



**THE OPTIMIZATION OF LOW-COST
PHOSPHORUS REMOVAL
FROM AGRICULTURAL WASTEWATER
USING CO-TREATMENTS WITH
CONSTRUCTED WETLANDS**

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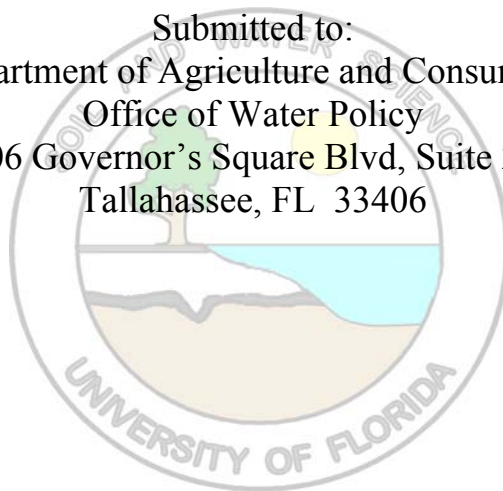
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EXECUTIVE SUMMARY

A novel wastewater treatment system was designed and constructed to test a combination of strategies for low-cost (of construction and operation) phosphorus (P) removal from agricultural wastewater. The experimental systems combined co-treatment reactors containing either iron or calcium drinking water treatment residuals (DWTR) with vertical flow constructed wetland mesocosms containing coarse sand and the native soft-stem bulrush *Scirpus tabernaemontani* C.C. Gmel. (= *S. validus* Vahl). Eighteen of these systems were built and operated for one year. Wetlands paired with co-treatments generally removed P as well, or much better than, control wetlands. Also, there appeared to be no negative, and perhaps a small positive, impact from the co-treatments on wetland plant growth. The eighteen systems included two different wastewaters, using two DWTR's from Florida, plus controls, with three replicates of each in a complete randomized design at two sites in Alachua County, Florida. For the low-strength (secondarily treated municipal) wastewater, average soluble reactive phosphorus (SRP) concentrations were reduced from 0.695 mg L⁻¹ to 0.030 mg L⁻¹ (95% reduction) or 0.014 mg L⁻¹ (98%) by systems with the calcium or iron co-treatments respectively (compared to 0.089 mg L⁻¹ or 87% with the controls). In preliminary data for the same wastewater, total phosphorus (TP) concentrations were reduced from 0.993 mg L⁻¹ to 0.065 mg L⁻¹ (93%) and 0.050 mg L⁻¹ (95%) by the same treatments (compared to 0.148 mg L⁻¹ or 85% with the controls). For the high-strength wastewater (anaerobically digested flushed dairy manure), average SRP was reduced from 7.68 mg L⁻¹ to 6.43 (16%) or 5.95 mg L⁻¹ (22%) by the systems with calcium or iron respectively (compared to 7.37 mg L⁻¹ or 4%

with the controls). The TP was reduced from 48.50 mg L⁻¹ to 22.48 mg L⁻¹ (53%) and 22.74 mg L⁻¹ (53%) by the same treatments (compared to 24.10 mg L⁻¹ or 50% with the controls). The high-strength (dairy) wastewater had much higher Total Suspended Solids (TSS) and dissolved organic carbon (DOC) and it was suspected that this reduced the co-treatment's efficiency of P removal from this wastewater. The co-treatment and wetland systems greatly reduced TSS in the dairy wastewater from 2390 mg L⁻¹ to 68 mg L⁻¹. The co-treatments preceded the wetland cells in this 52-week experiment but for agricultural wastewaters with high TSS, the co-treatment may remove P more efficiently when used following an initial wetland cell in the treatment sequence. An additional short-term experiment was added to the research and completed with dairy wastewater and has supported this hypothesis with initial SRP reductions from 7.28 mg L⁻¹ to 3.48 mg L⁻¹ (52%) and 0.28 mg L⁻¹ (96%) by the systems with calcium or iron, respectively (compared to 3.77 mg L⁻¹ or 48% with the control). Initial TP reductions were from 28.43 mg L⁻¹ to 12.26 mg L⁻¹ (56%) and 8.12 mg L⁻¹ (71%) by the systems with calcium or iron, respectively (compared to 24.47 mg L⁻¹ or 14% with the control). The preliminary data suggests the potential for the successful application of these systems, with some design elements modified to match particular wastewaters. A conceptual design layout for testing the proposed system at full-scale is provided in the **Appendix** of this report. It is designed specifically for agricultural wastewaters like the one tested with high [TP] and high TSS. As discussed in the report, it should be noted that before full-scale application of this technology, other information would be required. For example, the cost feasibility of obtaining, transporting and land applying the particular DWTR for the

particular wastewater treatment and crop utilization would need to be confirmed for the specific agricultural operation and location. Both DWTR's in this research have already been land-applied, in various forms, for agriculture in Florida. Also, the data derived from this research was based on experimental vertical-flow treatment wetlands and for reasons discussed elsewhere, a surface-flow wetland system would be recommended for most agricultural applications. It is suggested that a pilot-scale treatment system might best be constructed at a university research farm to further test and demonstrate the technology. The use of co-treatments containing inexpensive, non-toxic, and reusable by-products, such as these drinking water treatment residuals, has potential for increasing the sustainability of P removal by constructed wetlands for animal waste treatment.

AUTHOR'S NOTE: *The operational objectives of the research were achieved and the experimental results of critical parameters support the central hypothesis tested. In addition, another hypothesis generated by early results was tested with a side experiment and provided valuable insight for design improvements for agricultural wastewater treatment with this type of system. Further analysis of the data continues to provide information towards ancillary scientific objectives for university researchers. This supplemental information will also be provided to FDACS when completed.*

INTRODUCTION

Background

Constructed wetlands (CW's) are increasingly being used for economically treating agricultural and municipal wastewater (WW) while providing ancillary environmental benefits. In addition to the improved optimization and characterization of phosphorus (P) removal by this emerging technology, the proposed research also incorporates the recycling of non-toxic by-products or wastes for increasing the P removal, P retention and CW sustainability. There is also the possibility of reusing these by-products, once they become saturated with P, as soil amendments and fertilizers. As soil amendments the by-products could reduce P mobility in the sandy native soils above Lake Okeechobee. There is a potential to develop a more sustainable, as well as more environmentally sound, use of P in agriculture. The combined benefits of low-cost by-product use, wastewater treatment, and nutrient re-use, could favor the economic feasibility of this type of system for water quality protection.

Enhanced P removal is a common goal when downstream systems are biologically P-limited (as most freshwater systems are). Since P levels in living biomass plateau as seasonal die-back returns P to the water column, sustainable removal by CW's is limited to soil sorption or sediment burial of precipitated forms and organic matter. The central hypothesis of the proposed research is that by optimizing hydrology and co-treatments, the removal and retention of P by CW's can be enhanced. The use of non-toxic by-products as substrates in rechargeable pre-treatment tanks may increase the

effective longevity of P removal by CW's while maintaining the advantage of low cost treatment.

The first two tasks of this research began with the screening of several by-products as potential co-treatment substrates. Substrates were tested with multi-point P isotherms to provide critical P removal parameters including Equilibrium P Concentration (EPC) and P Sorption Maxima (Smax). Substrates tested included: coated and un-coated sands, organic wetland soil, aluminum materials, sandblast grit, a dried humate by-product of titanium mining, an iron-humate drinking water treatment residual (DWTR) from Tampa, a lime sludge DWTR from Gainesville, and a magnesium by-product of fertilizer manufacturing in Florida. Based on the lab results, several of the most promising materials were used in a greenhouse column study with actual wastewater.

The greenhouse column experiment was undertaken to test some of the hydrologic, as well as P removal characteristics, of the conceptual design. Dairy wastewater and a low P municipal wastewater were tested with several of the most promising co-treatment substrates. The co-treatment stage was followed by a sand column stage to approximate the role of a vertical-flow constructed wetland in the system.

In order to more adequately test the feasibility of these CW and co-treatment systems, further research was needed at the outdoor mesocosm level. Results from the laboratory and greenhouse column experiments guided the design of the larger scale outdoor wetland mesocosms and co-treatment tanks. The mesocosms provided a more

realistic test of the principles examined in the laboratory and greenhouse studies. The results should provide data to support a better understanding of, and optimization of, P removal and retention during the design and operation of CW wastewater treatment systems for agriculture.

Task 1- The Lab Studies:

Organic (wetland) soil, sands and by-products containing organic matter, iron, aluminum, calcium and/or magnesium (**Table 1.**) were tested under laboratory conditions for their relative abilities to remove P from solution. Multi-point P isotherms were conducted and P remaining in solution was analyzed. Potential substrates were also analyzed for metals, OM-LOI, turbidity in solution, mineral content and particle size distribution.

Task 2-Greenhouse Column Studies

Based on the initial screening process in the lab, substrates were chosen for the greenhouse column studies.

Phosphorus forms and levels in influent, effluent, substrates and column sands were tested to measure P removal and storage. This stage provided insight into hydraulic conductivity issues associated with clogging of the substrates, sand and gravel drainage beds. Clogging of systems by biofilms (Wu et al., 1997) was a concern and was monitored in the later mesocosm studies by periodically measuring tank drainage rates.

Algal growth was observed at the beginning of the column studies (before they were protected from the sun). Therefore, the co-treatment reactor barrels in the later mesocosm study were covered with black plastic to minimize this confounding variable.

At the conclusion of this stage, the number of substrates and hydrologic conditions were narrowed to those with the good potential for P removal and optimal performance in a co-treatment system. Considering this and the other relevant factors, two substrates, one HLR and one HRT was chosen for use in the mesocosm experiment.

A novel wastewater treatment system was designed and constructed to test a combination of various strategies for low-cost phosphorus removal. The experimental systems combine co-treatment reactors (CTR) containing drinking water treatment residuals (DWTR) with vertical flow constructed wetland mesocosms (CWM) containing coarse Florida sand and native bulrush plants. Eighteen of these systems were built and operated for one-year. The eighteen systems include: two different wastewaters; two DWTR's from Florida plus controls; and three replicates of each in a complete randomized design at two sites in Alachua County, Florida.

Numerous parameters relevant to the optimization of phosphorus removal were measured and the results analyzed. Final destructive sampling of all eighteen CTR and CWM units was necessary at the end of 52 weeks to obtain critical data required for a thorough analysis and critique of the design features. Initial observations and the preliminary data provide some insight into the ultimate application of these design features to agricultural wastewater treatment.

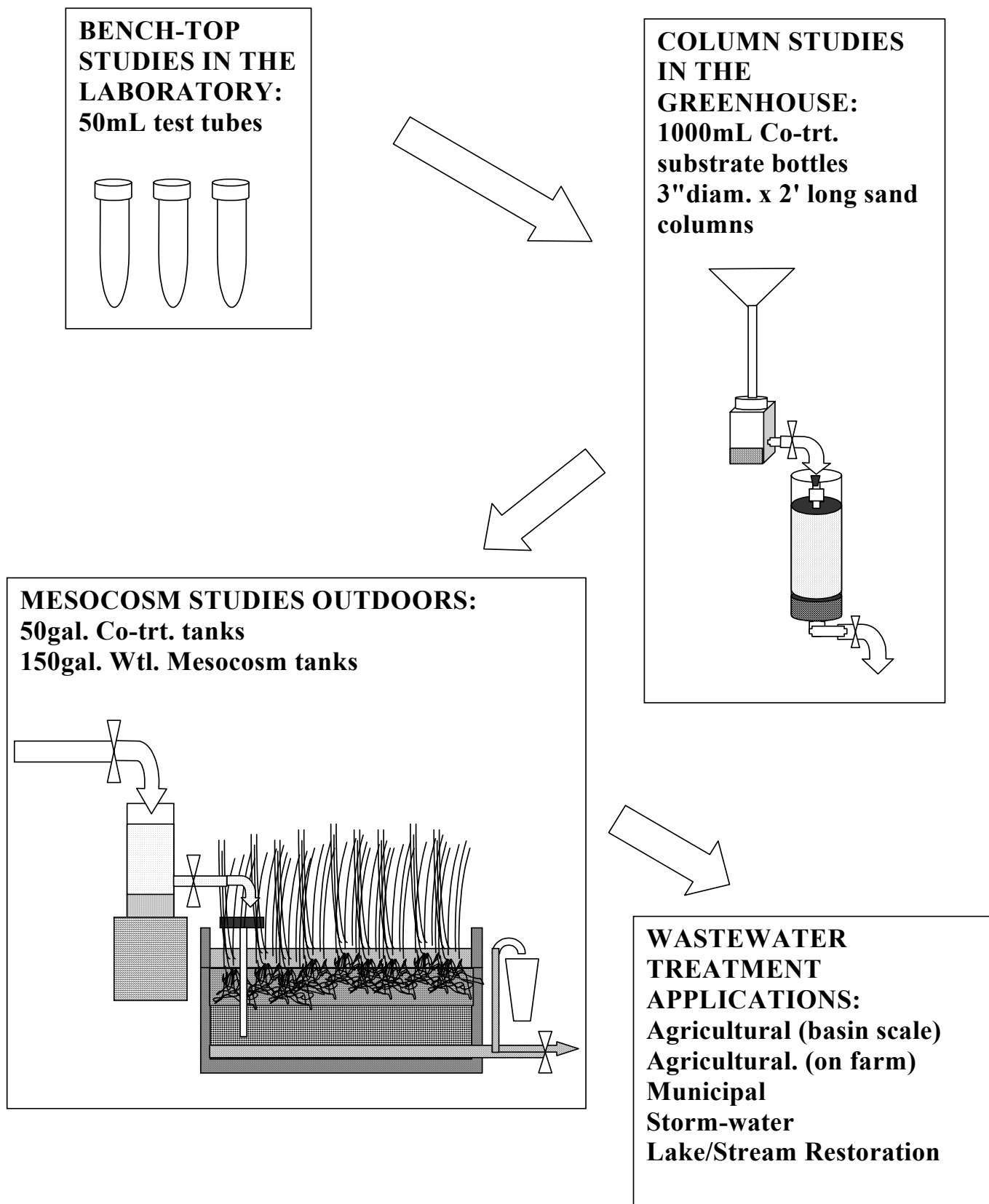


Fig. 1. Diagram of Research Sequence for Development of this Technology.

Table 1. Description of Substrates Considered for Co-Treatments.

SUBSTRATE:	COMPOSITION:	SOURCE:	SUPPLIER/LOCATION:	COMMENTS:
Iron humate	Fe humates & hydroxides	DWTR	Water treatment plant (FL)	Already used as agricultural soil amendment in Florida
Lime sludge	Ca	DWTR	Water treatment plant (FL)	Very Sticky/cohesive
Magnesium fines	Mg, S	Mg fertilizer production	Fertilizer facility (FL)	Fertilizer material; clumps when wet
Dried humate	Humates, Al, Fe, Ca, Mg,	Titanium mining	By-product processor (FL)	Works well; Cost/supply issues
Coated sand	Sand, Fe, Al	Sand mining	Sand mine company (FL)	Mining overburden; natural soil material
Sand – concrete	Sand, Fe, Al	Sand mining	Sand mine company (FL)	Other market for it; used only for coarse/clean root-bed media in this project
Sand – masonry	Sand, Fe, Al	Sand mining	Sand mine company (FL)	Other market for it
Aluminum #1 (white)	Al	Aluminum ore mining/processing	Aluminum companies (facilities in US)	Other market for it at high price
Aluminum #2 (gray)	Ca, Al, Fe alumina-coke mixture	Aluminum ore mining/processing	Aluminum companies (MO)	By-product that is currently landfilled
Dehydrated Fe sludge	Fe	Vortex dehydrator (processed wasted)	Waste processor (Kansas)	Not locally available
Sandblast grit	Mostly Fe; other metals	Ship repair (sand-blasting)	Tampa ship repair facilities (FL)	Long-term toxicity concerns

Hypotheses and Objectives

The central hypothesis was that optimizing hydrology and co-treatments would enhance the ability and sustainability of constructed wetlands (CW) to remove P from agricultural wastewater.

The specific objectives of the research were to: 1.) screen potential by-product co-treatment substrates in the lab for P removal/retention properties and other relevant parameters; 2.) test system hydrology (flood/drain cycle) and P removal/retention in a greenhouse co-treatment bottle and sand column experiment; 3.) test the substrates, hydrology, and aquatic plants in an outdoor co-treatment and wetland mesocosm system for P removal from wastewaters; and 4.) analyze the combined data from lab, greenhouse and outdoor mesocosm experiments to determine an optimization plan for P removal/retention by the co-treatment and wetland system.

The research questions were pursued using a sequence of lab, greenhouse, and outdoor mesocosm studies (**Fig.1**). Forms and amounts of P were measured in all major components of the systems before and after loading. A mass balance of P in the mesocosm systems will thus be acquired. Sequential extraction and fractionation procedures were used to identify the levels and forms of P. Numerous parameters relevant to P removal and retention were measured at each stage of the research. The goal was to find out which variables have the most significant impact on P removal by these systems.

The entire research project was divided up into four major tasks: 1.) Lab Studies;

2.) Greenhouse Column Studies; 3.) Outdoor Mesocosm Studies; and 4.) Synthesis of Combined Results.

The research supported by the FDACS funding included tasks 3 and 4. The entire research project is being completed as part of a doctoral dissertation at the University of Florida. Any additional data coming out of this research project that may be relevant to agricultural wastewater treatment will be provided to FDACS.

Before the conclusion of the field experiments at the dairy site, effluent (from experimental cohort 25) was collected from the control tanks to conduct a side experiment. This side experiment was designed to test two hypotheses regarding phosphorus (P) removal from the agricultural wastewater at this site.

The first hypothesis was that the relatively poor P removal performance by the co-treatments with the dairy wastewater, compared to with the municipal wastewater, was not simply due to the higher P concentration. It was suspected that high total suspended solids (TSS) and high dissolved organic carbon (DOC) in the dairy wastewater were impairing the ability of the co-treatment material to remove P from solution. Suspended and dissolved organic matter is known to reduce the effectiveness of chemical treatments for phosphorus removal.

The second hypothesis was that placing the co-treatment after, rather than before, the wetland cell would improve P removal from a wastewater with high TSS. This was based on the large reduction of TSS by the experimental system observed earlier.

Rationale and Technical Significance

Phosphorus (P) is a common nutrient in agricultural and municipal wastewater. When not removed from the wastewater it can cause eutrophication of the surface waters to which it is discharged. Eutrophication occurs as excess nutrients enter an aquatic ecosystem and cause an imbalance in the growth of aquatic plants. Excess P is linked to algal blooms in fresh surface waters such as Lake Okeechobee when it is the limiting nutrient. Blooms result from the accelerated growth of surface algae which shades out the submerged vegetation and thus reduces aquatic habitat and oxygen production. Upon senescence the algae decompose, consuming dissolved oxygen and acidifying the water. This cascade of events can cause fish kills and damage aquatic ecosystems (Wetzel, 1983). The eutrophication of Lake Okeechobee has increased due to the high levels of phosphorus in agricultural runoff (Nair et al, 1998). More recently it has been suggested that P from agricultural sources, discharged to surface waters elsewhere along the Atlantic coast, has stimulated blooms of a virulent form of the aquatic microorganism *Pfiesteria*. This organism represents a threat to human and ecosystem health as well as to the tourism and seafood industries (Burkholder, 1999).

The US-EPA has identified agriculture as a source of excess P that is damaging surface waters. However, management of excess P with conventional wastewater treatment can be cost-prohibitive to the agricultural industry (Sharpley, 1999). Natural wetlands are known to buffer some of the impact on downstream waters of excess P in effluent and runoff (Reddy et al., 1994; Richardson, 1999). Man-made or "constructed wetlands" (CW's) are now an accepted low-cost technology for removing P from wastewater (US-EPA, 1993). However, questions of mechanisms, predictability and sustainability persist (Richardson, 1999) and there is a need to optimize P removal by these systems (Kadlec and Knight, 1996).

Current CW treatment systems rely on the sequestration and burial of P in organic and inorganic sediments (Kadlec, 1997) and are thus ultimately unsustainable as the wetland eventually fills in. This process of accretion may take many years to fill in the treatment wetland. However, treatment wetlands can decline in performance over the years and can even cease to remove phosphorus. Although CW's may be managed to act as sink for P, their functional longevity and cost effectiveness are limited by their size. There is also a need for finding ways to capture P from wastewater and return it to agriculture as a nutrient source in order to balance inputs and outputs of P in agricultural systems (Sharpley, 1999). By sequestering the P with non-toxic materials it could possibly be re-used by agriculture. The use of by-products in co-treatments could be a low-cost way to improve the performance and longevity of CW's or could be used to reduce the wetland area required for a given level of treatment.

Soil, sand, and non-toxic by-products containing iron, aluminum, calcium, magnesium, organic matter or clay were selected for initial evaluation due to the influence of these factors on P removal (Khalid, 1977; Richardson, 1985; Gale et al., 1994; Reddy et al., 1996; Bridgham et al., 1998). These by-products can be effectively used to optimize P removal. However, interactive effects of individual factors needs further evaluation (Ann et al., 2000; Gruneberg et al., 2000). There is also concern in the Okeechobee basin about using conventional chemical treatments that include iron and aluminum due to possible biological toxicity (Anderson et al., 1995). One of the iron-containing by-products, a Tampa drinking water treatment residual, is already being used as a soil amendment by citrus growers in Florida. Citrus agriculture is increasing in the Okeechobee basin (Bottcher et al., 1995) thus creating the potential for cooperative local P management.

Other aspects of using constructed wetlands for treating agricultural wastewater were investigated in this research. Several authors have noted that spatially or temporally adjacent aerobic/anaerobic conditions optimizes nutrient removal from wastewater by the aquatic plant, microbe and sediment communities in wetlands (Khalid, 1977; Sah 1989; Toerien et al., 1990). Conventional wastewater treatment systems, as well as wetlands, usually include aerobic and anaerobic stages or zones for the removal of nitrogen (N) (Reddy et al., 1989; Toerien et al., 1990). Under aerobic conditions nitrogenous wastes are converted to nitrates by the process of nitrification. Under anaerobic conditions nitrates are converted to nitrogen gas that escapes to the atmosphere. This allows for treatment systems to theoretically be sustainable for N removal, since the atmosphere

provides a safe and unlimited sink for nitrogen. Phosphorus (P), however, is not significantly converted to gaseous form and thus a wetland treatment system alone cannot be completely sustainable unless P is separated and removed in the dissolved or solid form. A treatment wetland designed for nitrogen removal will have a finite life-span for the removal and storage of P. One distinguishing feature of this research is the concept of removing P in a refillable co-treatment tank preceding the wetland and thereby extending its functional life-span.

It has been suggested that an oxygenated (aerobic) microzone forms in the wetland below the sediment-water interface preventing diffusion of P back into the water column after adsorption. Continuing reactions seem to cause a shift from loosely bound to tightly bound P in the sediment (Reddy et al., 1998; Syers, 1981). Aerobic and anaerobic zones exist in the designed system. Although the use of separate aerobic and anaerobic tanks is common in conventional wastewater treatment, few constructed wetland system designs employ a single basin that alternates between both conditions. One common conventional wastewater treatment process consists of four cyclic anaerobic and aerobic phases in a single treatment basin. Usually, however, the aerobic and anaerobic treatment cells are placed in series (Toerien et al., 1990). In the designed system, individual treatment cells were flooded and drained enhancing aerobic and anaerobic conditions alternating in individual cells. Hydrologic manipulations are a practical full-scale management tool and could be optimized for P removal (Kadlec and Knight, 1996).

Many other factors influence P dynamics in constructed wetlands. The uptake of P by the aquatic plants is considered only a short-term sink for P in the Lake Okeechobee basin due to their annual senescence (Reddy et al., 1996). However, plant type, quantity and ability to oxygenate the rhizosphere can all have an impact (Barko and Smart, 1980; Emery et al., 1996). Temperature and microbes can influence P indirectly by influencing pH, dissolved oxygen, and oxidation-reduction potential or "redox" (Eh). Each of these factors contributes to the overall P dynamics of constructed wetlands (Gachter et al., 1993; Reddy et al., 1999) and were examined in this research.

Key Features of the System Investigated:

- 1. Free or inexpensive** drinking water treatment residuals, and other non-toxic **by-products available in Florida**, with phosphorus binding potential used in co-treatments with constructed wetlands.
- 2. Once they have ceased to efficiently remove phosphorus, the co-treatments are materials that could be land applied for agriculture.**
- 3. Co-treatments are in cells before the wetlands** and thus can be emptied (when saturated) and refilled with “fresh” material **without disturbing the established wetland.**
- 4. Passive mixing** of wastewater with co-treatment materials **minimizes mechanization and energy costs** for wastewater treatment.

5. **Separate co-treatment cells allow for flexibility in future to modify** co-treatments based on availability and performance of various **co-treatment materials** (used singly or in combination).
6. Using phosphorus-removing materials in separate co-treatment cells **increases the control**, and **decreases the exposure** of the materials **to wetland flora and fauna**.
7. A small amount of co-treatment material will be carried with the wastewater into the constructed wetland and may **increase the stability of phosphorus in the wetland itself**.
8. System is designed with both **vertical and horizontal flow of wastewater** in wetland to maximize contact with wetland root-bed.
9. **Alternating flood and drain cycles in each cell** encourage anaerobic and aerobic conditions **to optimize phosphorus removal and retention**.
10. **Cells are batch-fed allowing controlled** hydraulic retention time (**HRT**) and hydraulic loading rate (**HLR**).

MATERIALS AND METHODS:

Preparation of Site, Equipment and Materials

It is costly and difficult to conduct experimental, as opposed to merely observational, research on full-scale constructed wetlands (CW's). Likewise, in situ mesocosms within large wetlands are also problematic due to the heterogeneity of soils, plants, and other confounding variables. Without being able to systematically vary the major controlling factors it would be difficult to make general conclusions regarding causality or treatment effects. With lab or "bench top" studies, confounding variables can be controlled but the results might be unrealistic relative to the full-scale system. Mesocosm studies however, such as the one completed, bridge the gap between "bench top" or greenhouse research and observational studies of full-scale systems. The controlled experimental design with mesocosms improves knowledge transferability. The need exists for wetland mesocosm studies where confounding factors can be controlled (Kadlec, 1987). There is also a need to bridge the gap between lab studies and field studies before full-scale implementation (Kadlec and Knight, 1996; Richardson, 1999). Wetland mesocosms are considered to be a practical and useful tool in testing wetland design features. The mesocosms used in this experiment were very similar to others commonly used in wetland research (Ahn et al., 2001).

Results from the earlier lab and greenhouse column experiments were used to set up the design characteristics of the outdoor wetland mesocosm systems. Not only P sorption properties but also mixing turbidity, metals content, redox values and algae observations from the column study were considered. Practical considerations such as

by-product cost and availability, potential toxicity, and handling properties were also taken into account.

In the "Task 3-Mesocosm Studies", outdoor tanks were set up with sand and aquatic plants to represent constructed wetland treatment cells. The tanks were plumbed for vertical flow and to allow control of the wastewater hydraulic retention time (HRT) or flood/drain cycles. Based on the results of the first two tasks, substrates were selected and enclosed in co-treatment tanks preceding the wetland cells (**Fig.2**). The co-treatment tanks contained either one of two by-product substrates or were filled to an equivalent depth, with site tap water, to serve as controls. There were three replicates of each of these tanks. The experiment will test two different wastewaters representing high and low P level wastewater treatment. There were thus three treatments (including the control), times two wastewaters, times three replicates, for a total of eighteen units. Random assignment and replication of treatments were employed to reinforce the statistical validity and interpretation of results.

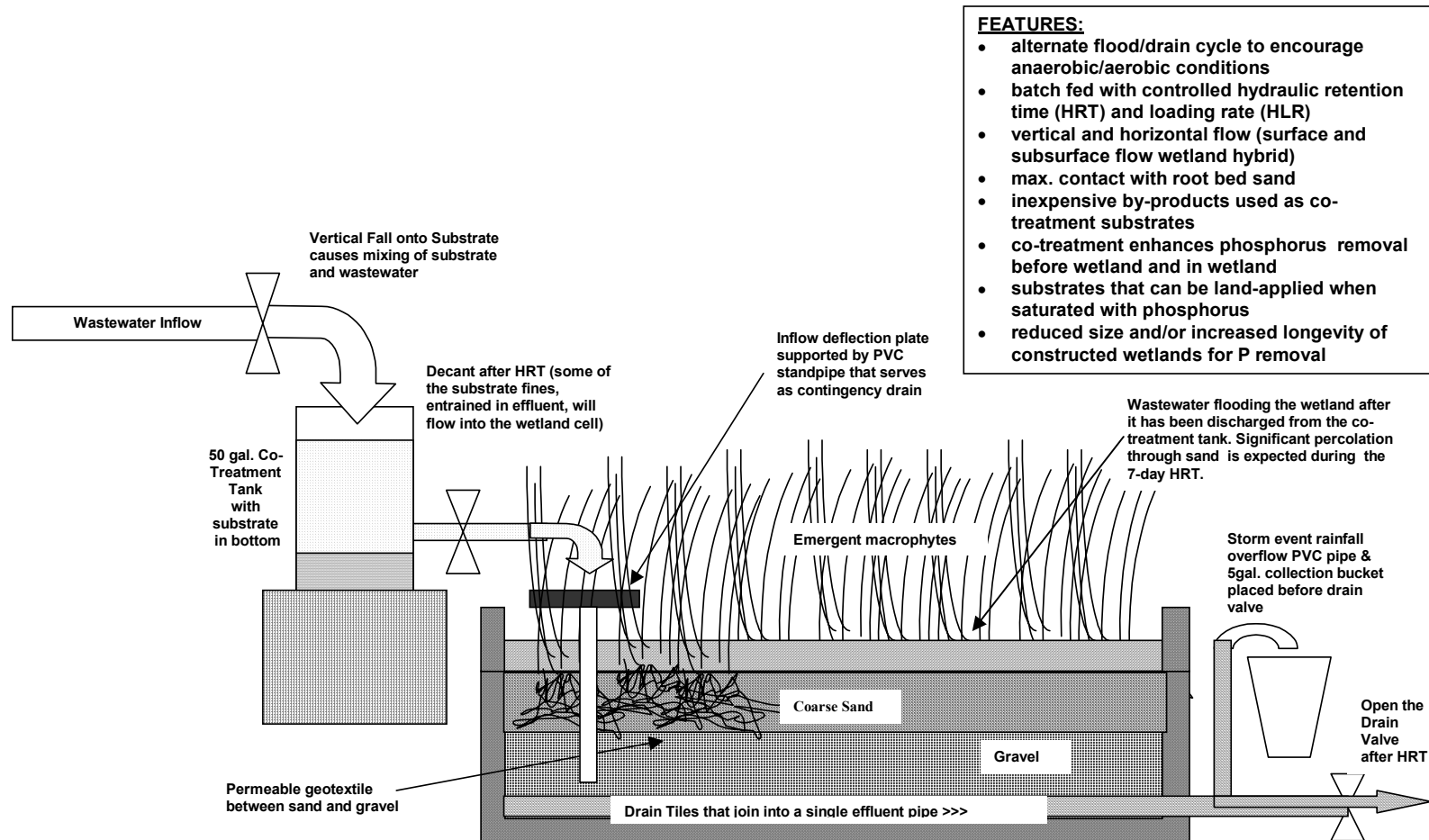


Fig. 2. Co-Treatment Reactor (CTR) and Constructed Wetland Mesocosm (CWM)

Eighteen constructed wetland mesocosm (CWM) tanks were constructed with sand and aquatic plants to represent constructed wetland treatment cells. The tanks were plumbed for vertical flow and to allow control of the wastewater hydraulic retention time (HRT). Co-treatment reactor (CTR) barrels were set up ahead of the CWM's to contain either one of two by-product substrates or tap water only to serve as a control. The experiment is testing two different wastewaters representing high and low P level wastewater treatment. There are thus three treatments (including the control), times two wastewaters, times three replicates of each, for a total of eighteen units. Random assignment and replication of treatments used will reinforce the statistical validity and interpretation of the final results.

Two wastewaters were tested and are characterized in **Table 2.** below. The first was a dairy effluent that had undergone anaerobic digestion for primary treatment but still had high phosphorus levels. This anaerobic digester effluent (ADE) was considered a “high strength wastewater”. The fixed-film anaerobic digester was designed for Florida dairy farms. It is being used to treat barn-flushed manure at the University of Florida Dairy Research Unit (DRU). It reduces odors, produces energy from the biogas generated, reduces pathogens, and improves water and nutrient recovery (Wilkie, 2000). The second was a secondarily treated municipal wastewater with relatively low P levels. It was the effluent from the Gainesville Regional Utilities (GRU) Main Street wastewater treatment plant. This was considered a “low strength wastewater”.

The initial three-foot fall of wastewater pumped into the CTR barrels at loading was the only mixing energy that was used for the wastewater and co-treatment substrates.

After a hydraulic retention time (HRT) of 7-days, the wastewater was drained into the constructed wetland mesocosms where it remained for another 7-days before final draining (and thus completion of the treatment cycle).

Table 2. Characterization of the two wastewaters tested and conditions in the Co-Treatment Reactors and Constructed Wetland Mesocosms.

Anaerobically Digested Dairy (DRU) Wastewater:		Secondarily Treated Municipal (GRU) Wastewater:	
[SRP] (mg/L)	3.8 - 15.6	[SRP] (mg/L)	0.44 - 1.8
[TP] (mg/L)	33 - 74	[TP] (mg/L)	0.47 - 2.5
pH	6.7 - 7.4	pH	6.7 - 7.4
TSS (mg/L)	2390	TSS (mg/L)	(undetected.)
DOC (mg/L)	453	DOC (mg/L)	< 7
DO (mg/L)	< 1	DO (mg/L)	> 8
Conductivity (mS/cm)	4.5	Conductivity (mS/cm)	0.7
Salinity (ppt)	2.2	Salinity (ppt)	0.3
TSS Measurements from Inflowing Wastewater to Co-Treatment Reactor effluent to Constructed Wetland Mesocosm effluent at Each Site:			
TSS (mg/L) at DRU:	2390	229	68
TSS (mg/L) at GRU:	Below detection limit (< 1mg per 500mL)		
Changes in Oxidation-Reduction Potential (Redox) in CWM at each Site:		Flooded with wastewater	Drained of wastewater
at DRU:	Redox (mV)	-147	+95
at GRU:	Redox (mV)	+136	+440

Two mesocosm research sites were chosen near the wastewater sources. One site was at the University of Florida's dairy farm, near the fixed-film anaerobic digester. The second site was at the GRU Main Street plant. These two sites, with different levels of P in the wastewater, provide data applicable to a greater range of P treatment scenarios. Influent wastewater, effluent, and system P levels were analyzed to obtain a mass balance for P removal and storage by the various system combinations. Phosphorus concentrations and forms in all major components, inflows, and outflows of the systems were measured before and after loading. Metals content, pH, and oxidation-reduction potential (redox) were also measured in these systems in order to better characterize the mechanisms of P removal and retention. A better understanding of these mechanisms will enhance the operator's ability to control and predict the performance of these systems. For each phase of this research published standard methods were used where possible (some standard methods have been modified at the UF Wetland Biogeochemistry Lab to better accommodate the special conditions of wetland systems). All laboratory analyses were done in accordance with accepted Quality Assurance and Quality Control (QA/QC) standards and protocols.

Experimental Set Up

Operation of Co-Treatment and Mesocosm Systems

Sampling of System Materials

Monitoring Measurements

Side Experiment at DRU Site

As in the column study described earlier, the dry mass of each co-treatment substrate used was the same to allow for a fair comparison of P removed per mass of substrate. Also as in the column study, the initial mass of by-product substrate used in the co-treatment tanks was determined based on expected P levels of the wastewater, volumes of wastewater treated, and expected P removal potential of the material as determined by the lab and greenhouse column experiments. The hydraulic loading rate (HLR) was calculated as in the column studies. After filling and planting, the mesocosm tanks were able to receive 35 gallons (~132.5 L) of wastewater per cycle (with ample freeboard to allow for rainfall additions). Assuming a wetland mesocosm surface area of 7000 cm², and a 7day HRT, the HLR was 2.7 cm day⁻¹. As with the column studies, this HLR coincides with typical design parameters for a wastewater treatment wetland (Kadlec and Knight, 1996). It is also on the same order of magnitude of other wetland mesocosms being used in research elsewhere (Ahn et al., 2001). It should be noted that the HRT of the co-treatment reactor and wetland combined totaled 14 days and would thus make the HLR for the total treatment system 1.35 cm day⁻¹. Complete wastewater treatment systems often include several stages, with each contributing to the total HRT.

To test the hypotheses set forth for the side experiment at the DRU discussed earlier, a large volume of the effluent was collected from the twenty-fifth cycle of the larger scale experiment. Effluent was only collected from the three control experimental

wetlands. This effluent had only been through a control co-treatment reactor (i.e., no co-treatment substrate) and a wetland cell with no contact with the iron or lime materials. Effluent from the three control tanks was combined and composite samples were added to nine five-gallon containers on site. The containers were covered, just like the larger co-treatment reactors, to keep out sunlight and prevent algal growth. Three of the randomly chosen buckets contained the lime material, three the iron, and three were empty to serve as experimental controls. The mass of co-treatment material, and the volume of effluent added to each bucket, was in the same proportion as in the larger scale experiment. After seven days the water in these buckets was tested for P concentration.

Analytical Methods

Wastewater

Sand

Substrates

Macrophytes

Forms and amounts of P were measured in all the major components of the systems (wastewater, sand, substrates and macrophytes) before and after loading. A mass balance of P in the mesocosm systems was thus acquired. Sequential extraction and fractionation procedures were used to identify the levels and forms of P. Numerous other parameters, relevant to P removal and retention, were measured. These included: the metals iron, aluminum, calcium and magnesium; oxidation-reduction potential; pH; dissolved oxygen; conductivity and salinity; total suspended solids (TSS); dissolved organic carbon (DOC) in the form of non-purgeable organic carbon (NPOC) from filtered (0.45 micron) samples; temperature; bulrush stem counts; and wetland draining rates. Each of these will aid in the assessment of the features of this system design.

Results

Data from the earlier lab and greenhouse experiments indicated that certain co-treatment by-products such as the DWTR's could remove and retain soluble reactive phosphorus (SRP) from wastewater. This SRP is considered the more immediately and biologically available component of the total phosphorus (TP) in wastewater and thus was the focus of the design of the co-treatment reactors (CTR). The total phosphorus in many wastewaters also includes particulate and dissolved organic phosphorus forms. The two wastewaters used in this research differed greatly in both phosphorus amounts and forms. There was also a tremendous difference in the amounts of particulate materials (measured as total suspended solids or TSS) and dissolved organic carbon (measured as non-purgeable organic carbon or NPOC) as shown in **Table 2** and **Figures 7, 12, 13**. The TSS of the digested dairy wastewater was 2390 mg/L. The TSS of the secondary municipal wastewater was undetectable by the same method. The NPOC of the dairy wastewater was 452.83 mg/L whereas the municipal wastewater had only 6.62 mg/L. These differences may be responsible for the large differences in the P removal performance between the two different wastewaters (**Figures 3 and 5**). It is suspected that both the high TSS and NPOC levels in the dairy wastewater (anaerobic digester effluent or ADE) interfered with the ability of the DWTR's to capture soluble phosphorus in the co-treatment reactors. This hypothesis was tested in a side experiment and the data (**Figures 9 and 10**) and results are discussed below.

The data provided below (**Figures 3, 4, 5** and **Table 3**) present the mean effluent phosphorus data from the co-treatment reactor (CTR) and constructed wetland mesocosm

(CWM) systems. Data for both the low strength and high strength wastewaters are provided. The graphs show the changes in phosphorus concentrations of the wastewaters as they flow from source, to CTR, to CWM, and then are finally discharged. The concentrations of the effluents from control, lime DWTR, and iron DWTR treatment trains are shown separately to examine differences between treatments and controls. It should be noted that the CWM's are uncovered and thus subject to both rainfall additions and evapotranspiration losses. Based on identical initial construction, similar plant coverage, and complete random placement of treatments at each site, volume changes are essentially identical for treatments and controls, thus allowing for comparisons of concentrations. Volume changes were measured each week and were used to convert the concentrations to masses for the final phosphorus mass balance of the systems.

For the low-strength (secondarily treated municipal) wastewater, average soluble reactive phosphorus (SRP) concentrations were reduced from 0.695 mg L^{-1} to 0.030 mg L^{-1} (95% reduction) or 0.014 mg L^{-1} (98%) by systems with the calcium or iron co-treatments respectively (compared to 0.089 mg L^{-1} or 87% with the controls). In preliminary data for the same wastewater, total phosphorus (TP) concentrations were reduced from 0.993 mg L^{-1} to 0.065 mg L^{-1} (93%) and 0.050 mg L^{-1} (95%) by the same treatments (compared to 0.148 mg L^{-1} or 85% with the controls). For the high-strength wastewater (anaerobically digested flushed dairy manure), average SRP was reduced from 7.68 mg L^{-1} to 6.43 mg L^{-1} (16%) or 5.95 mg L^{-1} (22%) by the systems with calcium or iron respectively (compared to 7.37 mg L^{-1} or 4% with the controls). The TP was reduced from 48.50 mg L^{-1} to 22.48 mg L^{-1} (53%) and 22.74 mg L^{-1} (53%) by the same treatments

(compared to 24.10 mg L⁻¹ or 50% with the controls). For the high-strength wastewater the small differences in the TP reduction between treatments and controls could indicate that there is no major effect of the treatments on the P in the wetland effluents for at least short-term (one year).

The TP data from the dairy wastewater site in **Figure 3** show reductions in phosphorus from over 48 mg/L down to less than 23 mg/L (52% reduction). This compares favorably with the published average removal from 24 mg/L to 14 mg/L (42% reduction) for animal wastewater treatment wetlands (Knight et al, 1996). However, it should be noted that hydraulic loading rates and other features of the various system designs would have to be taken into account for a fair comparison of performance.

As discussed earlier, the high-strength (dairy) wastewater had much higher Total Suspended Solids (TSS) and dissolved organic carbon (DOC) and it was suspected that this reduced the co-treatment's efficiency of P removal from this wastewater. The co-treatment and wetland systems greatly reduced TSS in the dairy wastewater from 2390 mg L⁻¹ to 68 mg L⁻¹ (**Figure 6**). The TSS appeared to be somewhat higher in the effluents of the co-treatment systems as seen in **Figure 11**. The co-treatments preceded the wetland cells in this 52-week experiment but for agricultural wastewaters with high TSS, the co-treatment may remove P more efficiently when used following an initial wetland cell in the treatment sequence. An additional short-term experiment was added to the research and completed with dairy wastewater and has supported this hypothesis. As described in the Materials and Methods section the effluent used had only been through a control co-treatment reactor (i.e., no co-treatment substrate) and a wetland cell

with no contact with the iron or lime materials. Thus the only major difference suspected was the much lower TSS and DOC. Initial SRP reductions were from 7.28 mg L⁻¹ to 3.48 mg L⁻¹ (52%) and 0.28 mg L⁻¹ (96%) by the systems with calcium or iron, respectively (compared to 3.77mg L⁻¹ or 48% with the control). Initial TP reductions (**Figure 9**) were from 28.43 mg L⁻¹ to 12.26 mg L⁻¹ (56%) and 8.12 mg L⁻¹ (71%) by the systems with calcium or iron, respectively (compared to 24.47 mg L⁻¹ or 14% with the control). The improvement in P removal performance is evident when compared to the TP data in **Figure 8** for the first cycle of the DRU system used for the 52-week experiment.

The total solids in the DRU system effluents shown in **Figure 14** suggest that there were no significant differences between treatments and controls suggesting that the co-treatment substrates do not increase the particle mass loading to the treatment wetlands. However, in both control and treatment wetlands did appear to increase TS and this is thought to be due to algal growth in the wetlands with this high nutrient wastewater or to the outflow of some sand particles from the vertical-flow wetlands. Organic matter (OM), measured as percent lost on ignition (LOI), appeared to be reduced as seen in **Figure 15** at the DRU site by controls and treatments and is thought to be due to sedimentation, decomposition, and entrapment of fiber materials in the dairy wastewater.

Bulrush stem counts were done initially and quarterly throughout the one year mesocosm experiment. In terms of green stem counts (**Figure 16**) there appears to be no negative effect on bulrush plant growth as a result of the co-treatment materials. In fact,

there seems to be a small positive impact on plant growth when comparing treatment to control wetland mesocosms in **Figure 17**.

The soluble reactive phosphorus data for the DRU site is provided in **Table 3** to illustrate the changes in performance of the systems over the course of one year with two change-outs of co-treatment substrates. Initially CTR effluents were lower in treatments than controls as predicted. Initial CWM effluents were not very different as expected due to the initial removal of P by the newly constructed sand and bulrush wetland mesocosms. After 52 weeks (26 treatment cycles) there does appear to be some difference in SRP between treatments and controls but not as well as expected as discussed and explained elsewhere.

Table 3. Effluent soluble reactive P (SRP) patterns with the high-strength (dairy) wastewater.

		[SRP] (mg/L)			[SRP] (mg/L)		
	Digester Effluent	Co-Treatment Reactor (CTR) Effluents			Constructed Wetland Mesocosm (CWM) Effluents		
Cohort	[SRP] (mg/L)	Control CTR	Lime CTR	Iron CTR	(Control) CWM	(Lime) CWM	(Iron) CWM
1	9.34	8.50	6.55	5.20	1.76	1.77	1.58
2	9.63	9.24	6.12	5.10	2.93	2.24	2.20
3	5.49	4.78	5.20	4.54	2.83	2.96	2.27
4	7.51	8.46	6.44	6.74	3.96	4.00	3.38
5	8.700	9.068	7.971	7.786	3.831	3.545	3.557
6	15.654	9.789	7.849	8.397	4.615	4.758	4.612
7	8.655	11.119	7.830	7.394	5.997	5.752	5.767
8	9.988	12.269	8.552	10.490	11.011	9.619	9.355
9	7.127	9.579	6.859	7.351	10.091	6.555	7.178
10	<i>(Systems Not Loaded with Wastewater During Change-out of Substrates in Co-Treatment Reactors)</i>						
11	7.185	7.436	8.929	8.369	9.088	9.081	7.035
12	7.543	10.525	9.539	10.353	10.645	8.955	9.696
13	4.845	7.978	8.954	8.167	9.793	8.391	7.623
14	6.791	10.011	8.988	8.494	14.355	10.734	10.214
15	3.779	7.580	5.933	5.634	10.834	11.098	6.629
16	8.056	10.126	8.427	8.173	10.217	6.683	8.208
17	6.953	7.872	7.958	8.143	8.972	6.647	6.888
18	9.076	10.026	7.908	8.124	9.004	5.732	8.164
19	6.885	6.984	7.404	7.774	5.117	4.209	4.933
20	6.083	9.274	8.024	7.291	5.696	5.238	4.949
21	<i>(Systems Not Loaded with Wastewater During Change-out of Substrates in Co-Treatment Reactors)</i>						
22	5.537	5.241	4.640	3.900	8.566	7.696	5.327
23	5.336	7.244	6.571	6.548	6.472	7.636	5.126
24	8.816	7.602	6.145	6.967	5.851	5.970	4.894
25	6.746	8.719	8.175	7.74	7.98	6.674	6.356
26	8.652	7.333	8.075	9.237	7.291	8.34	6.902
Average:	7.68	8.61	7.46	7.41	7.37	6.43	5.95
Std. Error:	0.28	0.21	0.15	0.19	0.37	0.30	0.28

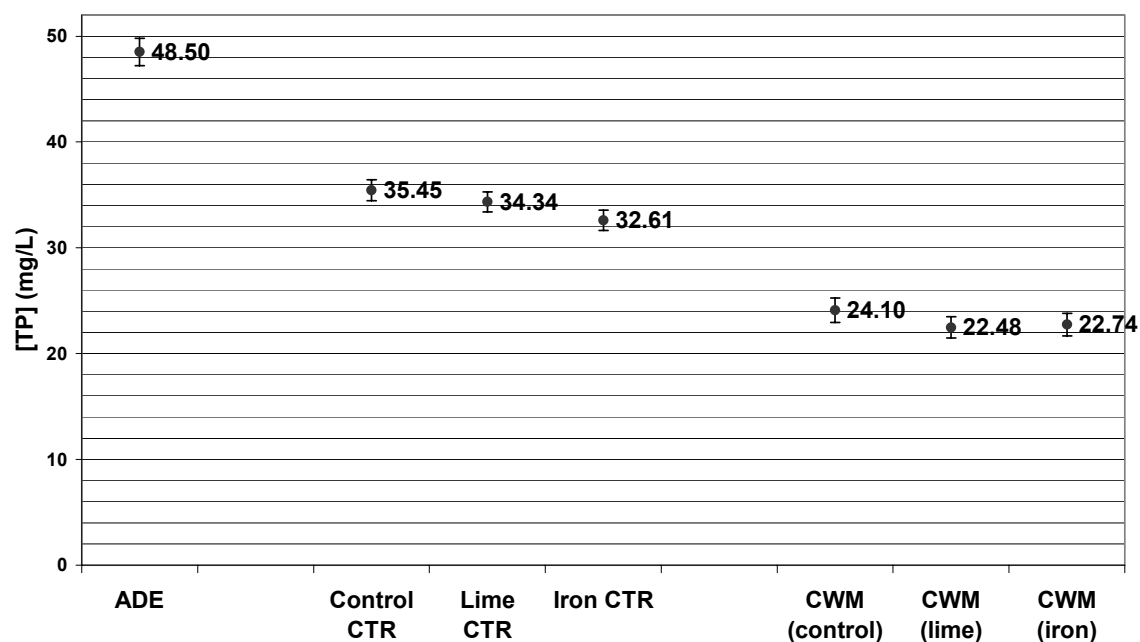


Fig. 3 Effluent Total Phosphorus [TP] (+/- S.E.) 52 week means with the high-strength (dairy) wastewater.

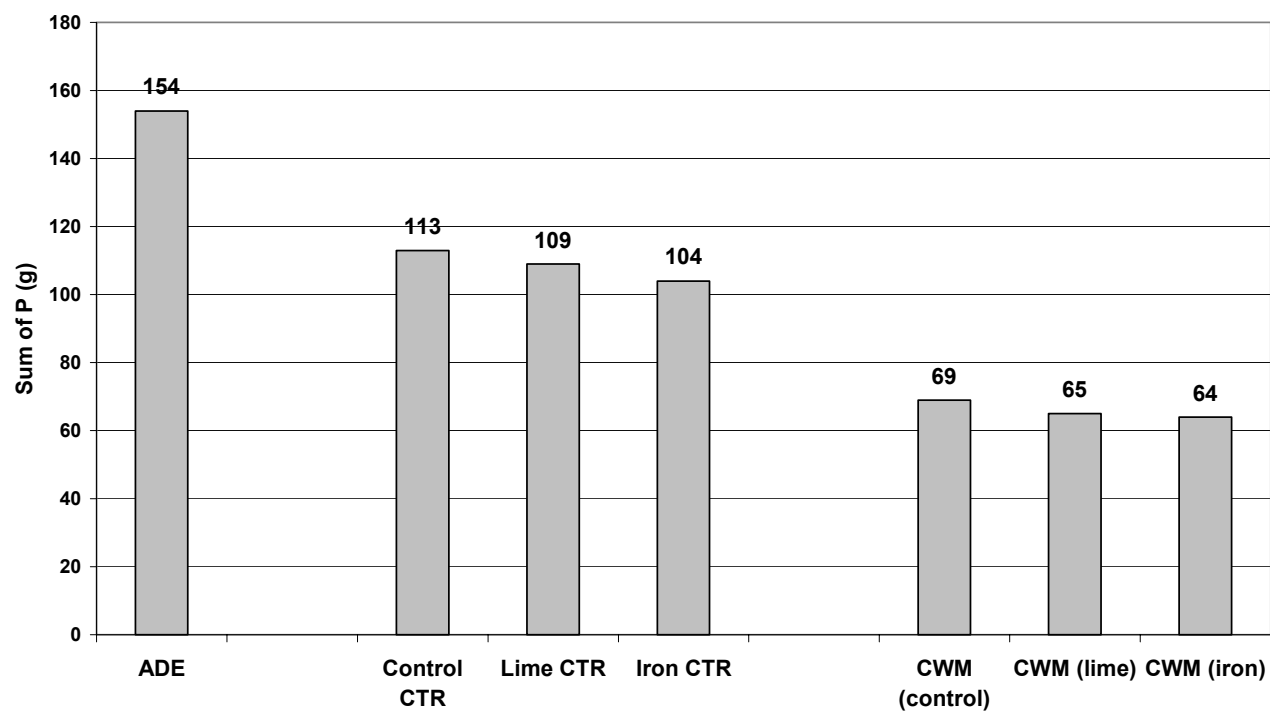


Fig. 4 Sums (52 Weeks) of P Masses in Effluents from Experimental Systems at Dairy

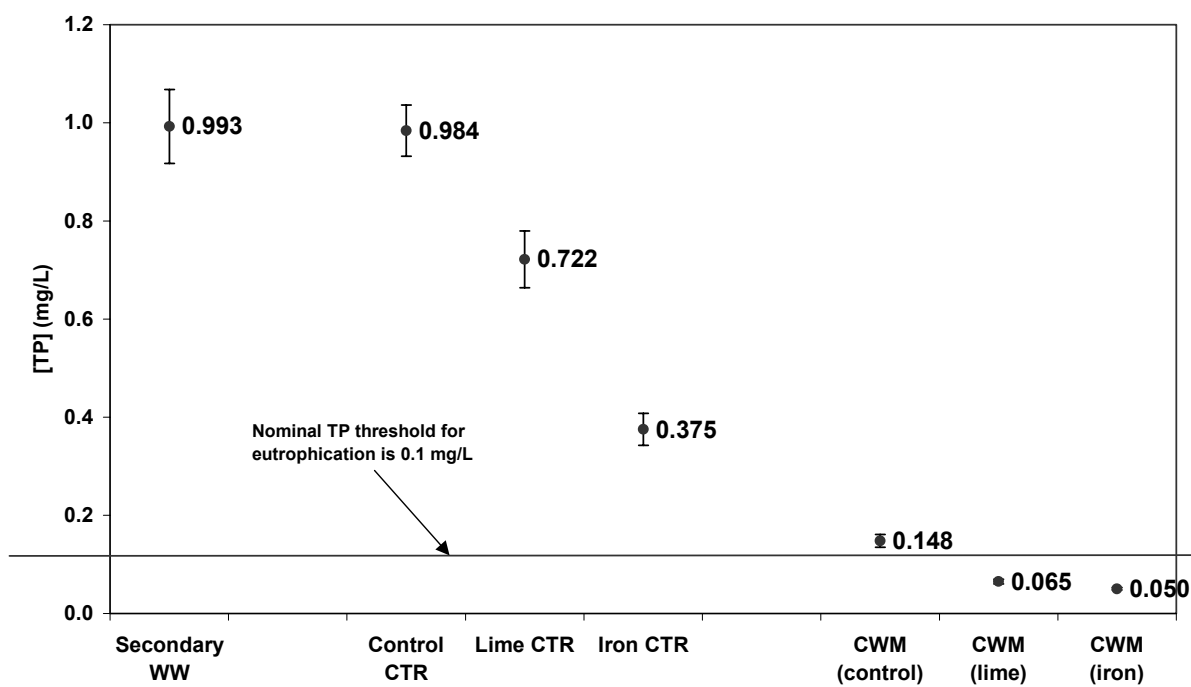


Fig. 5 Effluent Total Phosphorus [TP] (+/- S.E.) means with the low-strength (GRU) wastewater.

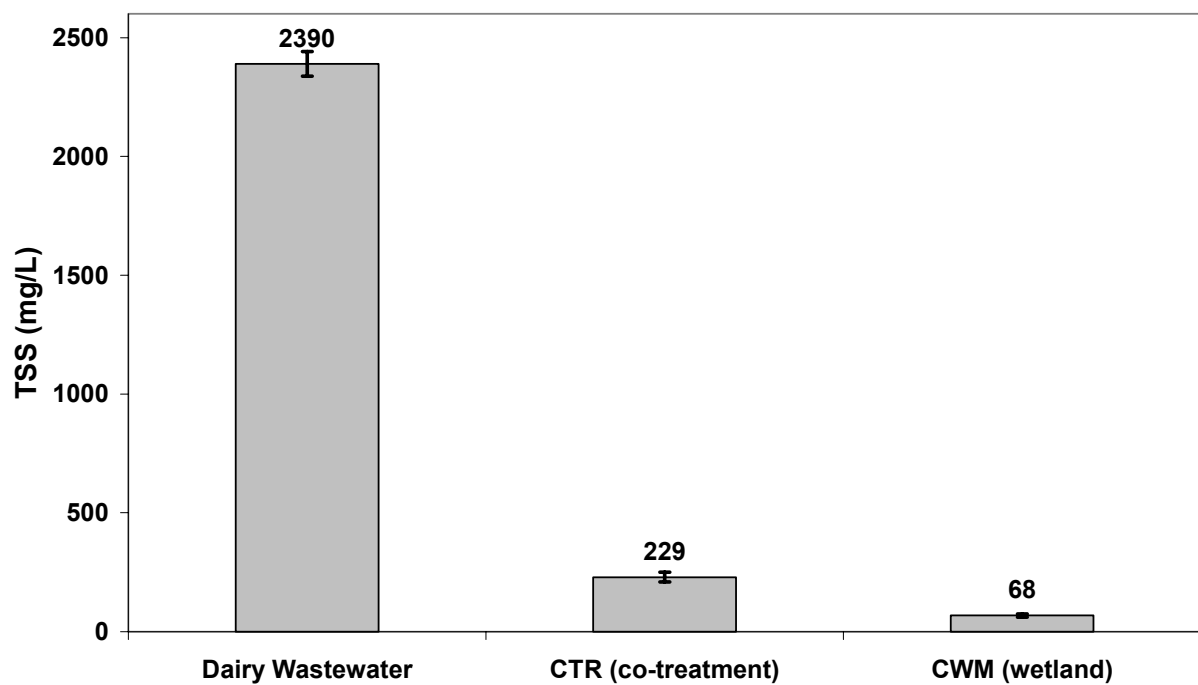


Fig. 6 Mean Total Suspended Solids (TSS) (+/- S.E.) in DRU Effluents by Sampling Point

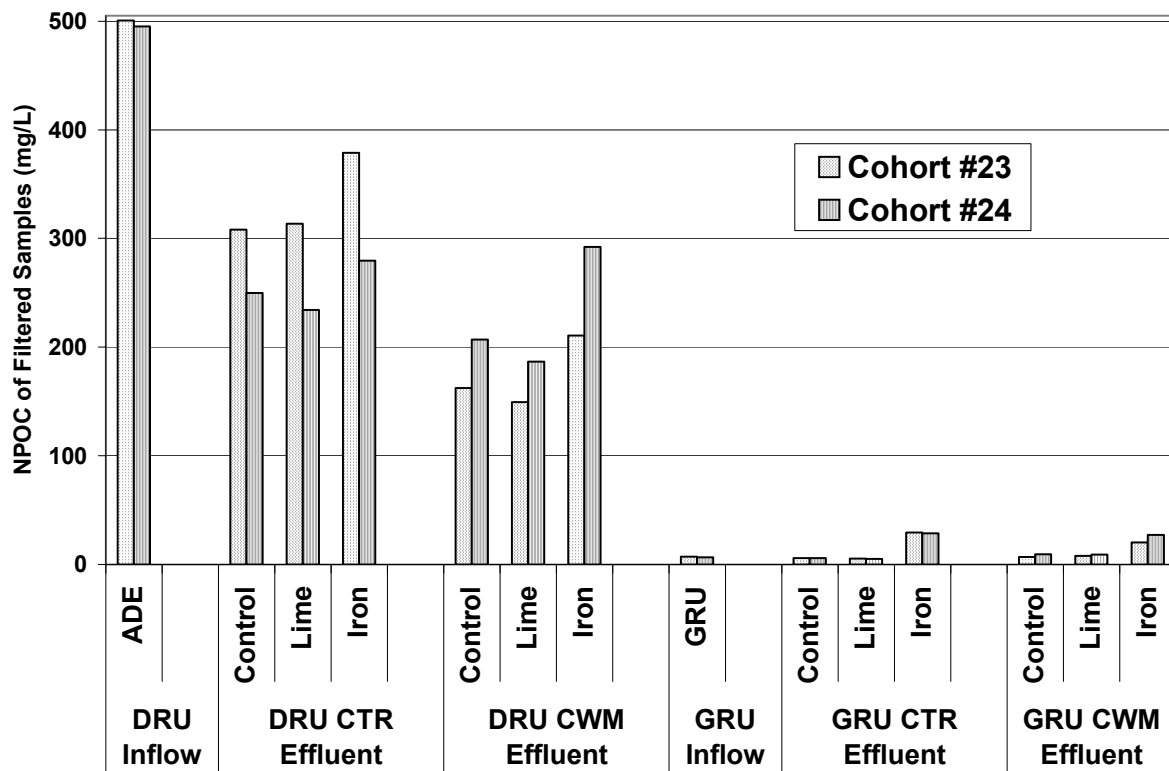


Fig. 7 Mean filtrate organic carbon (NPOC) at DRU and GRU by Sampling Point and Treatment

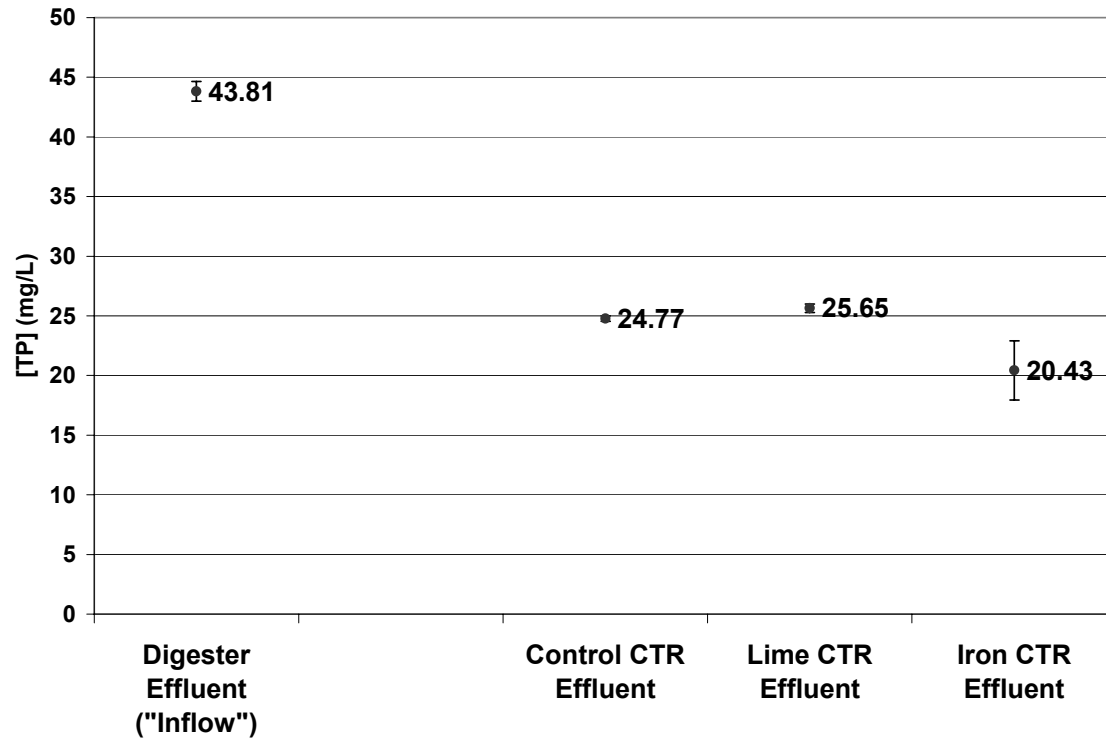


Fig. 8 Total Phosphorus [TP] (+/- S.E.) in Co-Treatment Reactor (CTR) effluents for first cycle with the high strength (dairy) wastewater.

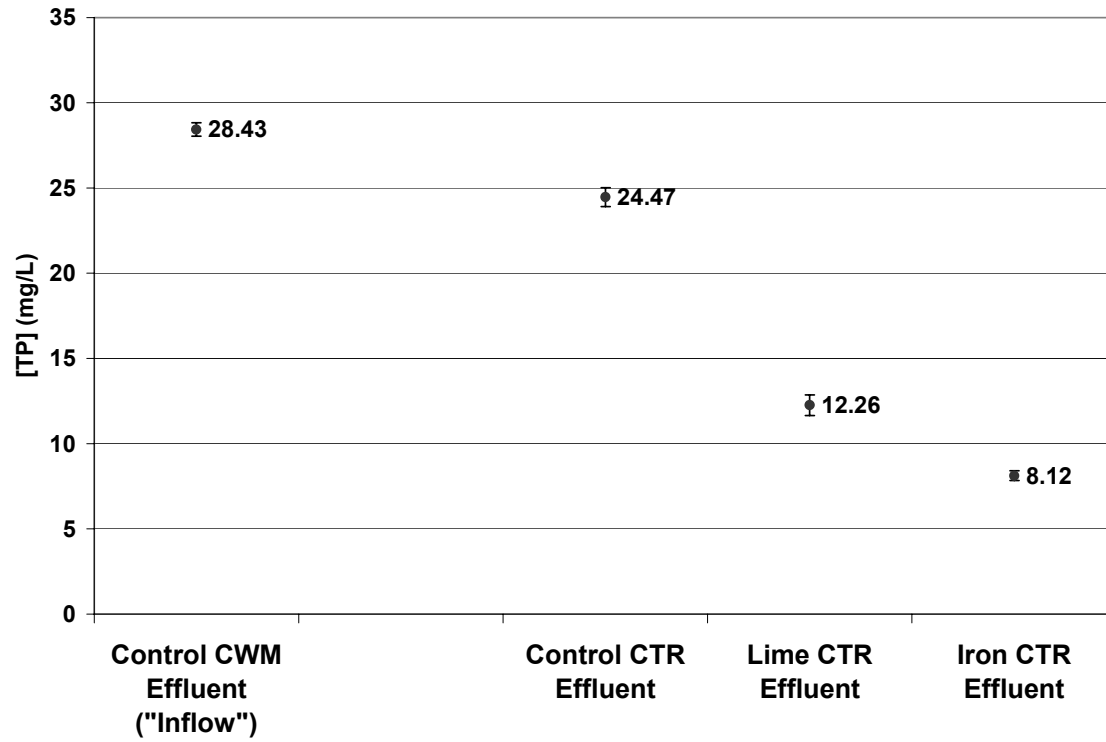


Fig. 9 Total Phosphorus [TP] (+/- S.E.) in Co-Treatment Reactor (CTR) effluents for side experiment with DRU control Constructed Wetland Mesocosm (CWM) effluent as the inflow.

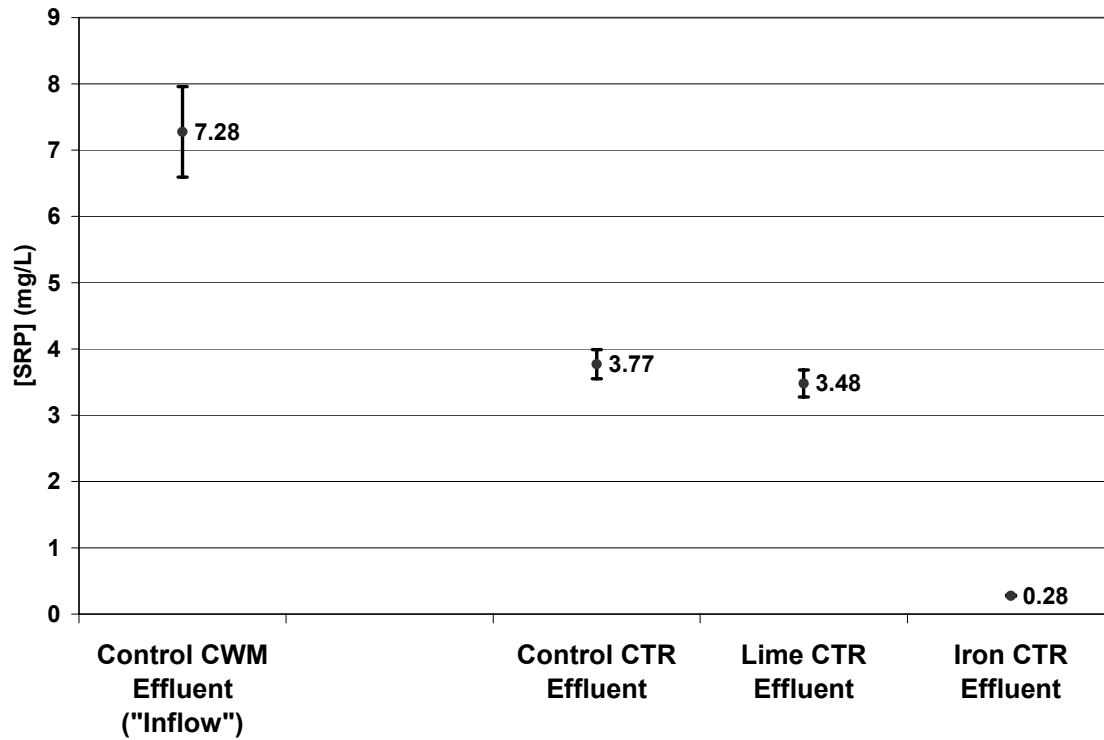


Fig. 10 Soluble Reactive Phosphorus [SRP] (+/- S.E.) in Co-Treatment Reactor (CTR) effluents for side experiment with DRU control Constructed Wetland Mesocosm (CWM) effluent as the inflow.

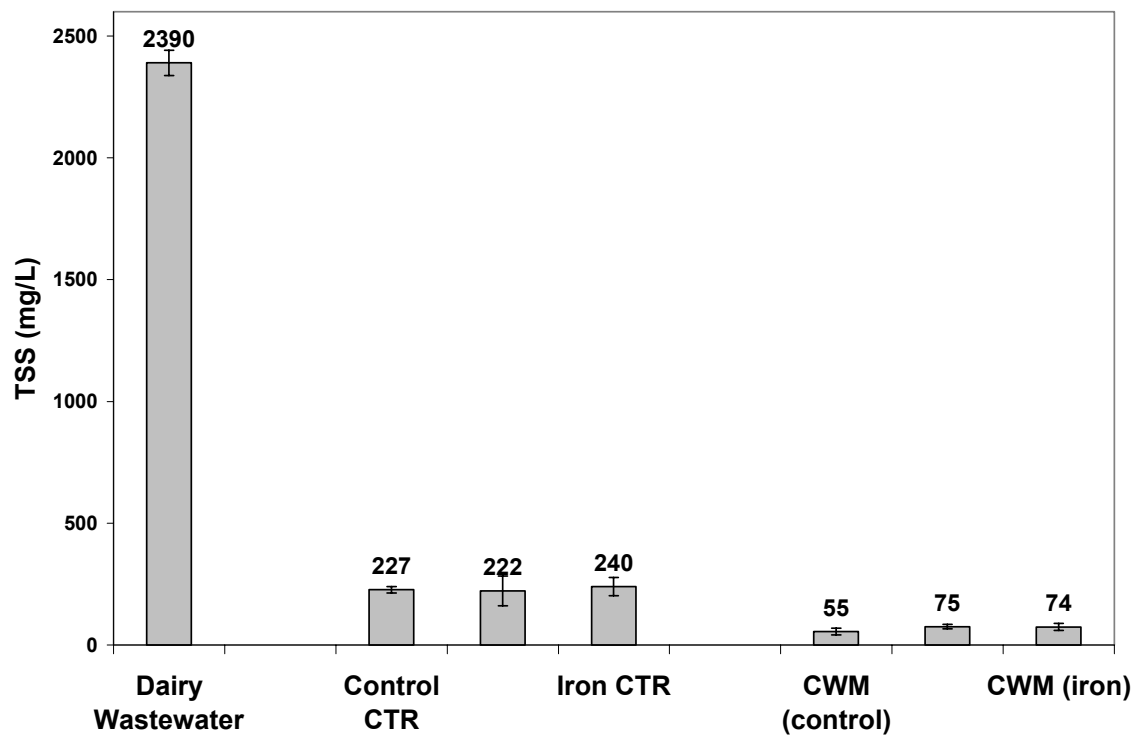


Fig. 11 Mean Total Suspended Solids (TSS) (+/- S.E.) in DRU Effluents by Treatment

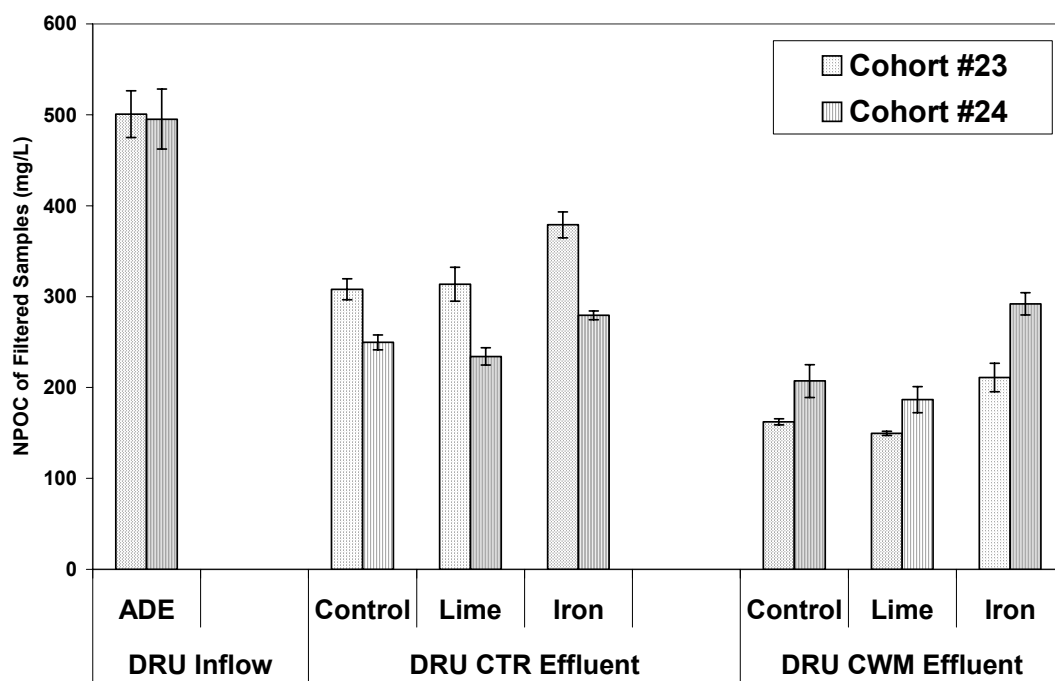


Fig. 12 Mean (+/- S.E.) filtrate organic carbon (as NPOC) at Dairy site by sampling point and treatment.

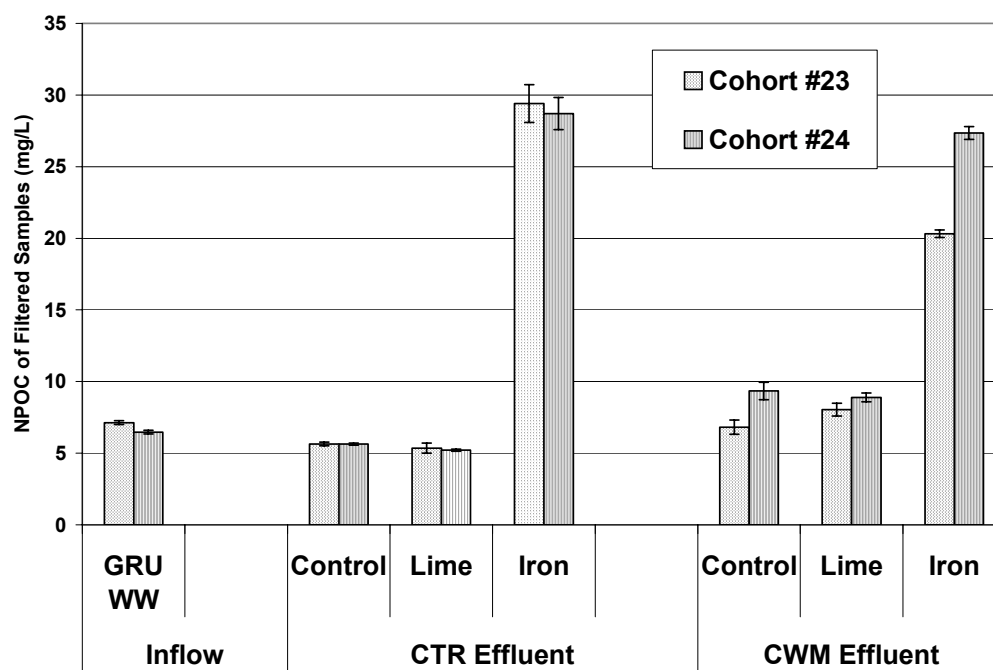


Fig. 13 Mean (+/- S.E.) filtrate organic carbon (as NPOC) at GRU site by sampling point and treatment.

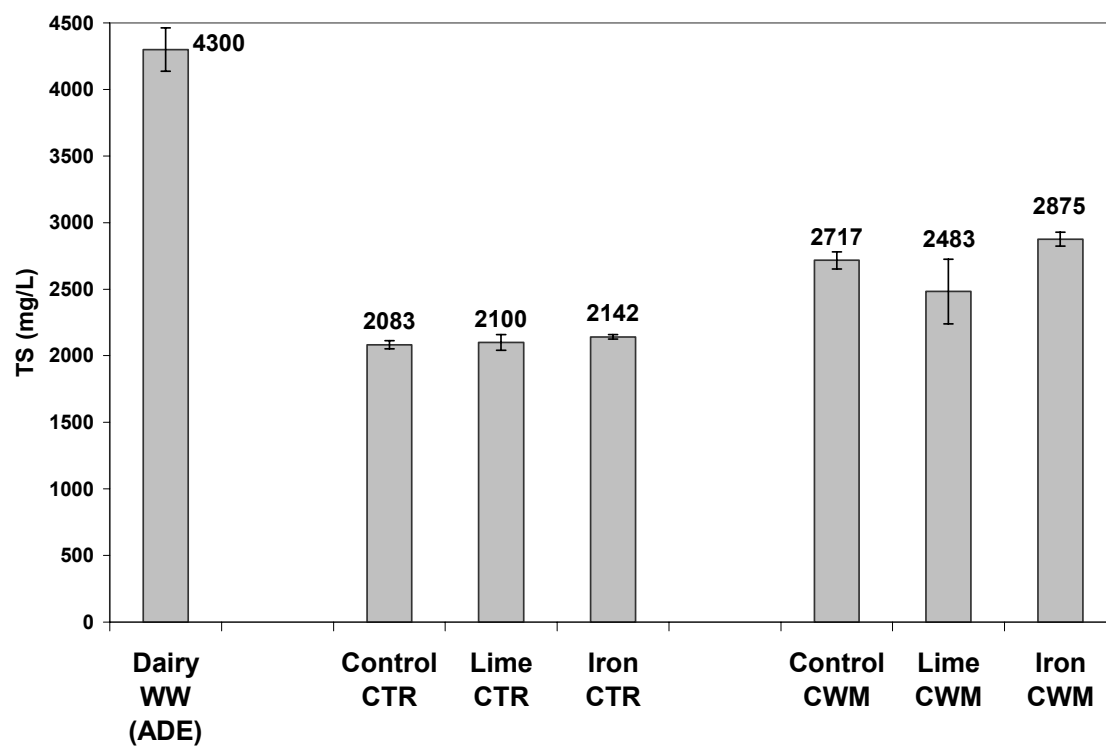


Fig. 14 Mean (+/- S.E.) Total Solids (TS) in Dairy site effluents by treatment.

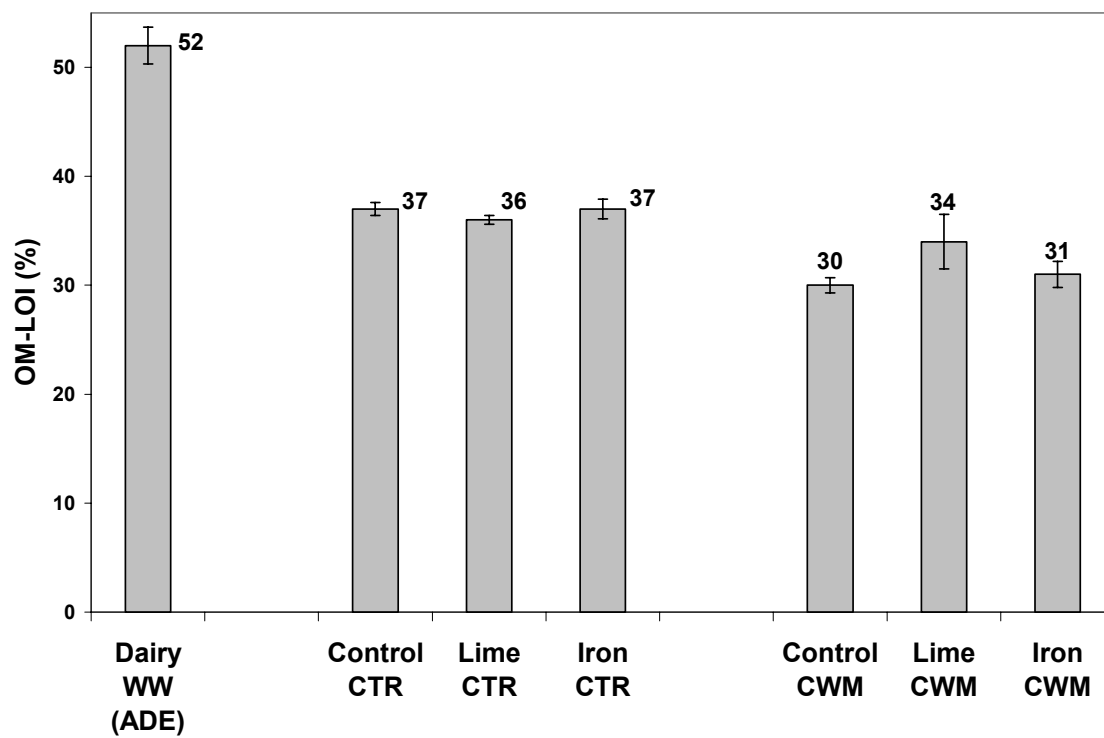


Fig. 15 Mean (+/- S.E.) organic matter (as % LOI) in effluents at Dairy site by sampling point and treatment.

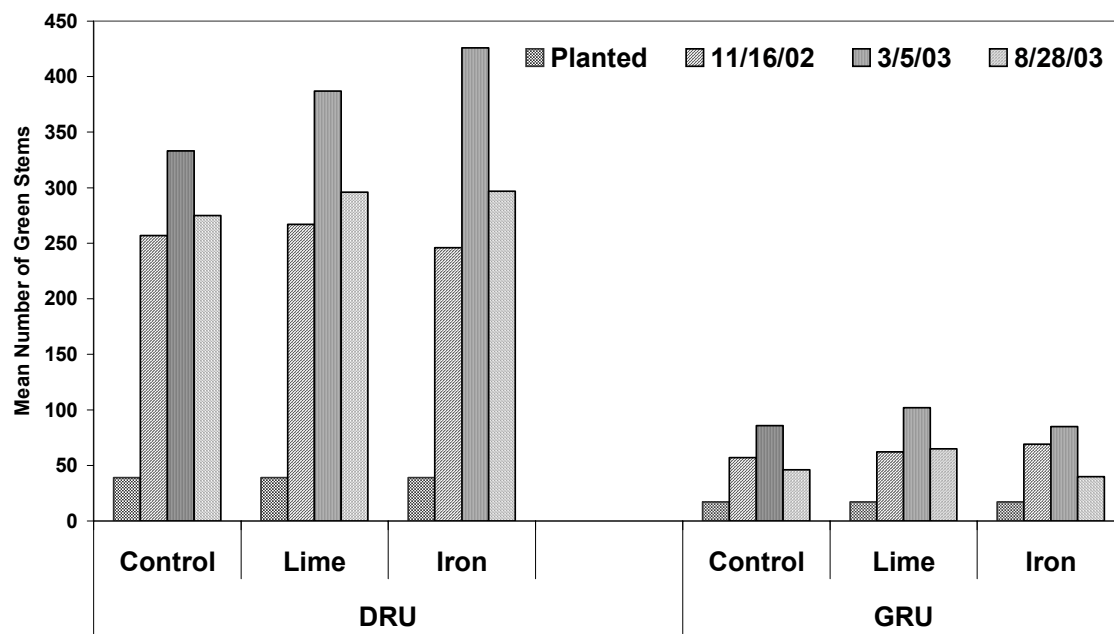


Fig. 16 Mean number of green stems counted in mesocosms by site, treatment and survey date.

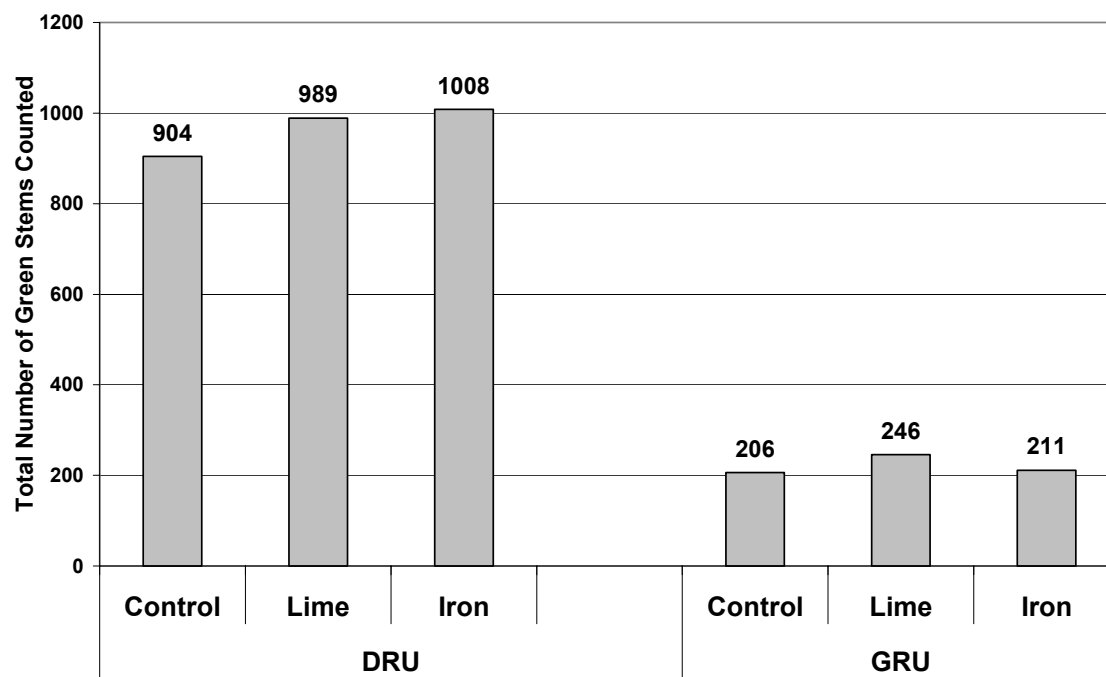


Fig. 17 Total number of green stems counted in mesocosms by site and co-treatment.

Discussion

A novel wastewater treatment system was designed and constructed to test a combination of strategies for low-cost (of construction and operation) phosphorus (P) removal from agricultural wastewater. The experimental systems combined co-treatment reactors containing either iron or calcium drinking water treatment residuals (DWTR) with vertical flow constructed wetland mesocosms containing coarse sand and the native soft-stem bulrush *Scirpus tabernaemontani* C.C. Gmel. (= *S. validus* Vahl). Eighteen of these systems were built and operated for one year. Wetlands paired with co-treatments generally removed P as well, or much better than, control wetlands. Also, there appeared to be no negative, and perhaps a small positive, impact from the co-treatments on wetland plant growth.

For the high-strength wastewater, the overall TP reduction of these systems compares favorably with the average reduction for animal wastewater treatment wetlands (Knight et al., 1996). The high-strength (dairy) wastewater had much higher Total Suspended Solids (TSS) and this may have reduced the effectiveness of P removal by the co-treatments preceding the wetland cells. The co-treatment and wetland systems reduced TSS in the dairy wastewater from 2390 mg L⁻¹ to 68 mg L⁻¹ (**Figure 6**) For agricultural wastewaters with high TSS, the co-treatment may remove P more efficiently when used following an initial wetland cell in the treatment sequence. Additional experimentation has supported this hypothesis and is included in this report.

Discussion of Ten key features of this system design as they were described in the original proposal addendum.

1. Two Florida drinking water treatment residuals (DWTR) were obtained and both exhibited favorable characteristics for this research based on earlier lab and greenhouse experiments. A lime-sludge DWTR from Gainesville Regional Utilities and an iron-sludge DWTR from the Hillsborough River Water Treatment plant in Tampa were used.

2. Data and observations suggest that the DWTR's used in the co-treatments favorably affected the growth of bulrush in the wetland mesocosms over the controls. This may be an indicator of the potential to use them as beneficial soil amendments. However, their affect on plants in a non-wetland system has not been tested as part of this research. The use of the iron DWTR on crops in Florida has been tested elsewhere.

3. The DWTR's were removed from the co-treatment reactors (CTR), and fresh material was placed back in, without disturbing the constructed wetland mesocosms (CWM).

4. No mixers, aeration systems or pumps were used within the experimental system. The effluents being pumped or discharged from their sources were simply directed into the CTR's and then drained by gravity through the CWM's after the predetermined hydraulic retention time (HRT) of seven days. Valves were operated manually every seven days.

5. When performance of the treatment substrates declined in the CTR's, they were removed and replaced with "fresh" material. This would not have been possible if the phosphorus sorbing substrates were placed directly in the wetlands.

6. Wetland fauna including birds, insects and amphibians were observed using even these small experimental wetland tanks. Having separate CTR's minimized direct exposure of wildlife to the DWTR's.

7. Final destructive sampling of the systems was completed to determine the forms and stability of phosphorus in the wetlands.

8. Vertical flow drainage of the effluents through the coarse sand substrate of the wetland mesocosms continued to work with both wastewaters with no apparent reduction in drainage rate. The contingency drains were only used on one occasion to prevent tank overflow during a severe storm event.

9. Oxidation-reduction probes placed at two depths in all eighteen tanks indicate that the sand in the wetland systems alternated between aerobic and anaerobic conditions.

10. Hydraulic retention time (HRT) and hydraulic loading rate (HLR) were easily and precisely controlled by the weekly manual operation of valves. The application of this feature greatly increases user control over the treatment system. The batch-fed systems (flooded 7 days and then drained 7 days) appeared to have no negative affect on the growth of the bulrush plants.

The phosphorus data in **Fig.5** from the lower strength (GRU) wastewater site do however demonstrate the ability of the DWTR's to remove SRP, and thus TP, down to much lower levels than in the controls and could be a "proof of concept" for this treatment design. The difference in performance may not be due to the initially lower phosphorus concentrations. The low phosphorus wastewater also had much lower particulate and dissolved material that could interfere with the removal of SRP. In this experiment, with both wastewaters, the co-treatments preceded the wetland treatment cells. These phosphorus results indicate that perhaps with a wastewater high in particulates and high dissolved carbon, the co-treatment should follow a wetland treatment cell. Wetland cells can reduce TSS considerably by filtration and entrapment of particulates. Standard designs for constructed wetland treatment systems in the literature and design manuals include multiple wetland cells. The DWTR's in a co-treatment between wetland cells might be most appropriate for high TSS and high DOC wastewater.

In "Task 4-Synthesis of Combined Results", conclusions as to the mechanisms and efficacy of the hydrologic manipulations, aquatic plants and co-treatments are made. Studying the biogeochemical processes in the soil and substrates focused the research on the key components of P removal and retention. By uncovering more of the underlying mechanisms for efficient and cost-effective P removal, the design and management of CW wastewater treatment systems can be improved. The economic feasibility, as well as the treatment effectiveness, of this type of co-treatment and constructed wetland system for removing P from agricultural wastewater is discussed. Final conclusions are based on

the combined results of laboratory, greenhouse column, and outdoor mesocosm experiments. Recommendations as to the general application of this technology to agricultural wastewater treatment can be made at this time. However, a pilot scale system would need to be designed, engineered, constructed, and then operated and monitored for a few years before widespread application of this new design would be prudent.

This research began with lab and greenhouse experiments to direct the research toward the most promising P removal design features (especially co-treatment materials and hydrology). The outdoor wetland mesocosm systems with co-treatment tanks provide additional "proof of concept" and verify preliminary lab and greenhouse results at a larger, and more realistic, scale. The final synthesis of these results will improve insight into the cycling of P in constructed wetland wastewater treatment systems, and the results of this study should be beneficial to CW designers and operators and the agricultural clients they serve.

The outdoor wetland mesocosm research presented here provides "proof of concept" data to test results obtained from lab and greenhouse experiments. This study provided further insight into the enhancement of P removal from agricultural wastewater (WW) using non-toxic by-product co-treatments with constructed wetlands. The effects of co-treatment substrates, plants and cyclic flooding of treatment cells were measured to determine optimal conditions for P removal and the major controlling mechanisms. The study used randomized experiments so that inferences can be made based on treatment differences and the results will have more universal application. Mass balance of P can be

obtained to avoid the common "black box" approach that includes just inflow and outflow measurements. Not only effluent P concentrations are reported but also mass removal rates ($\text{g/m}^2/\text{yr}$) in order to demonstrate reduction of the "footprint" of a constructed wetland (CW) by using co-treatments. This demonstrates potential for increased efficiency, longevity, and cost savings of CW WW treatment systems.

The study of by-products as co-treatment substrates with wetland mesocosms will aid in the optimization of P removal. Contents of the by-products may affect P sorption not only in the co-treatment cells but also in the wetland mesocosm cells downstream in the treatment sequence. The use of co-treatments with inexpensive and non-toxic by-products has great potential for increasing the sustainability of P removal by CW systems. Conventional wastewater treatment chemicals could be costly and may even result in the production of an additional solid waste. Chemical amendments, such as the by-products in this study, if applied directly to a CW might also have negative environmental impacts or cause negative public perception of impacts. Also, chemical amendments may be less effective at P sorption when applied directly to a CW due to complexation of P-binding metals by the high levels of dissolved organic matter present (Ann et al., 2000). Furthermore, restricting the chemical amendment mostly to a co-treatment cell preceding the CW allows for retrieval and replenishment of P-saturated materials without disturbing the established flora and fauna of the wetland treatment cell. By-products were also tested based on their potential to be used as agricultural soil amendments and fertilizers after they have been saturated with phosphorus in this system. This feature of re-use could increase both the environmental and economical feasibility of

this design. A less mechanized and energy intensive system that utilizes by-product co-treatments with CW's, and returns P back to agriculture, could conserve substantial amounts of these limited resources.

Two drinking water treatment residuals (DWTR's) were tested as potential co-treatments. One was a lime sludge from Gainesville, Florida and the other was an iron humate sludge from Tampa, Florida. A fine magnesium material leftover from fertilizer manufacturing in Florida has also shown promise for P removal from wastewater. Both the iron and the magnesium materials have potential to be used as agricultural fertilizers or soil amendments after they are used by this system to remove phosphorus. The iron humate DWTR material is already being used by the citrus industry in Florida and the magnesium is a micro-nutrient fertilizer. The addition of P to these materials from the proposed treatment process may even enhance the re-use value of these by-products.

In the final task of the research conclusions as to the mechanisms and efficacy of the hydrologic manipulations, aquatic plants and co-treatments can be made. Studying the biogeochemical processes in the soil and substrates focused the research on the key components of P removal and retention. By uncovering more of the underlying mechanisms for efficient and cost-effective P removal, the design and management of CW wastewater treatment systems can be improved. The economic feasibility, as well as the treatment effectiveness, of this type of co-treatment and constructed wetland system for removing P from agricultural wastewater is discussed. Conclusions are based on the combined results of laboratory, greenhouse column, and outdoor mesocosm experiments. Recommendations as to the application of this technology to different agricultural

wastewater treatment scenarios are made. A conceptual design layout for testing the proposed system at full-scale is provided in the **Appendix** of this report.

All other data derived from this research project and pertinent to the treatment of agricultural wastewater will be made available to the FDACS when completed. Many parameters other than phosphorus concentrations in the wastewaters were measured and the data continues to be analyzed. Additional parameters examined include: phosphorus masses in all components of systems; inorganic P fractionation of the sands and substrates; total suspended solids (TSS); dissolved organic carbon (DOC); TKN; organic matter content; pH; air and water temperature; oxidation-reduction potential; dissolved oxygen; conductivity/salinity; tank drainage rates; plant stem counts; plant biomass; HCl-extractable P, Fe, Al, Ca, Mg in sands and substrates; Oxalate-extractable P, Fe, Al in sands and substrates; soluble Fe, Al, Ca, Mg in wastewaters; and *Fecal coliform*, *Enterococcus*, and *Staphylococcus* counts. Additionally a kinetic study was done to measure both P concentrations and oxidation-reduction potentials at 1,2,4, and 7 days after flooding of co-treatments. Concentrations of soluble P were also measured in both acidified and non-acidified wastewater samples to indicate presence of soluble calcium or iron phosphates.

Conclusions

The final synthesis of these results improves insight into the cycling of P in constructed wetland and co-treatment wastewater systems, and the results of this study should be beneficial to CW designers and operators and the agricultural clients they serve. The outdoor wetland mesocosm research presented here provided “proof of concept” data to test results already obtained from lab and greenhouse experiments. This study provides further insight into the enhancement of P removal from agricultural wastewater (WW) using non-toxic by-product co-treatments with constructed wetlands. The effects of co-treatment substrates, plants and cyclic flooding of treatment cells was measured to determine optimal conditions for P removal and the major controlling mechanisms.

The use of co-treatments with inexpensive and non-toxic by-products, such as the drinking water treatment residuals (DWTR) used in this experiment, has potential for increasing the sustainability of P removal by CW systems. The DWTR's used were chosen in part based on their potential to be used as agricultural soil amendments and fertilizers after they have been saturated with phosphorus in this system. This feature of re-use could increase both the environmental and economical feasibility of this design. A less mechanized and energy intensive system that utilizes by-product co-treatments with CW's, and returns P back to agriculture, could conserve these limited resources. The iron DWTR used in this experiment, is already being used as a soil amendment by citrus growers in Florida. Citrus agriculture is increasing in the Okeechobee basin thus creating the potential for cooperative local P management.

The ultimate application of the features of this wastewater treatment system design will depend on the type and quality of wastewater being treated. Some features of this design might be successfully incorporated in existing or new agricultural wastewater treatment systems. This research will help to determine where this type of system might be appropriate and how it could be optimized.

At this date we are still adding to the data set for this research project. However, significant changes in the overall conclusions are not expected. Much of the data remaining will be used to further understand the biogeochemical behavior of these systems. The data analyzed already provide a demonstration of the potential of these systems for removing phosphorus (P) from agricultural wastewater. Results from the parallel experiments run with both high-strength (anaerobically digested flushed dairy manure) and low-strength (secondarily treated municipal) wastewater provided both “proof of concept” for the use of co-treatments with wetlands, and added insight for improved design for specific wastewaters.

Co-treatments cells containing drinking water treatment residuals (DWTR), such as the lime and iron materials used in this research, do appear to enhance the removal of phosphorus (P) from wastewater. In addition, there appears to be no negative effect on the wetland plants in the cells following the co-treatments. In fact, greater growth was observed in those cells over control cells. This technology may be a viable way to increase the sustainability of treatment wetland systems by providing for the harvesting of P from the wastewater. Without some type of harvesting the wetland systems continue

to accumulate P and could eventually export this excess P. When the DWTR materials cease to remove P they could be collected and field applied to recycle the P for agronomic use.

As initially arranged for the experiment, the co-treatments preceding the wetland cells did function well at removing P from the low-strength wastewater. Both the iron and lime co-treatments performed better than controls. However, the performance of the co-treatments was not different from the controls for the high-strength wastewater. This is thought to be due to the high total suspended solids (TSS) in the high-strength wastewater and not to the higher initial P concentration. It was suspected that placing the co-treatment after an initial wetland treatment cell would alleviate this problem. This was demonstrated in a side experiment where the iron treatment reduced soluble reactive phosphorus (SRP) concentrations to one-tenth that of the controls. For high-strength wastewater, placing the co-treatment between two wetland cells is thus recommended and this is compatible with the multiple wetland cells in a typical agricultural wastewater treatment system (USDA-NRCS, 2002). Overall the preliminary data does demonstrate the ability of co-treatments to serve as sinks for P in a co-treatment and wetland system.

The advantages of using constructed wetlands for wastewater treatment is the relatively low cost to build and operate them if land space is not economically limiting. They can be built and maintained by the farm operator with standard equipment if proper design and training is provided. Treatment wetlands are compatible with existing lagoon systems on farms and could be added on to meet more stringent treatment needs. Pumps and flow control valves or structures are needed but mixing and aeration equipment are

not necessary (but could be added to improve performance if not cost-prohibitive). This reduces both maintenance and energy demands.

One feature of the recommended parallel treatment trains for the system is the ability to batch-feed the systems alternately rather than have continuous flow in any cell. The systems studied in this project were batch-fed and that is recommended, if feasible considering flow rates and space limitations at a particular site.

The systems in this project were a hybrid type of constructed wetland with surface water cells with subsurface vertical drainage. Although there was no detectable reduction in drainage rates of the experimental wetland mesocosms after one year of loading, surface-flow wetlands are recommended. Phosphorus removal may be initially less with surface flow wetlands but the subsurface removal of P is finite. Also, surface flow wetlands are easier and cheaper to construct and have less potential for long-term clogging.

In the experimental treatment systems, the co-treatment reactors were covered to block sunlight and thus prevent the confounding effects of algal growth in the tanks. This was done for experimental convenience and would probably not be feasible in a large-scale system. Algal growth probably would occur in the recommended open co-treatment basins and this might affect P removal positively or negatively depending on co-treatment material. Algal growth is known to affect water column pH and this in turn affects P removal by iron or calcium as discussed earlier.

Although results indicated that either the iron or lime type DWTR could enhance P removal, the choice of either would be dictated by the individual site and situation.

Operators should consider the local availability and transportability of the co-treatment material. The pH of the wastewater also affects the choice. The end-use or discharge requirements of the treated water should be considered as well as the potential for local reuse of the P-saturated co-treatment material.

Finally, only the effect of the co-treatment materials on wetland plant growth was measured in this research. It was assumed that they contained primarily non-toxic materials since both DWTR used in this study have been land-applied in Florida. Before large-scale application though it would be prudent to have samples of the DWTR analyzed for contaminants. Also, end-use of the phosphorus-saturated DWTR material should be planned. It's apparent agronomic value to local end-users, as well as non-toxicity, should be confirmed prior to construction of the system.

The preliminary data suggests the potential for the successful application of these systems, with some modifications to match particular wastewaters. The use of co-treatments with inexpensive, non-toxic, and reusable by-products, such as these drinking water treatment residuals, has potential for increasing the sustainability of P removal by constructed wetland systems. A conceptual design layout for testing the proposed system at full-scale is provided in the **Appendix** of this report. It is designed specifically for agricultural wastewaters like the one tested with high [TP] and high TSS.

Appendix

Conceptual Design Layout for Testing this Technology at Full-Scale:

This design is a modification of the “typical layout” presented in the USDA-NRCS National Engineering Handbook Part 637 for constructed wetlands for animal waste treatment (USDA-NRCS, 2002). The modification mainly incorporates the addition of co-treatment basins containing drinking water treatment residuals (DWTR) for enhanced phosphorus removal. Once it has ceased to remove phosphorus, the co-treatment basin should be drained and the DWTR material removed for land application. The design of the co-treatment basins should thus allow for the removal of the DWTR with conventional farm or sludge-handling equipment. Since this is a new technology, the recommended layout allows for bypassing these basins if needed for: treatment adjustments, DWTR removal and refill, or testing requirements. A certain amount of redundancy and flexibility in the design is a prudent engineering approach prior to further development of this technology. The basis for these design suggestions is a research project done at the University of Florida Dairy Research Unit and the Gainesville Regional Utilities Main Street Wastewater Reclamation Facility. One of the two wastewaters used in that research was anaerobically digested flushed dairy manure. The design might need to be altered for substantially different types of agricultural wastewater. The exact dimensions are not provided and would need to be determined based on the wastewater volume and characteristics, treatment needs, and site factors of a particular agricultural operation. Variations in irrigation and fertigation needs and/or local discharge requirements would also demand site-specific design details.

Components of System Described

Animal housing - any confined livestock areas from which runoff or flush-water is collected for treatment.

Initial Treatment - any type of floatable debris, sand or solids removal prior to primary treatment.

Primary Treatment - any anaerobic wastewater treatment lagoon or anaerobic digestion system.

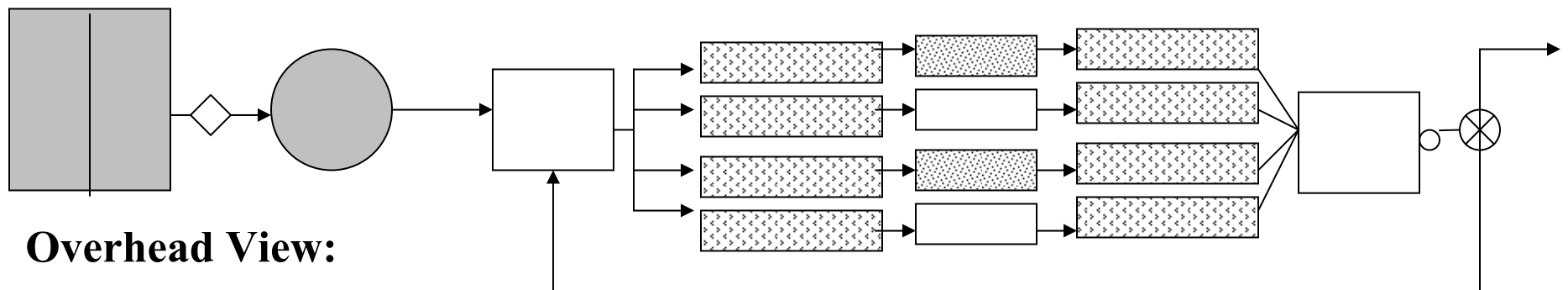
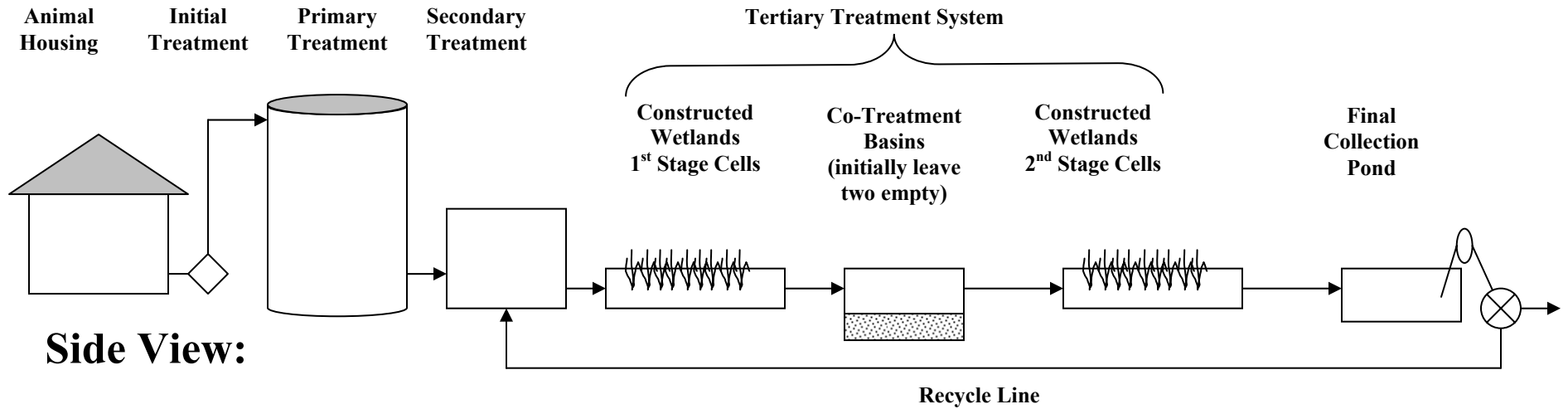
Secondary Treatment - settling pond for clarification and/or winter storage.

Tertiary Treatment System - combination of wetland treatment cells with co-treatment basins for enhanced P removal.

Final Pond - pond for collection and storage of treated wastewater for irrigation needs or final discharge if permitted.

Recycle Line - pipeline to allow for recycling of treated wastewater back to an earlier stage if required to meet discharge needs.

Conceptual Design Layout for Testing this Technology at Full-Scale: Constructed Wetland and Co-Treatment System for Agricultural Wastewater Treatment to Optimize Phosphorus Removal



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