121	0.125
202	0.413	0.331	0.221	0.208
203	0.190	0.102	0.092	0.074
204	0.260	0.221	0.210	0.205
205	0.202	0.202	0.198	0.219
206	0.118	0.153	0.140	0.161

Sample ID	Days after Saturation with 2 mg P L^{-1} 3	6	9	12	**15**
	---------mg L^{-1}---------				
001	1.83	1.53	1.47	1.56	1.49
002	2.06	1.83	1.77	1.85	1.68
003	2.08	1.85	1.79	1.86	1.68
004	1.14	1.31	1.10	1.30	1.17
005	1.55	1.08	0.99	1.02	0.91
006	2.39	1.75	1.74	1.77	1.59
101	1.32	0.87	0.82	0.79	0.68
102	1.31	0.95	0.98	0.92	0.78
103	1.41	1.05	1.00	0.96	0.80
104	1.04	0.75	0.80	0.74	0.69
105	1.22	0.84	0.91	0.78	0.85
106	1.08	0.49	0.60	0.54	0.54
201	0.60	0.28	0.25	0.21	0.29
202	0.75	0.68	0.43	0.39	0.43
203	1.24	0.78	0.66	0.61	0.59
204	1.13	0.72	0.70	0.64	0.61
205	1.29	0.87	0.79	0.76	0.72
206	0.77	0.42	0.44	0.38	0.38

Sample ID	Days after Saturation with 75 mg P L^{-1} 3	6	9	**12**	**15**
	---------mg L^{-1}---------				
001	73.57	64.58	58.97	57.60	48.49
002	68.39	61.45	57.00	57.13	47.41
003	67.47	59.47	53.47	49.25	39.49
004	49.89	40.53	35.31	32.22	25.71
005	57.42	49.63	48.97	44.57	37.80
006	72.39	71.37	65.77	66.49	49.54
101	66.08	67.55	63.64	61.79	50.70
102	71.67	65.26	60.55	59.95	51.93
103	71.30	61.89	56.78	54.49	45.35
104	70.48	62.09	57.14	53.10	45.44
105	65.69	69.72	59.09	55.87	43.46
106	71.15	67.27	59.48	52.67	47.35
201	65.81	62.51	54.86	53.53	45.12
202	67.42	67.12	57.36	56.84	46.47
203	74.06	73.60	64.81	64.97	53.69
204	69.20	69.25	60.56	60.07	49.24
205	74.09	71.75	66.29	65.94	54.88
206	68.40	65.58	58.24	56.95	45.24

Sample ID	M3P	TP	PSI
	--------------mg kg^{-1}-------------		
001-0	153.2	1227.0	784.6
001-1	116.0	1035.0	840.8
001-2	73.4	879.0	941.0
001-3	30.2	670.4	917.7
001-4	13.1	496.8	892.5
001-5	2.3	420.2	888.3
001-6	3.0	318.6	880.3
001-7	6.3	246.6	883.9
002-0	180.6	1631.0	823.4
002-1	163.2	1451.0	887.5
002-2	86.1	1147.5	1031.1
002-3	60.3	1097.5	1041.8
002-4	49.8	1012.5	1028.1
002-5	63.9	867.9	920.8
002-6	46.1	539.6	901.6
002-7	9.8	349.5	911.1
003-0	173.8	1323.5	881.7
003-1	171.9	1352.0	923.9
003-2	135.6	1345.5	973.3
003-3	111.0	1241.0	982.1
003-4	90.6	896.8	1000.1
003-5	52.2	643.6	990.7
003-6	10.8	446.7	989.9
003-7	3.2	423.9	978.1
004-0	203.7	1569.5	902.2
004-1	108.6	1093.5	944.2
004-2	93.5	1037.5	952.6
004-3	99.9	890.5	928.9
004-4	61.4	771.9	885.7
004-5	58.7	744.3	970.1
004-6	22.7	577.0	569.1
004-7	12.1	482.8	575.1
005-0	191.4	1476.5	325.3
005-1	118.4	1146.0	417.0
005-2	92.7	922.2	465.6
005-3	86.7	870.5	467.6
005-4	75.9	1463.0	492.4
005-5	40.0	759.0	556.4
005-6	15.5	558.6	616.5
005-7	9.5	632.7	549.9
006-0	187.6	1434.0	328.5
006-1	94.1	955.3	351.7

Sample ID	M3P	TP	PSI
	-------------mg kg^{-1}-------------		
006-2	64.4	555.7	303.9
006-3	23.2	612.7	411.6
006-4	14.2	845.8	495.2
006-5	11.9	738.1	486.2
006-6	16.6	541.1	517.2
006-7	12.8	775.7	577.5
101-0	172.4	2030.0	373.7
101-1	72.5	1280.0	476.7
101-2	83.4	631.5	587.5
101-3	69.6	955.3	637.0
101-4	48.3	537.6	578.4
101-5	19.8	708.8	581.7
101-6	18.0	602.6	604.7
101-7	16.4	854.2	634.0
102-0	237.9	1352.0	618.9
102-1	133.7	2153.0	689.7
102-2	116.9	1058.0	648.2
102-3	137.2	1515.0	702.7
102-4	67.7	939.6	791.9
102-5	33.5	680.5	765.7
102-6	8.8	468.7	742.7
102-7	4.0	572.3	761.4
103-0	298.7	3504.0	715.7
103-1	124.6	2373.0	709.7
103-2	125.6	1365.0	752.3
103-3	103.8	1246.0	752.6
103-4	70.5	828.9	690.2
103-5	33.3	1323.0	675.5
103-6	24.4	911.3	531.8
103-7	21.3	532.7	503.2
104-0	370.2	2830.0	515.0
104-1	200.8	1053.0	585.5
104-2	193.0	1700.0	607.1
104-3	173.4	2281.0	606.3
104-4	176.3	1488.0	591.1
104-5	176.3	1462.0	624.2
104-6	139.0	871.4	613.4
104-7	17.6	715.5	660.7
105-0	133.1	1418.0	568.0
105-1	68.0	711.5	571.1
105-2	70.2	801.4	528.3
105-3	52.5	763.6	467.6

Sample ID	M3P	TP	PSI
	--------------mg kg^{-1}-------------		
105-4	55.0	685.3	487.6
105-5	52.5	646.0	241.4
105-6	58.5	624.3	274.5
105-7	38.0	575.4	416.1
106-0	275.7	1483.0	459.1
106-1	144.1	735.6	379.8
106-2	121.4	799.2	397.1
106-3	101.5	675.1	397.9
106-4	63.3	603.6	426.0
106-5	13.7	459.4	429.8
106-6	10.3	415.7	497.8
106-7	18.3	527.9	416.6
201-0	146.0	1156.5	483.6
201-1	63.9	710.3	535.5
201-2	46.9	700.4	618.9
201-3	49.4	670.3	563.0
201-4	46.1	677.9	595.0
201-5	43.9	692.6	615.1
201-6	25.1	555.2	571.8
201-7	12.6	476.6	504.1
202-0	143.1	1264.0	594.1
202-1	84.0	762.1	563.4
202-2	59.1	694.5	603.3
202-3	52.2	677.4	608.0
202-4	49.6	716.5	605.3
202-5	53.0	708.8	589.6
202-6	19.2	542.6	451.7
202-7	13.3	518.6	460.6
203-0	118.7	706.8	485.8
203-1	43.2	490.8	529.1
203-2	42.9	473.5	552.2
203-3	41.2	508.0	542.6
203-4	43.2	470.7	571.7
203-5	44.0	514.0	570.1
203-6	23.0	492.1	468.5
203-7	9.2	444.6	419.9
204-0	140.6	1037.5	300.7
204-1	287.5	869.5	349.9
204-2	26.1	845.4	414.5
204-3	43.1	690.2	356.4
204-4	131.7	764.9	338.6
204-5	88.9	780.3	464.3

Sample ID	M3P	TP	PSI
	--------------mg kg^{-1}-------------		
204-6	95.4	598.0	311.0
204-7	102.9	521.9	297.6
205-0	120.9	1124.5	347.9
205-1	179.4	932.8	397.4
205-2	165.3	771.0	375.4
205-3	159.0	828.7	401.6
205-4	165.2	1130.5	382.7
205-5	194.1	831.2	399.7
205-6	28.3	788.3	437.4
205-7	10.8	513.4	388.5
206-0	257.1	408.8	286.1
206-1	118.2	660.2	390.9
206-2	97.4	594.9	544.0
206-3	100.9	604.2	580.2
206-4	102.2	697.6	555.1
206-5	91.5	602.9	561.2
206-6	14.5	364.6	294.5
206-7	2.5	233.8	223.6

APPENDIX F

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *in situ* tillage simulation Mehlich 3 phosphorus (M3P).

Source	DF	Type III SS	F Value	Pr > F
Treatment	1	2627.3655	0.51	0.5134
Depth	9	166856.1819	44.08	<0.0001
Treatment*Depth	9	1024.0745	0.27	0.9787

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *in situ* tillage simulation water extractable phosphorus (WEP).

Source	DF	Type III SS	F Value	Pr > F
Treatment	1	3.52262	0.05	0.8348
Depth	9	713.61486	7.30	<0.0001
Treatment*Depth	9	64.05896	0.65	0.7429

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *in situ* tillage simulation total phosphorus (TP).

Source	DF	Type III SS	F Value	Pr > F
Treatment	1	32.234	0.00	0.9938
Depth	7	3910663.272	10.80	<0.0001
Treatment*Depth	7	171893.959	0.47	0.8446

Repeated measures analysis of variance tests of hypotheses for within-subjects effects for *in situ* tillage simulation phosphorus sorption index (PSI).

Source	DF	Type III SS	F Value	Pr > F
Treatment	1	433271.1634	0.94	0.3867
Depth	9	49329.2664	0.59	0.7988
Treatment*Depth	9	25345.3130	0.30	0.9694

APPENDIX G

The following data correlates to the *in situ* tillage simulation. The sample ID's four digits respectfully identifies the cell, location, transect repetition, and depth. For example, sample ID 1230, the first digit identifies the cell as cell 1 (5 = reference wetland, 9 = sedimentation basin). The second digit identifies that it was the second sample location in cell 1. The third digit labels it as the third or final sample on the transect. It also identifies pre- or post-tillage. Values 1-3 are pre-tillage and values 7-9 are post-tillage The fourth digit identifies depth of sample, with 0 being the surface horizon and 9 being the 30-35 cm sample from the soil core. All values are mg kg^{-1}.

Sample ID	M3P	WEP	TP	PSI
	-------------------mg kg^{-1}	-----------------		
1110	78.3			
1111	70.6			
1112	79.3			
1113	36.7			
1114	39.0			
1115	31.9			
1116	19.2			
1117	17.5			
1118	14.0			
1119	13.5			
1120	107.3	22.0	1828.5	748.9
1121	37.3	5.2	666.7	624.5
1122	33.9	3.1	584.1	622.9
1123	28.7	2.8	581.4	564.4
1124	29.9	4.0	576.8	591.7
1125	20.9	2.3	511.7	516.4
1126	17.5	2.0	506.6	436.9
1127	14.1	2.1	466.2	470.4
1128	14.8	2.1		450.4
1129	10.2	1.7		444.8

Sample ID	M3P	WEP	TP	PSI
	-------------------mg kg^{-1}-----------------			
1130	95.5			
1131	51.3			
1132	42.5			
1133	43.1			
1134	33.2			
1135	26.2			
1136	16.2			
1137	8.7			
1138	6.4			
1139	5.5			
1310	92.1			
1311	128.7			
1312	111.4			
1313	70.6			
1314	40.6			
1315	27.1			
1316	28.7			
1317	21.6			
1318	13.7			
1319	19.4			
1320	102.2	2.3	801.7	460.9
1321	92.1	2.1	739.2	503.9
1322	72.3	2.0	645.9	502.8
1323	20.8	10.8	486.2	598.5
1324	18.5	1.8	470.6	467.5
1325	11.8	1.2	448.7	564.5
1326	10.7	1.1	427.7	582.4
1327	11.6	1.0	417.8	574.5
1328	12.9	1.2		572.5
1329	13.9	0.8		582.0
1330	109.0			
1331	100.4			
1332	74.4			
1333	55.4			
1334	79.9			
1335	24.0			
1336	7.3			
1337	6.1			
1338	6.1			
1339	6.5			
1410	117.0			
1411	96.3			

Sample ID	M3P	WEP	TP	PSI
	-------------------mg kg^{-1}-----------------			
1412	85.3			
1413	77.3			
1414	82.7			
1415	87.3			
1416	74.6			
1417	33.7			
1418	25.3			
1419	14.9			
1420	139.2	12.7	1361.0	248.1
1421	82.3	11.7	1162.0	391.8
1422	83.0	9.7	1186.0	430.7
1423	58.9	11.2	1082.0	426.9
1424	59.0	4.1	1051.0	393.9
1425	67.5	3.7	766.1	177.7
1426	64.3	3.5	584.5	380.8
1427	21.1	1.8	353.7	590.4
1428	3.7	0.5		598.3
1429	3.3	0.5		556.1
1430	76.5			
1431	73.2			
1432	60.5			
1433	65.0			
1434	60.8			
1435	26.5			
1436	20.2			
1437	10.3			
1438	7.3			
1439	6.2			
1170	105.1	13.1	1291.5	456.7
1171	99.4	7.2	1170.5	499.0
1172	93.3	6.2	1166.0	513.3
1173	74.1	4.8	1074.5	518.0
1174	83.5	5.6	1289.5	509.6
1175	88.7	6.6	730.0	326.7
1176	38.4	4.2	491.5	331.0
1177	21.6	2.8	376.7	324.6
1178	15.0	2.7		318.1
1179	6.5	1.7		306.8
1180	91.8	10.0	1194.5	414.4
1181	93.2	6.9	1105.5	496.2
1182	80.0	5.5	1048.0	509.2
1183	78.3	4.3	771.9	428.2

Sample ID	M3P	WEP	TP	PSI
	-------------------mg kg^{-1}-----------------			
1184	64.0	3.4	529.1	364.5
1185	20.3	2.1	323.2	522.5
1186	6.6	1.0	234.0	488.3
1187	3.0	3.6	258.2	539.0
1188	2.6	3.0		490.5
1189	3.9	1.0		518.6
1190	129.0	14.4	1232.5	512.2
1191	133.3	14.5	1261.0	526.3
1192	125.7	11.8	1343.5	582.5
1193	119.4	8.8	1199.0	599.1
1194	127.0	9.7	1185.5	581.3
1195	90.8	7.8	1067.0	579.4
1196	84.5	5.5	760.1	499.9
1197	79.3	6.7	649.7	421.2
1198	41.0	4.5		446.7
1199	21.5	2.8		484.3
1370	106.4	10.3	1220.0	593.9
1371	76.2	6.6	878.9	665.0
1372	78.4	3.7	810.8	530.1
1373	84.6	3.9	756.3	609.6
1374	65.2	3.2	674.6	672.8
1375	57.3	4.7	708.9	549.0
1376	37.6	3.9	642.2	579.5
1377	32.8	0.4	622.4	678.8
1378	31.9	0.4		552.8
1379	23.8	0.4		561.6
1380	122.5	10.8	1266.0	725.5
1381	95.2	6.1	823.1	646.9
1382	90.9	3.9	746.6	714.7
1383	79.7	3.0	664.4	742.4
1384	69.2	2.8	645.6	562.5
1385	52.5	2.4	687.1	597.3
1386	36.5	1.9	499.7	624.8
1387	41.2	2.3	529.4	599.3
1388	22.6	1.7		608.9
1389	15.5	1.2		576.5
1390	130.8	14.1	1198.5	710.6
1391	89.7	4.9	902.5	721.3
1392	67.9	2.9	623.9	586.0
1393	54.9	2.2	558.5	756.7
1394	33.5	1.6	477.9	558.7
1395	29.4	1.4	485.1	566.3

Sample ID	M3P	WEP	TP	PSI
	-------------------mg kg^{-1}-----------------			
1396	15.3	1.1	427.9	614.0
1397	8.1	1.5	390.2	808.1
1398	5.8	1.2		783.8
1399	5.5	1.5		797.7
1470	122.6	5.8	837.5	753.4
1471	118.3	5.1	929.8	722.4
1472	98.9	4.9	1005.0	723.8
1473	77.9	3.6	804.7	774.1
1474	57.0	3.0	745.9	772.3
1475	45.1	2.0	588.8	769.7
1476	40.6	1.8	578.3	763.9
1477	21.4	1.0	463.2	806.1
1478	16.6	0.7		793.1
1479	13.9	0.7		800.1
1480	73.7	4.2	740.7	807.7
1481	72.1	1.4	756.8	830.4
1482	24.8	4.8	506.6	784.8
1483	19.9	2.0	468.2	835.3
1484	12.5	1.6	406.9	853.1
1485	7.3	1.2	402.2	848.8
1486	5.4	1.0	321.7	837.2
1487	4.6	1.0	334.4	825.0
1488	4.1	1.1		788.0
1489	3.9	1.1		803.1
1490	77.9	1.8	784.1	808.9
1491	75.7	2.6	739.1	818.6
1492	29.7	3.8	491.3	831.1
1493	21.5	2.3	467.7	810.2
1494	22.6	1.8	455.4	835.4
1495	11.8	1.5	389.0	850.2
1496	13.9	1.6	376.6	928.0
1497	12.5	1.7	434.4	937.7
1498	8.3	1.8		800.0
1499	7.3	2.7		800.0

VITA

T. Wells Shartle was born in Crockett, Texas in 1982. He lived in Crockett while attending Crockett High School. Wells graduated from Baylor University in the fall of 2005 with a Bachelor of Business Administration in Management and a minor in Environmental Studies. He entered the graduate program at Stephen F. Austin in the spring of 2009 to pursue a Master of Science degree in Environmental Science.

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