Re-use of clean coal technology by-products in the construction of low permeability liners: Medium-scale wetland experiments

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Introduction

Engineered wetlands have provided natural alternatives for wastewater treatment, storm water storage, and flood diversion (Mitsch and Gosselink, 2000; Mitsch and Jorgensen, 2004). A new market is evolving around the use of natural landscapes as beneficial and cost effective treatment alternatives. Recent advances in wastewater treatment follow this trend to avoid more typical chemical and energy intensive methods. Research attempting to characterize and quantify the range of nutrient and pathogen removal has resulted in a highly variable range of efficiencies (Werker et al, 2002). A perceived niche for small-scale decentralized wastewater treatment wetlands encourages the development of more predictable and sustainable solutions to water quality management.

Researchers at the Olentangy River Wetland Research Park (ORWRP) have experimented with the use of clean coal technology by-products as liners to prevent groundwater contamination and retain water in the wetland basins. Early studies at the ORWRP using small (1 m^2) mesocosm tubs showed that while there was some minor effect of coal combustion product liners on plant growth, phosphorus retention in the mesocosms lined with the material were effective in removing phosphorus from flow-through river water (Wolfe et al., 2000; Ahn et al., 2001; Ahn and Mitsch, 2002a; Ahn and Mitsch, 2002b). Stabilized flue gas desulfurization (FGD) material is a solid form of sulfur oxides precipitated by lime scrubbing techniques in coal-fired electric plants and mixed with fly ash and lime. Principally composed of sulfites, un-reacted lime, fly ash, and water, the FGD material should fit well in the role of reducing phosphates in municipal or agricultural wastewater because of the high concentrations of calcium carbonate and lime, both of which have an affinity for phosphorus.

Laboratory experiments have shown a range of permeability characteristics for stabilized FGD materials (Butalia and Wolfe, 1999). These findings encouraged field studies using compacted FGD material as liners for treatment wetlands at the mesocosm (1m^2) scale (Wolfe et al., 2000; Ahn et al., 2001). Results from our mesocosm experiments found greater removal of total phosphorus and soluble reactive phosphorus in mesocosms lined with FGD material than unlined mesocosms.

Our current research used FGD liner material to constructed treatment wetlands at a pilot medium-scale (12 m^2) scale over three growing seasons (2001-2003). Basins lined with FGD material were compared to similar basins lined with clay to test the hydrologic and ecological efficacy of FGD-liners in constructed wetlands. Objectives to meet that goal included: investigating the effect of FGD liner on water quality, plants and soil chemistry, and examining the hydrologic efficacy of FGD liners compared to clay liners in treatment wetlands. If techniques such as using FGD material for wetland liners can be perfected, then significant expenses could be saved in creating wetlands for cleaning up wastewater.

Methods

Basin Construction

The pilot-scale experiments were carried out in four created 12-m^2 wetland basins in the northwest corner of the Olentangy River Wetland Research Park in Columbus, Ohio, USA (Figures 1, 2, and 3). Construction on the wetlands (Figures 4 to 11) began on August 30, 2000 after permits were obtained from Ohio EPA to allow minor on-site discharge of water from the wetland basins. Four basins were excavated and lined with HDPE plastic liner material. The HDPE plastic liner (Figure 6) served as an impervious liner between the wetland and the underlying soil and water table and captured and contained any water that leached through the experimental liners. One foot of pre-washed river gravel was placed in a trench at the bottom of each basin and covered with Geonet fabric to form a leachate collection system. Two separate extensions of PVC pipe were inserted at opposite ends of gravel-filled trenches and extended up above the ground surface. These collection wells were used to access samples of leachate from the underlying gravel trenches. Stabilized FGD material, received from the Conesville power plant of America Electric Power, was compacted in a six-inch layer above the Geonet fabric in the two FGD-lined basins (Figure 7), and local clay soil was compacted in a six inch layer similarly in the two clay-lined basins. The Geonet layer kept the respective liner materials from mixing into the interstitial spaces of the gravel filled layer. Compaction in both clay and FGD basins was done with a vibratory compactor (Figure 8). The compactor was used in the FGD material only until it began sinking into the material. Compaction in the FGD basins was completed by using the bucket from a back hoe stabilized on the edge of the basins. Both FGD and clay-lined basins were then filled with two feet of local topsoil suitable for wetland

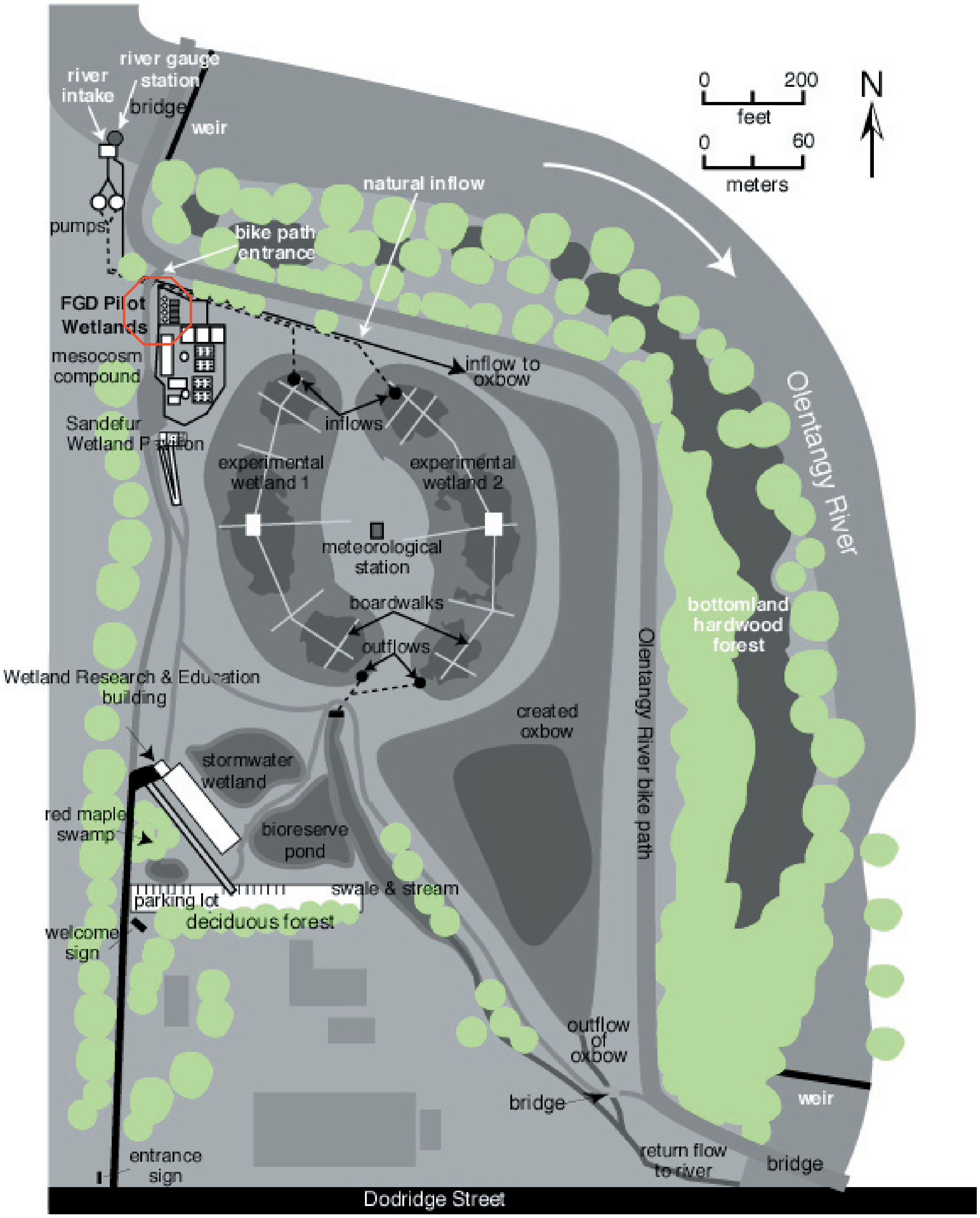

Figure 1. Olentangy River Wetland Research Park at The Ohio State University with location of FGD and clay-lined experimental wetland basins shown in the northwest corner of site.

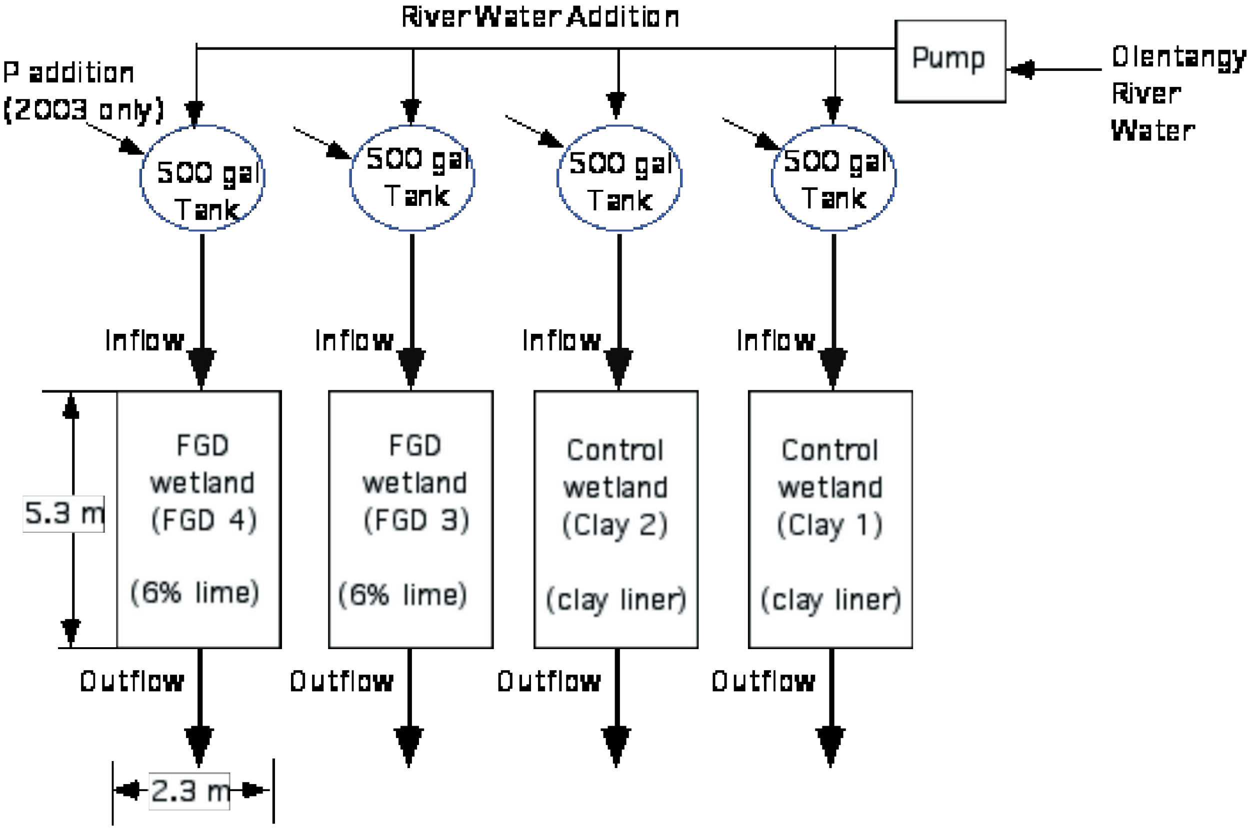

Figure 2. Schematic of medium-scale wetland experiments. Two basins were lined with FGD material and two basins were lined with clay.

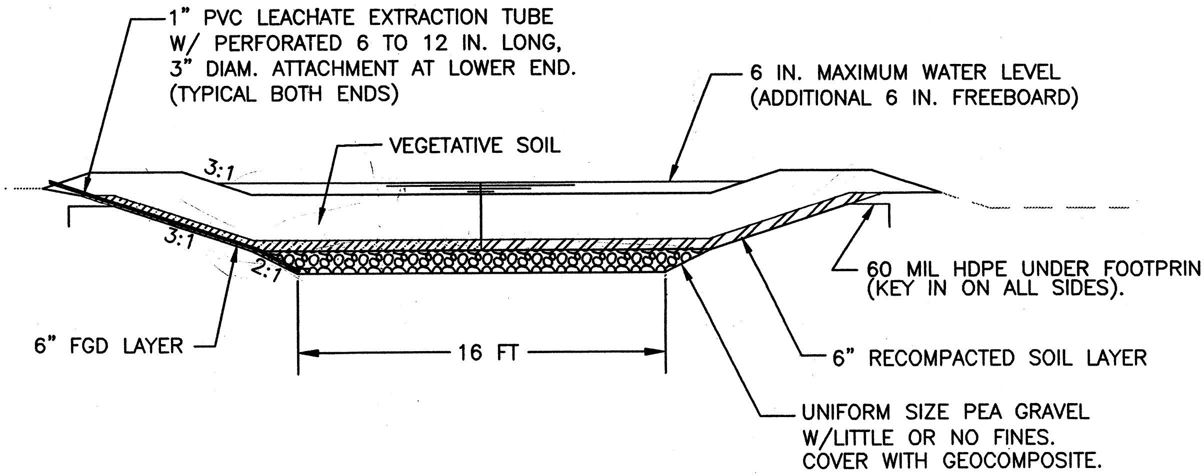

Figure 3. Construction cross-section of wetland basins used in this coal combustion project experiment.

Figure 4. Sign at wetland experiment, Olentangy River Wetland Research Park summarizing OCDO support for this experiment

Figure 5. Excavation of wetland basins, August 30, 2000

Figure 6. Placement of impervious liners and leachate collection system, September 1, 2000

Figure 7. Addition of FGD material to two experimental wetland basins, September 13, 2000

Figure 8. Liner in FGD wetland basin showing initial compaction, September 13, 2000

Figure 9. Installation of water delivery system to experimental wetland basins, April 25, 2001

Figure 10. FGD-lined basin after one growing season of planting, September 15, 2001

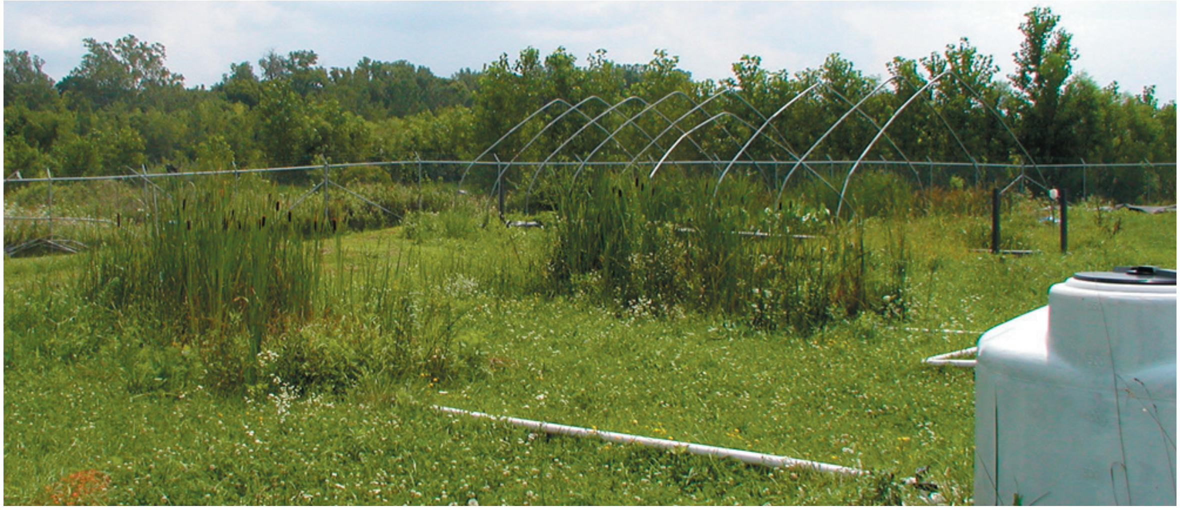

Figure 11. FGD-lined basins after three full growing seasons, August 6, 2003

vegetation growth.

The initial elemental composition of the liner materials and topsoil is shown in Table 1. The FGD material is notably more alkaline than the clay because it is treated with lime as a part of the stabilization process. The FGD material is relatively high in concentrations of S as well as Ca from the unreacted lime. Higher concentrations of metals Mg, Ca, and metalloids Al and B were detected in the FGD material than in the clay liner material.

Flow systems were installed in April 2001 (Fig. 2 and 9). A Teel® 4RJ42 pump drew water from the Olentangy River inflow pipes that fed the two experimental wetlands nearby. The water was fed to four 500-gallon plastic tanks (Fig. 2). A network of poly vinyl chloride (PVC) piping gravity fed water from each drum to its respective basin. A 2-inch ball valve at the head of each pipe allowed control of inflow rates by loosening or tightening. T-branch end pieces were fitted to the opening of each inflow pipe to reduce erosion on basin topsoil. Standpipes controlled the outflow of each basin allowing waters above 13 cm to drain out through an underground pipe into a landscape trench. The outflow trenches lie below the elevation of the basins. Staff gages were installed in each basin to display basin water level.

Two species of bulrush were planted in the topsoil of each basin in July 2001. Twenty root bundles of *Scirpus americanus* were planted in the outflow half of each basin, and twenty root bundles of *Schoenoplectus tabernaemontani* were planted in the inflow half of each basin. Both rhizomatous perennials are common in shallow marshes, and fluoresce June through September. The relatively shallow growth pattern of the rhizomes and roots of these wetland plants should minimize the possibility of roots penetrating 2 feet to the liner material.

Initial design conditions were to add water at a hydraulic loading rate (HLR) of 5.5 cm/day during each growing season. This is a typical rate for surface flow treatment wetlands and was designed to result in a water retention rate in the basins of 3 days.

Data Collection and Analysis

Hydrology

River water was first introduced to the four basins on April 23, 2001. Inflow valves were initially manipulated to achieve a hydrologic loading rate (HLR) in a range of 10-15 cm/week. On alternating days, river water was pumped into each of the four 500-gallon drums at the head of each hydrologic flow system. Each basin flooded freely up to the height of the standpipe outflow (12.8 cm). When water was deeper than 12.8 cm it discharged out of the standpipe to a low-lying ditch, and eventually returned to groundwater. The 500-gallon inflow from the hydrologic flow system took about 8.5 hours to flow into the wetland. By the first week of the study FGD-lined basins showed a shorter retention time of standing water than the clay-lined basins.

Water levels were recorded weekly in each basin, both prior to loading and after loading of water. Water was added to the basins from filled water tanks, first on a weekly basis and, after it was determined that standing water did not persist, on a more frequent basis. The overall number of water pulses added to the basins for each of the 3 years of study are shown in Table 2.

Leachate accumulated in the collection system and was

Table 1 Element composition of liner materials (FGD and clay) and topsoil used in the wetland experiment, October 10, 2000

Elements	Liner material		
	FGD	Clay	Topsoil
pH	11.8	7.9	7.5
(mg /g)			
Al	19.5	<11	<11
Ca	167.4	10.0	4.3
Fe	49.1	34.3	39.0
K	2.74	9.0	10.1
Mg	8.3	4.0	4.6
S	86.0	0.6	0.3
N	0.18	1.53	1.39
(ug /g)			
B	342	38.1	41.6
Mn	130	655	990
Mo	4.0	9.7	8.4
Na	402	47.0	450
Ni	33.4	44.4	53.7

purged on alternate months in 2001. The following two years (2002-2003) leachate was purged on alternate weeks as more leachate had accumulated than expected.

The pump system was dismantled during the freezing months of November 2002 - March 2003, and reassembled in early spring for each year of the study. On June 3, 2003 the outflow piping for basins 2 (clay-lined) and 3 (FGD-lined) were examined for leaks and the standpipes in both basins were refitted with adhesive. On June 7, 2002 and July 1, 2003 rodent holes on the perimeter of the basins were filled with local topsoil and manually compacted.

Water Quality

On-site water quality data were collected at the inflow, where waters from each of the four drums entered the respective basins, and outflow where waters exit the standpipe. A handheld YSI 600XL water quality monitor manually inserted into the overlaying waters of each basin for 1 minute to measure the following parameters: temperature, conductivity, dissolved oxygen, redox potential, and pH. During 2002 and 2003, a portion of the detector on the YSI malfunctioned, and reliable redox data were not recorded. One 500-mL sample of surface water was collected at the inflow and outflow of each basin weekly from August 2001 to September 2003. No samples were taken in winter and surface plumbing was drained then to avoid ice damage. In 2003 sampling holes were drilled into the PVC pipes leading to the inflows of each basin and surface water samples were then collected just prior to exiting the pipe at the inflow of each basin. This minor change in inflow sampling was done to make it easier to minimize backwater effects on inflow sampling. The method for collecting water at the outflow remained the same throughout the study. Water was sampled just as it was leaving through the outlet structure in each basin.

Surface water samples were refrigerated or frozen until analysis. Two categories of sub-samples were prepared from the field-collected samples: inorganic and organic. Organic samples were preserved by adding 0.5 ml of H_2SO_4 to 100 ml of sample and frozen for no more than 10 days. Thawed samples were examined for Total Phosphorus concentration by spectrophotometric analysis using a Lachat 8000 series FIA+ after appropriate digestion. Inorganic samples were filtered through 0.5 μm cellulose filters, and digested in a Lachat block digester BD-46 according to the Quik Chem® method (Lachat Instruments, 2000). Cooled samples were examined for SRP concentration using a Lachat spectrophotometer.

Wastewater Pulsing Experiment

High-phosphorus wastewater was simulated by adding phosphorus fertilizer to the inflow river water in the 2003 growing season. This was done because previous studies at the Olentangy River Wetland Research Park and supported by the Ohio Coal Development Office (Ahn et al. 2001; Ahn and Mitsch, 2002) suggested that small wetland mesocosms lined with FGD material has significantly higher phosphorus retention. Hi-yield® triple super Phosphate containing 0-45-0 Phosphorus Oxide (P_2O_5) was added to river water in the headwater drums to achieve two treatment regimes: (1) very high phosphorus inflow concentration of 120 mg-P/L, and (2) high concentration of 40 mg-P/L. Very high phosphorus concentration water was added to all four basins weekly between June 14, 2003 and August 1, 2003. Plain river water was added August 11, 2003, and high concentrations resulted for the period August 1 through September 11, 2003.

Vegetation

Number of stems for both of the planted species was recorded twice a month throughout the duration of the study. Stem length was measured for 40 random individuals of both planted species. Numbers of flowers were recorded from 20 subsamples to make inferences about plant maturation and species fecundity. In each basin, four 1 m^2 areas were harvested August 16, 2001, September 15, 2002, and September 15, 2003. Harvested plants were separated according to species, and weighed in bundles. A sub-sample of each bundle was dried at 60ºC in a forced air oven for no more than two days, weighed, and ground to pass a 2 mm sieve. Ground plant tissue was analyzed for all major elements using spectrophotometeric analysis by ICP at the STAR lab in Wooster. Several plant species not introduced during the study became established in the basins, particularly in the third growing season.. These colonizing plants were identified and included in total biomass harvesting. Flowering bodies were removed from the highly aggressive *Typha* sp. to suppress the spread to adjacent sites.

Table 2 Number of water pulses added to the experimental wetlands, 2001-2003 and average hydraulic loading rate (HLR) each year

		Pulsing schedule			
	Pulses/week	Weeks	Number of Pulses	HLR cm/wk	HLR cm/day
Dates					
8/10/01-11/15/01	4	12	48	63	9.0
3/18/02-8/8/02	3	20	60	47	6.8
5/13/03-9/11/03	3	18	54	47	6.8

Soil

Local topsoil was sampled prior to completion of the basins in 2001. Local clay, used to line the control basins, and FGD material used to line the treatment basins were also sampled and analyzed. After the first and second full growing season (2002 and 2003), soil cores were collected at four points throughout each basin. Soil samples were air dried near 30°C, and ground to pass a 2 mm sieve. Complete element analysis by ICP spectrophotometer was conducted after microwave 3051 digestions, and according to the EPA standard method.

Leachate Water

At the onset of the study, water was not expected to leach through either liner materials. The leachate collection system was more of a precautionary device, and allowed leachate to be sampled prior to passing into groundwater. During the study, the leachate collection systems were estimated to have held up to 2000 liters per 7 days of basin inundation. The frequency of purging the leachate collection system was increased accordingly to remove water regularly and collect fresh sample of leachate. An Isco 150 portable pump was used to draw 500 ml water samples from each leachate well monthly in 2001, and biweekly in 2003. Leachate storage systems were completely purged after sampling. Water quality parameters were determined in the field with the YSI water quality monitor. Leachate samples were separated, treated and analyzed similarly to the surface water samples using the Lachat Quik Chem® method and ICP systems.

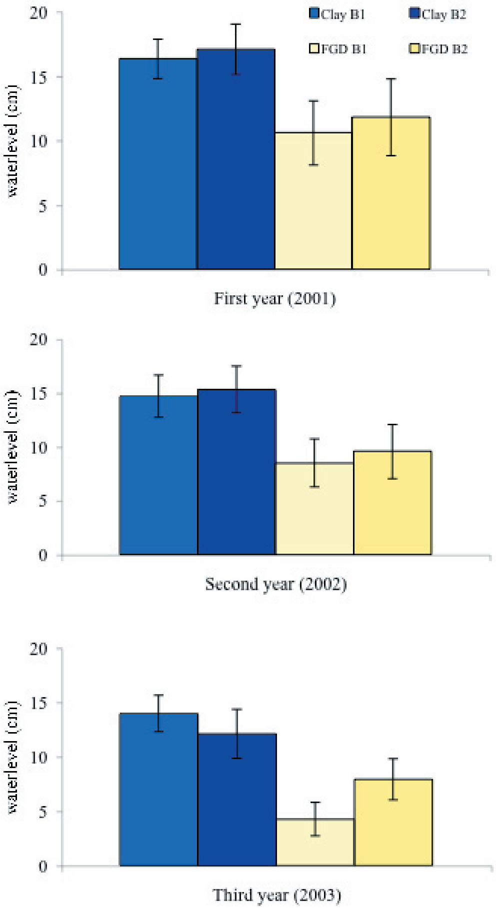

Figure 12. Average weekly water level in four pilot scale basins (2 clay-lined and 2 FGD-lined) for years 2001, 2002, and, 2003.

Observations and Results

Hydrology

The average HLRs (hydraulic loading rates) for the

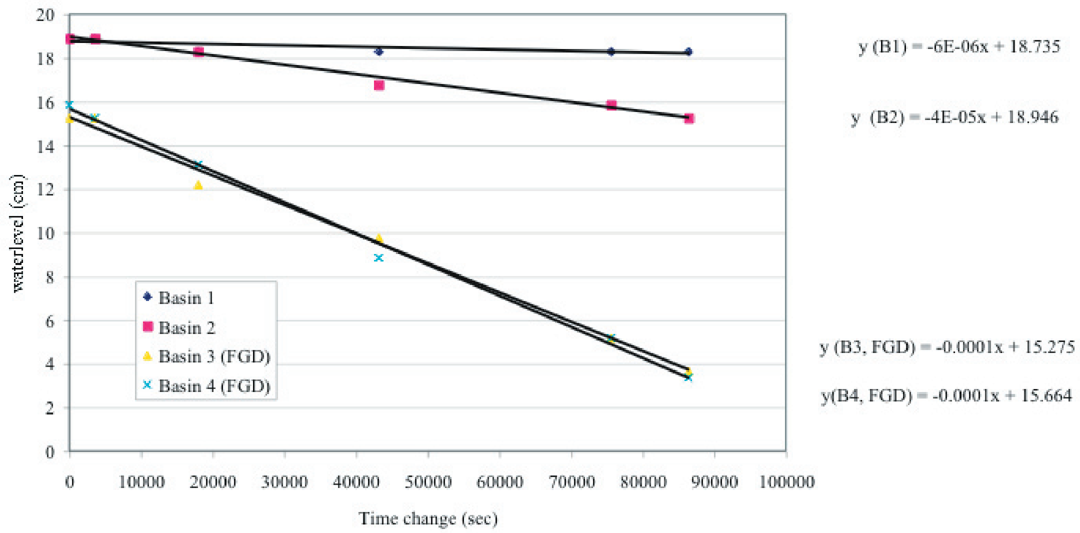

Figure 13. Water level decrease experiment of wetland basins, July 25, 2003.

wetlands basins for each of the 3 years are illustrated in Table 2. During the last 2 years, a hydraulic loading rate of 6.8 cm/day was maintained, about 24% higher than proposed flow conditions. Water was added as 3 to 4 "pulses" per week rather than a continuous flow (Table 2), as flow as low as 0.1 gal/min was difficult to sustain. In addition, more water was added than originally designed to keep surface water in the more rapidly leaking FGD-lined basins. Water levels in the FGD-lined basins were consistently lower than clay-lined basins in 2001, and were statistically lower in 2002 and 2003 (Figure 12). This trend is because the permeability of the FGD-liner was higher than the permeability of the clay-liner.

A field infiltration study was conducted in the four wetland basins in July 2003 to verify the different hydrology in the FGD basins. The study showed that while the water level dropped at 4-6 x10^{-6} cm/sec in the clay-lined basins, it dropped 100 times faster (10^{-4} cm/sec) in the FGD lined basins (Figure 13). This validated the interpretation of the water level results described above. High permeability of the FGD liner prevented sufficient ponding in the FGD basins. Thus, effects that could be interpreted as being caused by the FGD liner could, in fact, be due to the consistently less water in the FGD-lined basins.

Surface Water Quality

Typical fluctuations in surface water quality were observed in the basins from inflow to outflow water in both treatments (Table 3). There were no significant differences in surface water outflows for clay-lined and FGD-lined basins in any of the 3 years for temperature dissolved oxygen, conductivity, pH, redox potential, and turbidity. Temperature increased across a spatial gradient, and pH ranged between neutral to slightly alkaline. Some fluctuations in turbidity may be

Table 3. Weekly water quality parameters for surface water and leachate water in clay-lined and FGD-lined basins, asterisks denote significant differences (SD)

	Surface water				Leachate		
	Inflow	Outflow clay-lined	Outflow FGD-lined	SD	Clay-lined	FGD-lined	SD
First year (2001)							
Temperature (°C)	17.9 ± 0.0 (22)	18.8 ± 1.3 (13)	19.5 ± 1.5 (13)	—	20.2 ± 1.2 (21)	20.0 ± 1.6 (19)	—
DO (mg/L)	7.3 ± 0.7 (22)	6.19 ± 0.8 (13)	6.9 ± 1.0 (13)	—	4.3 ± 0.5 (21)	3.8 ± 0.5 (19)	*
Conductivity (μS/cm)	596 ± 29 (22)	597 ± 28 (13)	591 ± 35 (13)	—	1044 ± 78 (21)	1679 ± 199 (19)	*
pH	8.1 ± 0.2 (22)	7.9 ± 0.2 (13)	8.5 ± 0.2 (13)	—	7.7 ± 4.2 (21)	9.8 ± 0.5 (19)	*
Redox (mV)	219 ± 55 (13)	151 ± 32 (8)	173 ± 63 (6)	—	290 ± 32 (5)	294 ± 25 (4)	—
Turbidity (NTU)	34.8 ± 12.8 (17)	31.6 ± 21.8 (8)	39.7 ± 16.7 (6)	—	6.8 ± 1.7 (14)	12.9 ± 1.2 (15)	—
Second year (2002)							
Temperature (°C)	21.8 ± 2.0 (11)	21.6 ± 2.1 (6)	21.8 ± 2.2 (6)	—	23.2 ± 0.3 (10)	20.9 ± 0.19 (8)	—
DO (mg/L)	5.3 ± 1.1 (11)	5.2 ± 0.5 (6)	5.4 ± 0.6 (6)	—	2.0 ± 0.5 (10)	1.7 ± 0.5 (8)	—
Conductivity (μS/cm)	671 ± 13 (11)	666 ± 11 (6)	659 ± 8 (6)	—	1011 ± 232 (10)	2194 ± 320 (8)	*
pH	8.2 ± 0.6 (11)	8.1 ± 0.7 (6)	8.1 ± 0.6 (6)	—	8.1 ± 0.52 (10)	9.41 ± 0.12 (8)	*
Turbidity (NTU)	36.2 ± 1.4 (11)	27.4 ± 3.5 (6)	33.4 ± 1.8 (6)	—	8.3 ± 0.8 (13)	9.5 ± 1.5 (11)	—
Third year (2003)							
Temperature (°C)	22.9 ± 0.9 (31)	22.3 ± 2.2 (8)	23.0 ± 2.0 (8)	—	18.8 ± 1.2 (9)	16.3 ± 0.5 (8)	*
DO (mg/L)	6.5 ± 0.4 (24)	7.9 ± 0.6 (10)	7.3 ± 0.8 (10)	—	3.3 ± 1.16 (6)	2.43 ± 0.84 (8)	—
Conductivity (μS/cm)	537 ± 65 (23)	558 ± 73 (8)	628 ± 71 (8)	—	957 ± 162 (12)	1514 ± 358 (10)	*
pH	7.3 ± 0.2 (21)	7.9 ± 0.5 (8)	7.7 ± 0.5 (8)	—	6.6 ± 0.2 (12)	8.7 ± 0.2 (12)	*
Turbidity (NTU)	49.2 ± 14.8 (23)	30.2 ± 15.8 (8)	32.12 ± 14.92 (7)	—	7.4 ± 0.7 (4)	8.7 ± 0.6 (4)	—

due to sampling at low water levels that caused artificial turbidity in the samples. Conductivity was generally higher in water collected at the outflow of FGD-lined basins than clay-lined basins but the differences were not statistically significant ($\alpha = 0.05$). All of the reported dissolved oxygen levels in surface water surpass the current EPA water quality criteria of 5 mg O_2/L (US EPA, 1986).

Leachate Water Quality

Leachate water from the FGD-lined basins showed significantly higher conductivity than did leachate water from the clay-lined basins for all three years of the study (Table 3). Leachate water from FGD-lined basins was also consistently more alkaline than leachate in the clay-lined basins, but both systems were less in the last year of the study. pH was 7.7 to 8.1 in the clay-lined leachate in 2001-02 and lower at 6.6 in the third year. In contrast, pH averaged 9.4 to 9.8 in the FGD-lined basins in 2001-02 and 8.7 in the third year. The differences between clay and FGD remained 2.1 pH units from the first to third years, but the pH itself dropped 1.2 pH units over that time. In the third year of the experiment, leachate was significantly cooler below the FGD-lined wetlands than below the clay-lined basins. This is probably due to the fact that water was retained longer in the clay basins and had more opportunity to be heated by sunlight and atmosphere.

Elemental analysis of leachate water shows significantly higher concentrations of K, Na, and Mo in the first year in leachate water from FGD-lined basins than clay-lined basins (Table 4). In the second year of sampling, K and Na continued to be higher in the leachate of the FGD basins but were joined by significantly higher concentrations of Ca, S, and B. The higher Ca, Na, and K are consistent with the significantly higher conductivity seen in the leachate (Table 3). The higher concentration of B in the leachate is worrisome and reflects a negative effect of the higher permeability of the FGD material in this experiment.

Nutrient Retention in Simulated Wastewater Treatment

There were no significant differences between the clay-lined and FGD-lined basins on retaining phosphorus when very high concentrations of phosphorus were added to all basins in the 2003 experiment (Table 5). We had

Table 4 Elemental composition of leachate water for clay-lined and FGD-lined basins in years 2001 and 2002 (asterisks denote significance differences ($\alpha = 0.05$))

(μg/mL)	N=4	N=4		N=4	N=4	
Al	0.02 ± 0.0	2.6 ± 0.9	—	0.02 ± 0.00	0.09 ± 0.03	—
Ca	104.6± 6.4	152.5 ± 42.2	—	104.6 ± 6.4	438.8 ± 14.6	*
K	3.3 ± 0.9	837.1 ± 190.5	*	1.08 ± 0.08	30.9 ± 7.3	*
Na	14.0 ± 0.8	214.7 ± 46.1	*	16.5 ± 0.9	23.0 ± 0.9	*
Mg	62.4 ± 5.9	0.3 ± 0.2	*	48.8 ± 2.0	1.6 ± 0.8	*
S	128.1 ± 41.6	112.4 ± 21.6	—	10.6 ± 1.7	363.6 ± 13.0	*
B	0.07 ± 0.00	0.15 ± 0.04	—	0.1 ± 0.0	1.5 ± 0.2	*
Ni	<0.1	<0.1	—	<0.1	<0.1	—
P	<0.1	<0.1	—	<0.1	<0.1	—
Mn	0.4 ± 0.1	0.1 ± 0.0	—	0.2 ± 0.0	0.01 ± 0.0	—
Mo	0.01 ± 0.0	0.34 ± .05	*	0.01 ± 0.0	0.01 ± 0.0	—
Fe	0.01 ± 0.0	0.01 ± 0.0	—	0.01 ± 0.0	0.3 ± 0.1	—

Table 5. Nutrient concentrations in surface water of clay-lined and FGD-lined basins before and after phosphorus addition.

		Surface water		
	Inflow	Outflow clay-lined	Outflow FGD-lined	SD
Before P addition				
SRP (mg-P/L)	0.17 ± 0.07 (15)	0.10 ± 0.04 (10)	0.17 ± 0.06 (8)	*
Total P (mg-P/L)	0.27 ± 0.01 (15)	0.26 ± 0.01 (7)	0.25 ± 0.07 (8)	-
NO_3-N (mg-N/L)	0.29 ± 0.08 (16)	0.13 ± 0.05 (8)	0.10 ± 0.04 (5)	-
After P addition				
SRP (mg-P/L)	36.7 ± 9.4 (66)	26.8 ± 8.0 (28)	31.4 ± 10.0 (25)	-
Total P (mg-P/L)	53.8 ± 11.7 (61)	41.5 ± 10.5 (26)	49.2 ± 11.1 (24)	-
NO_3-N (mg-N/L)	0.39 ± 0.15 (10)	0.31 ± 0.11 (8)	0.34 ± 0.16 (6)	-

** Significance level at $p<0.05$

hypothesized that there would be an effect based on the results of experiments with small (1 m^2) mesocosms (Ahn et al., 2001; Ahn and Mitsch, 2001, 2002a). The phosphorus concentrations in the outflows of the FGD basins during the phosphorus additions were (average ±std err.) 49±11 mg-P/L (n=24), and the outflow of the clay-lined basins were 41±10 mg-P/L (n=26). These outflow concentrations were only slightly lower than the average inflow concentrations of 54±12 mg-P/L (Table 5). Apparently the pulsed water did not spend much time in the wetland basins but discharged quickly to the outflow (or to the leachate collection system with the FGD basins) without much biogeochemical activity. This was another disadvantage of the pulse-flow system we found it necessary to implement compared to a more desirable continuous-flow system. The only significant difference seen in nutrient retention was before the increased concentrations of phosphorus were added. During that period, the clay-lined wetlands discharged significantly lower concentrations of soluble reactive phosphorus (SRP), 0.10 mg-P/L, than did the FGD-lined basins (0.17 mg-P/L). This may reflect another effect of the differences in hydrology rather than the differences in the basins. The samples from the FGD basins were taken with lower water levels and thus contamination due to sediments getting into the sample bottles is much more likely.

Vegetation Productivity

Wetland plant biomass was used as an indicator of ecosystem productivity in the experiment. Higher biomass would indicate a less-stressed ecosystem. Plant biomass in the FGD-lined basins was consistently lower than wetland plant biomass in clay-lined basins for all three growing seasons, though only significantly different for 2001 and 2002 (Table 6; Figure 14). This was somewhat unexpected and is likely a function of the shorter hydrologic retention time in the FGD-lined basins as much or more than any adverse effect of elements leached from the FGD liner. During the first two years, all basins were dominated by the two sedges that were originally planted—*Schoenoplectus tabernaemontani* (soft-stem bulrush) and *Scirpus americanus* (common three-square rush). During the third year, probably as a result of the very high levels of phosphorus added, both basins became dominated by *Typha* spp. (cattail). As shown in Figure 14, the FGD basin, while lower in productivity, had 5 species dominating while the clay basins had only 3 species dominating in 2003. Fewer stems were counted in the FGD-lined basins than the clay-lined basins, but greater richness of species was found in the FGD basins. There was substantially greater presence of the common marsh herbs *Eleocharis obtuse* and *Leersia oryzoides* in the FGD-lined basins implying that more species may have greater success in FGD-lined wetlands than in the clay basins during periods of high nutrients. But this conclusion is tempered by the point that the "stress" that caused lower productivity in the FGD basins is more likely low water levels than any chemical effects of the FGD material.

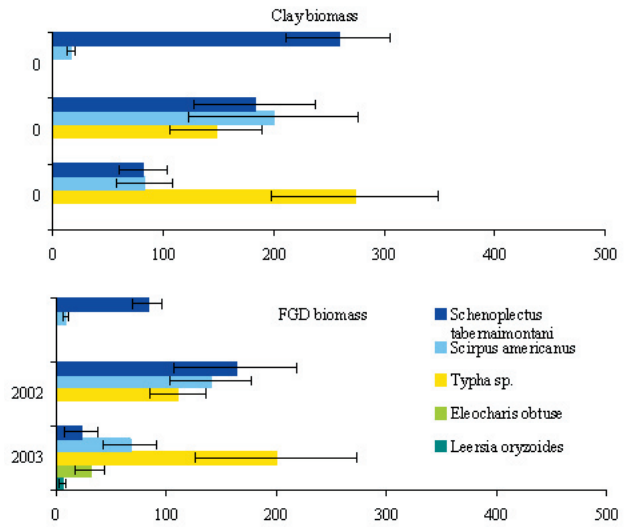

Figure 14. Annual peak biomass in clay-lined and FGD-lined basins for years 2001, 2002, and 2003

Some indicators of plant morphology illustrate differences between the clay and FGD basins (Table 7). There were significantly more plant stems in the clay basins in both 2001 and 2002. These data are reported for the two originally planted sedges *Scirpus americanus* and *Schoenoplectus tabernaemontani*. By the third year, *Typha* sp. (cattails) dominated the system and a good comparison of stem lengths and heights was not possible.

Table 6. Plant biomass in clay-lined and FGD-lined experimental wetland basins (avg ± std err (# sample plots)).

	clay-lined	FGD-lined	SD
		g-dry wt/m^2	
2001	275 ± 21 (8)	93 ± 10 (8)	**
2002	531 ± 39 (8)	415 ± 45 (8)	**
2003	439 ± 56 (16)	329 ± 61 (16)	—

* Significance level at p<0.10
** Significance level at p<0.05
*** Significance level at p<0.01

Table 7. Average plant morphology and stem flowering in clay-lined and FGD-lined basins in 2001 and 2002 for planted vegetation *Schoenoplectus tabernaemontani* and *Scirpus americanus*. SD = significant difference.

Element	First year (2001)			Second year (2002)		
	clay-lined	FGD-lined	SD	clay-lined	FGD-lined	SD
Ave. stem length, cm	139 ± 35	131 ± 34	—	334 ± 15	321 ± 20	—
Number of stems/ m^2	56 ± 5	33 ± 3	**	94 ± 13	60 ± 8	**
% of stems flowering	55	60	—	79	82	—

Plant Tissue Analysis

Chemical concentration of plant material in the basins could serve as indicators of whether plant roots extended into the liner material. Plant tissue analysis comparison is reported here for two wetland plants that were found in abundance in both the clay-lined basins and FGD-lined basins in the third year of study 2003 (Table 3.8). Greater concentrations of Al and Fe were detected in three-square rush (*Scirpus americanus*) plant tissue samples from FGD-lined basins in year 2003. These elements were present in higher concentrations in the FGD liner material than in the clay liner (Table 1), supporting the idea that some plant roots were able to reach through 2 feet (60 cm) of top soil and enter the liner material. This would be particularly the case if there were low water levels that would cause the plants to extend their roots deeper into the basins as was the case in the FGD basins. On the other hand, plants in the FGD basins did not have higher concentrations of Ca and B, two elements that are much higher in the FGD leachate. Scirpus had higher concentrations of Na, Mn and P in the clay-lined basins.

Soil

Topsoil was examined in both wetland basins in 2002 and 2003 to see if chemical analysis was different between the clay and FGD-line basins. A higher concentration after 2 or 3 years would indicate an upward movement of chemicals from the liners. Topsoil analysis after both full growing seasons (2002 and 2003) showed comparable concentrations of B between FGD-lined and clay lined basins (Table 9). Boron was an element of interest, as Ahn and Mitsch (2002a) and others have cautioned about the high concentration of B in FGD material. The concentrations of Ca and Mg were similar for topsoil in both treatment types. Topsoils from FGD-lined basins contained slightly greater concentrations of Fe and Mn during both years. There were statistically higher concentrations of S both years in the clay basins but the concentrations may not be ecologically different. After both full growing seasons (2002 and 2003), higher Mo was detected in the clay-lined basins than the FGD-lined basins (Table 9). This difference may be a reflection of the higher concentration of Mo in the clay-liner material (Table 1) although the clay-lined Mo concentration is only 12% higher than the FGD-lined Mo concentration.

Conclusions

Higher concentrations of elements common in FGD-liner material were found in leachate water in the FGD basins, suggesting that introduced river water was transported through the liners in these basins to the leachate collection system. Analysis of water level and seepage data supports this conclusion.

The FGD mixture as implemented in this project did not serve as an effective aquiclude to water movement. It was about 20 times more permeable than the clay liner material. Basins lined with the FGD material (vertical infiltration of 10^{-4} cm/sec) consistently showed lower water levels than basins lined with clay material (vertical infiltration of 5×10^{-6} cm/sec). These marked differences in hydrologic regime probably affected vegetative growth and nutrient removal.

Experiments with more impermeable FGD liners are needed to isolate the effects of the liner from the hydrologic effects observed in this study, some of which were due to different water levels.

There were no significant differences in phosphorus retention between the clay and FGD-lined basins during the high-phosphorus pulsing period, refuting the hypotheses generated by earlier small-scale mesocosm wetland studies. However these results cannot be firmly established because of three problems encountered in this study: 1) the phosphorus concentrations were 10 times those seen in wastewater wetlands; 2) the FGD basins were 20 times more permeable than the clay-lined basins, and 3) pulsing flow conditions rather than continuous flow conditions were necessary because of the instability of continuous flow conditions.

Plant productivity was lower in the FGD-lined wetland basins than in the clay-lined basins but we believe that this difference was caused more by difference in hydrology than by any effect of FGD material on plant growth. This conclusion is supported by the lack of substantial differences in elemental concentrations in plant tissue and topsoil between the FGD-lined and clay-lined basins.

Tradeoffs exist between productivity and diversity in most ecosystems. Plant data comparing FGD and clay-lined

Table 8. Elemental composition of wetland plant tissue (*Typha* sp. and *Scirpus americanus*) in clay-lined and FGD-lined basins in 2003. SD = significant difference.

Element	*Typha*		SD	*Scirpus americanus*		SD
	clay-lined	FGD-lined		clay-lined	FGD-lined	
(µg/g)	n= 8	n= 11		n= 6	n= 7	
Al	26±4	18±4	—	34±7	169±62	*
B	9±1	8±1	—	17±2	18±3	—
Cu	4±1	5±1	—	2±0	4±1	—
Fe	49±8	36±6	—	79±10	218±65	*
Mn	217±17	167±14	**	482±24	381±34	**
Zn	9±1	8±0	—	12±1	12±1	—
(mg/g)	n= 8	n= 11		n= 6	n= 7	
P	1.2±0.1	0.9±0.1	—	1.2±0.0	1.1±0.0	*
K	13.0±2.4	12.3±1.5	—	17.9±1.41	6.4±1.9	—
Ca	10.9±1.2	12.0±0.9	—	5.4±0.2	5.8±0.5	—
Mg	1.5±0.3	1.2±0.1	—	1.8±0.1	1.7±0.1	—
Na	3.2±1.0	1.9±0.6	—	5.5±0.7	2.2±0.3	***

* Significance level at $p<0.10$

** Significance level at $p<0.05$

*** Significance level at $p<0.01$

Table 9 Elemental composition of topsoil in clay-lined and FGD-lined basins in years 2002 and 2003 (asterisks denote significance differences ($\alpha = 0.05$))

Element	Second year (2002)			Third year (2003)		
	clay-lined	FGD-lined	SD	clay-lined	FGD-lined	SD
(µg/g)	N=8	N=8		N=8	N=8	
Cu	24.8 ± 0.3	26.1 ± 0.3	*	22.0 ± 0.1	23.8 ± 0.2	*
Mo	9.5 ± 0.3	8.5 ± 0.3	*	7.6 ± 0.2	6.4 ± 0.2	*
B	0.5± 0.0	0.5 ± 0.0	æ	15.5 ± 0.7	13.1 ± 0.9	æ
(mg/g)	N=8	N=8		N=8	N=8	
K	8.7 ± 0.1	10.0 ± 0.1	*	2.6 ± 0.1	2.6 ± 0.1	æ
Al	31.3 ± 0.3	36.2 ± 15.2	æ	13.5 ± 0.4	14.8 ± 0.4	æ
Ca	5.3 ± 0.7	4.1 ± 0.0	æ	4.3 ± 0.1	4.2 ± 0.4	æ
Mg	4.3 ± 0.3	4.1 ± 0.0	æ	2.8 ± 0.1	2.9 ± 0.2	æ
Fe	30.6 ± 0.2	32.4 ± 0.4	*	25.7 ± 0.1	28.7 ± 0.3	*
Mn	0.6 ± 0.0	0.7 ± 0.0	*	0.5 ± 0.0	0.6 ± 0.0	*
S	0.4 ± 0.0	0.3 ± 0.0	*	0.4 ± 0.0	0.3 ± 0.0	*
P	0.6 ± 0.0	0.6 ± 0.2	*	0.6 ± 0.0	0.5 ± 0.0	*

basins support this theory. The FGD-lined basins, which were stressed by low water levels, had a greater richness of plant species than did the clay-lined basins that had higher water levels. The clay-lined basins showed greater total plant productivity but with fewer plant species.

Additional studies are needed with FGD material designed to achieve low permeabilities similar to the clay material. We also propose additional studies that mix the FGD material in the topsoil so as to investigate the effectiveness of a topsoil/FGD mix on water quality and the effect of the mixture on plant productivity and wetland ecosystem health.

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