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EFFECTS OF RECYCLED FGD LINER MATERIAL ON WATER QUALITY AND MACROPHYTES OF CONSTRUCTED WETLANDS: A MESOCOSM EXPERIMENT

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Abstract—We investigated the use of flue-gas-desulfurization (FGD) by-products from electric power plant wet scrubbers as liners in wetlands constructed to improve water quality. Mesocosm experiments were conducted over two consecutive growing seasons with different phosphorus loadings. Wetland mesocosms using FGD liners retained more total and soluble reactive phosphorus, with lower concentrations in the leachate (first year) and higher concentrations in the surface water (second year). Leachate was higher in conductivity (second year) and pH (both years) in lined mesocosms. Surface outflow did not reveal any significant difference in physicochemical characteristics between lined and unlined mesocosms. There was no significant difference in total biomass production of wetland plants between lined and unlined mesocosms although lower average stem lengths and fewer stems bearing flowers were observed in mesocosms with FGD liners. Potentially phytotoxic boron was significantly higher in the belowground biomass of plants grown in lined mesocosms with low phosphorus loading. A larger-scale, long-term wetland experiment close to full scale is recommended from this two-year mesocosm study to better predict the potentially positive and negative effects of using FGD by-products in constructed wetlands. © 2001 Elsevier Science Ltd. All rights reserved

Key words—constructed wetland, FGD, liner, phosphorus retention, biomass production, phytotoxicity, boron.

INTRODUCTION

Constructed wetlands have been used as an attractive low-cost method for controlling water pollution from both point and nonpoint sources (Kadlec and Knight, 1996, Kadlec *et al.*, 2000; Mitsch and Gosselink, 2000). They have been especially effective in controlling nutrients (nitrogen and phosphorus) from municipal wastewater and farm runoff (Nichols, 1983; Richardson, 1985; Hammer, 1989; Olson and Marshall, 1992; Mitsch *et al.*, 2000). Some of these wetlands often require a liner of low permeability under the wetland basin to prevent the contamination of groundwater or to prevent groundwater from infiltrating into the wetland (Kadlec *et al.*, 2000). The most frequently used liners for constructed wetlands are imported clays, clay bentonite mixtures, and some synthetic materials such as polyvinylchlroride (PVC) and high-density polyethylene (HDPE) (Kadlec and Knight, 1996). However, synthetic liners are potentially expensive and are prone to more damage than clay or clay-bentonite liners (Kadlec and Knight, 1996). In addition, natural clays are not always plentiful where wetlands are to be constructed.

Flue-gas-desulfurization (FGD) by-products that are the residual of lime scrubbing of sulfur oxides from flue gases of coal-fired electrical generating stations have traditionally been treated as a waste product and landfilled. The disposal of the enormous volume of waste generated by every power plant with sulfur scrubbers, however, has become increasingly difficult as landfill costs increase and landfill space decreases (American Coal Ash Association Survey, 1997). Several studies have been carried out on the reuse of FGD by-products for such uses as land application, agricultural liming substitute, highway and civil engineering application, and waste-storage pond liners (Bigham *et al.*, 1993; Stehouwer *et al.*, 1995a, b, 1996; Butalia and Wolfe, 1997, 1999) but, no studies to our knowledge have investigated the use of this material as a potential liner for constructed

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wetlands. The idea of using FGD by-products as liners for constructed wetlands has three possible advantages. First, the FGD material, when properly applied, can have a very low permeability (Butalia and Wolfe, 1997, 1999). Second, these FGD by-products, high in calcium content, can lead to increased calcium-phosphate precipitation in the wetlands, thereby enhancing the water quality function of the constructed wetlands. Third, the FGD material could provide a good seal below constructed wetlands at an economically attractive price, particularly under wetlands being used for wastewater treatment.

There are concerns, however, for the land application of this material because FGD by-products can leach significant amounts of soluble salts as well as some trace elements of environmental concern (Stehouwer *et al.*, 1995b; Crews and Dick, 1998). One element of concern for plants grown on soils amended with FGD by-products is boron (B), since coal combustion products often contain considerably high levels of B (Crews and Dick, 1998; Sloan *et al.*, 1999). Although no serious phytotoxicity has been reported in previous studies (Stehouwer *et al.*, 1995a, 1996; Crews and Dick, 1998; Clark *et al.*, 1999; Sloan *et al.*, 1999), little is known about the effects of FGD by-products on rooted wetland macrophytes.

The purpose of this study was to identify advantages and disadvantages of using an FGD by-product as an artificial liner in constructed wetlands. We used experimental wetland mesocosms to investigate the effects of FGD liner material on both water quality and the health of wetland vegetation.

METHODS

Experimental design and treatments

Our experiment was carried out over two growing seasons (1997 and 1998). A set of 20 flow-through mesocosms ($1\,m^2 \times 0.6\,m$ deep polyethylene tubs; Fig. 1) was positioned at the Olentangy River Wetland Research Park (ORWRP), a 12-ha research site located on the Columbus campus of The Ohio State University (Fig. 1) (Mitsch *et al.*, 1998). Stabilized FGD by-products imported from Conesville electric power plant in Coshocton County, Ohio, USA were randomly assigned to half of the mesocosms; the other half with no FGD liner served as controls. Our stabilized FGD by-products was a mixture of the filter cake obtained from sulfur scrubbing process with dry fly ash and lime (CaO). Mesocosms were buried in the ground to insulate roots against freezing. All 20 mesocosms received 10 cm of noncalcareous river pea gravel (completely covering the drain to the standpipe) with the half of those overlain by 10–15 cm FGD by-product (Fig. 1b). The FGD by-product used in this study was a combination of fly ash to filter cake ratio 1.25 : 1 plus 5 wt% lime (CaO). Chemical analysis of the FGD by-product and topsoil used for the experiments was conducted at the Ohio Agricultural Research and Development Center (OARDC) Star lab in Wooster, Ohio (Table 1). Fifteen to 20 cm of topsoil was placed on top of the FGD material (Fig. 1b). The FGD material was not technically compacted as is usually the case in the construction of full-scale, FGD-lined lagoons for waste management (Goldman, 1988; Butalia and Wolfe, 1999). We also did not compact the FGD material into an impervious liner, so we would represent a worst-case scenario of FGD effects on water chemistry in mesocosm wetlands.

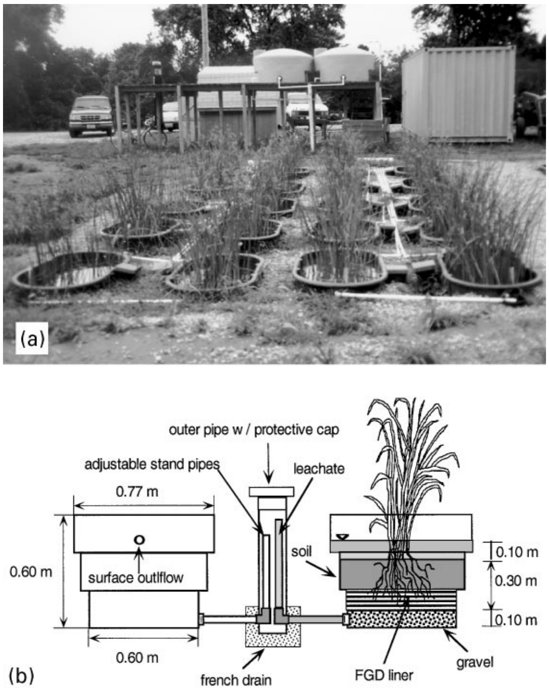

Fig. 1. Experimental wetland mesocosms used in this study.(a) Photograph of layout of 20 mesocosms at the Olentangy River Wetland Research Park. (b) Details of mesocosm drain system and FGD by-product placement in 10 of the 20 mesocosms.

Three rhizomes of *Schoenoplectus tabernaemontani* (soft-stem bulrush) were planted in all 20 mesocosms in May 1997, two months before the first-year experiment began. This macrophyte was chosen since it was the most representative wetland plant covering almost 80% of each of two basins of Olentangy River wetlands at the time of experiment and it is a typical plant used in constructed wetlands (Bouchard *et al.*, 1998). The rhizomes were equally spaced lengthwise in the mesocosm, pressed just below the surface of moist soil and buried (3 cm depth). Water levels in the mesocosms were initially adjusted by adding sufficient water to each mesocosm to cover the soil with approximately 3–4 cm of standing water. Water levels were changed by the introduction of inflow at the start of the experiment. Plants were established by the beginning of the first growing season experiment.

A water delivery system was constructed to simulate flow-through condition of full-scale created wetlands. This was accomplished through a series of manifolds and valves which distributed similar volumes of water pumped from the Olentangy River ($0.1\,mg\,P\,L^{-1}$) to each of the 20 mesocosms during the experiments. This water, which is contaminated by some agricultural and urban runoff, was first stored in two 1600L tanks (Fig. 1). A mercury float switch constantly maintained water levels in the tanks, and resulted in a flow to the mesocosms from the tanks. A #20 mesh pre-filter was installed in the pump and cleaned daily during data collection to prevent clogging in the numerous

Table 1. Chemical properties of the FGD by-product and topsoil used in the experiment and elemental composition of plant tissues after two growing seasons

Parameter	FGD[a]	Topsoil[a]	Plant mateiral							
			Aboveground tissue[b]				Belowground tissue[b]			
			L + R	N + R	L + P	N + P	L + R	N + R	L + P	N + P
pH	10.6	7.8	—	—	—	—	—	—	—	—
	($\mathrm{g\,kg^{-1}}$)									
Al	25.5	0.42	0.05 ± 0.02	0.05 ± 0.02	0.11 ± 0.03	0.07 ± 0.01	2.8 ± 0.7	1.4 ± 0.3	2.6 ± 0.7	1.4 ± 0.3
Ca	146	2.4	5.1 ± 0.5	5.4 ± 0.4	5.7 ± 0.6	4.9 ± 0.2	3.3 ± 0.4	2.4 ± 0.3	3.1 ± 1.0	2.5 ± 0.2
Fe	85	0.17	0.4 ± 0.1	0.2 ± 0.04	0.3 ± 0.08	0.2 ± 0.04	15 ± 1.5	9.9 ± 2.0	13.9 ± 4.3	12.0 ± 2.0
K	2.7	0.06	14.8 ± 0.5	13.7 ± 1.0	14.7 ± 1.0	15.4 ± 0.6	11.2 ± 0.6	10.5 ± 0.9	7.9 ± 2.0	10.1 ± 1.1
Mg	3.7	0.45	0.8 ± 0.1	0.9 ± 0.1	0.9 ± 0.1	0.9 ± 0.04	1.5 ± 0.1	1.3 ± 0.1	1.2 ± 0.3	1.1 ± 0.1
S	85	0.03	2.5 ± 0.2	2.2 ± 0.2	2.6 ± 0.2	2.2 ± 0.2	2.1 ± 0.2	1.7 ± 0.1	1.8 ± 0.6	1.5 ± 0.1
	($\mathrm{mg\,kg^{-1}}$)									
B	356[c]	2.1	11.9 ± 1.0	14.3 ± 1.8	14.7 ± 2.0	11.4 ± 0.3	11.1 ± 1.5	8.2 ± 0.6	9.2 ± 2.7	7.7 ± 0.5
Cu	49	5.0	23.9 ± 10	4.8 ± 0.9	8.1 ± 4.2	12.6 ± 9.3	8.3 ± 0.9	7.5 ± 0.7	7.8 ± 2.0	8.1 ± 0.4
Mn	130	146	1543 ± 184	1210 ± 101	1395 ± 169	1382 ± 231	596 ± 51	576 ± 39	565 ± 165	598 ± 28
Mo	15	< 0.1	2.8 ± 0.4	10.8 ± 3.7	3.7 ± 2.2	10.5 ± 2.8	4.6 ± 0.5	4.4 ± 0.5	4.5 ± 1.3	6.6 ± 1.6
Na	722	225	407 ± 69	597 ± 88	385 ± 63	494 ± 45	916 ± 28	1161 ± 116	839 ± 226	957 ± 132
Ni	48	3.3	45 ± 23	4 ± 1.1	20 ± 16	23 ± 22	9.7 ± 1.9	6.9 ± 1.5	10.4 ± 3.7	7.5 ± 2.4
P	573	8.4	1285 ± 31	1229 ± 59	1752 ± 125	1661 ± 146	1724 ± 198	1818 ± 146	1391 ± 365	1985 ± 71
Zn	133	5.2	35 ± 10	20 ± 2	13 ± 0.4	13 ± 1.3	45 ± 11	26 ± 2.1	29 ± 9.5	25 ± 1.3

[a] Average of two or three randomly taken samples for FGD and topsoil, respectively.

[b] Data are presented as mean ± SE; L + R = FGD liner + river water; N + R = no-liner + river water; L + P = FGD liner + P-spiked water; N + P = No-liner + P-spiked water.

[c] Total amount of B contained in FGD by-product; plant-available B extracted out of the material by hot-water was 29.4 $\mathrm{mg\,kg^{-1}}$.

pipes and valves involved in the water distribution system. A continuous inflow rate of $70\,\mathrm{mL\,min^{-1}}$ was chosen as a target inflow to each mesocosm during the experiments and the duration of flow was measured in the first-year experiment. This rate was a scale simulation of the full-scale wetlands (1 ha) at the ORWRP which are also fed by the same Olentangy River water and have an average inflow of approximately $0.7\,\mathrm{m^3\,min^{-1}}$(180 gpm). It was found that steady flow rates at this scale were difficult to maintain. To solve this problem, a pulse system was used which delivered a similar, per-day volume, but for one hour per day in the second year of mesocosm study. A sprinkler system timer was used to program the pulse time and duration. Table 2 provides a hydrologic information of the mesocosm wetlands.

In the second-year study, mesocosm plants used in the first year were much better established. We added phosphorus as super phosphate (P_2O_5, 46%) to one storage tank to provide high-P loading to half of the mesocosms, adding a second treatment to the experimental design in addition to the FGD material. The amount added simulated the phosphorus concentration of treated wastewater (2–$3\,\mathrm{mg\,P\,L^{-1}}$). The experimental design of the second-year study then consisted of four different treatment schemes: FGD liner plus riverwater (L + R), no-liner plus riverwater (N + R), FGD liner plus P-spiked water (L + P); and no-liner plus P-spiked water (N + P). Water level was checked three times a week during the experiment to ensure a similar hydrology to all 20 mesocosms with no differences among the treatments. The flow rate of river water into the mesocosms was measured with a graduated cylinder and a timer. Similar hydrology among the mesocosms was maintained. Comparison of hydrology among the mesocosms during the two growing seasons' experiments did not show any significant differences ($p = 0.45$ for the first year by water level, and $p = 0.52$ for the second year by flow rate).

Sampling and analysis of water

Water samples were intensively collected three times per week for inflow, surface outflow, and leachate during summer for four weeks (July through August) each year. Inflow samples were taken from the tanks (Fig. 1a) before the supply of the water to each of 20 mesocosms. Surface outflow samples were collected directly from the mesocosm outlets which are located at the opposite side of the inflow. Leachate, the water that would more directly contact the FGD liner material, was obtained from the standpipe connected to the bottom layer of the mesocosms (Fig. 1b). The FGD material applied in this experiment was not compacted for the impermeability required as a liner as mentioned earlier, allowing some portion of water in the mesocosms to seep through the FGD layer and around the sides of the mesocosm tubs to rise up in the standpipes as leachate. Leachate was collected by use of small suction pump from the standpipes. Standpipes were rapidly recharged with continually rising water after the sampling, indicating that we obtained a fresh sample. Two mesocosms that did not have sufficient leachate were removed from the study. Therefore, 18 mesocosms were included in the leachate analysis and 20 mesocosms were included in the analysis of surface outflow. Water samples were collected, transported to the laboratory in a cooler. One sample was filtered through 0.45 μm filter that had been soaked for 24 h in distilled water to remove contamination, and the filtrate was used for the analysis of orthophosphate. The other unfiltered samples were preserved by acidification with 2 mL of 36 N H_2SO_4 per liter of sample (to $\mathrm{pH} < 2$) immediately upon return to the Wetland Ecosystem Laboratory and kept at 4°C for the analysis of total phosphorus. The samples were colorimetrically analyzed by a Lachat QuickChem IV Flow Injection Analysis (FIA) System for total phosphorus (APHA, 1992 4500-PF), orthophosphate (APHA, 1992 Method4500-PF) and $NO_2 + NO_3$-N (APHA, 1992 4500-NO3E). Five prepared standards, a check standard and distilled water blank were run each time that an analysis was conducted. Standards were always within 10% of the prescribed values. Turbidity was determined on the day of sampling with a Hach Model 18900 Ratio Turbidimeter. A YSI Multiparameter Water Quality Data Transmitter was used on-site to measure pH, conductivity, dissolved oxygen, temperature and redox potential of water samples during the experiments. Weekly calibration of the YSI was carried out during the experiments.

Analysis of plant growth, biomass and tissue elements

Total number of stems, number of stems bearing flowers and stem lengths were investigated weekly in each mesocosm for two growing seasons during the experiments to measure the effects of FGD material on plant growth. For the stem length, 20 randomly chosen stems were measured for each mesocosm with a ruler. Plant biomass harvesting was conducted at the end of the second-year experiment. All aboveground stems and belowground roots and rhizomes were harvested after the drawdown of the mesocosms. Belowground parts of plants harvested were rinsed thoroughly with water to remove soil. The plant samples were placed in plastic bags and weighed in the field with a hanging balance (accuracy to 40 g). Sub-samples were taken to the laboratory where both wet weight and dry weight were determined to estimate dry/wet ratios. These ratios were multiplied by total wet weight of the biomass from each mesocosm to estimate each dry weight production afterward. Sub-samples were dried to constant weight at 60°C, and some of them were weighed, ground, and digested by heating in concentrated HNO_3 and $HClO_4$. Digests were analyzed for major and trace elements of plant tissues by inductively coupled plasma (ICP) emission spectrometry at the Ohio Agricultural Research and Development Center (OARDC) Star lab in Wooster, Ohio. The samples included above- and belowground parts of the plants. Plant-available boron was extracted using hot water and analyzed by ICP using EPA Method PB 84 - 128677 (USEPA, 1983).

Data analysis

Data were analyzed as a two-way analysis of variance using the general linear model (GLM) procedure in SAS (1988) with FGD liner material and phosphorus addition as main effects for all the items measured in water quality, plant morphometric measurements, plant biomass, and element analysis. Duncan's multiple tests were used to test all pairwise contrasts of means for significance at $p < 0.05$ (SAS, 1988; Steel *et al.*, 1997). Averages of the parameters measured from the experiments in both liner and no-liner mesocosms were calculated and

Table 2. Design parameters of mesocosm wetlands used for the study during two growing seasons' experiments

	Mesocosm wetlands	
	1997	1998
Hydraulic loading rate ($\mathrm{cm\,d^{-1}}$)	7.3	5.3
Mean water level (cm)	10.8	10.2
Water volume (average, m^3)	0.108	0.102
Hydraulic retention time (d)	1.48	1.92

compared via two-sample unpaired *t*-tests assuming unequal variance.

RESULTS AND DISCUSSION

Effects of FGD by-product on general water chemistry

Water quality results of the two years' experiments (first year and second year) are shown in Table 3. High alkalinity generated from the FGD by-product brought the pH of leachate over 10 in the first year; it decreased and stabilized at slightly alkaline levels in the second year, but significantly higher pH of leachate was maintained even after two growing seasons in the mesocosms with FGD liners. pH and conductivity of the leachate in wetland mesocosms with FGD liners were significantly higher ($p<0.05$) than in wetland mesocosms without liners in both years and in the second year, respectively. The high conductivity is related to higher concentrations of major elements contained in the FGD material such as calcium, potassium, and sulfur (Table 1). Redox values in leachate were much lower during the second-year experiment compared to the first year reflecting a more reducing condition developed in the mesocosm sediment over one year (Table 3). No differences were observed in the redox potential of leachate between lined mesocosms and unlined mesocosms in the first year, but significantly lower redox potential was observed in the lined mesocosms during the second year (Table 3). Presence of the liner could have retarded vertical flow enough to create greater reducing conditions in the sediments. Moreover, the FGD material used in the experiment mainly consisted of varying amounts of sulfates ($CaSO_4$) and/or sulfites of calcium ($CaSO_3$), unreacted lime and fly ash (Bigham *et al.*, 1993). $CaSO_3$, a strong antioxidant, may have contributed to lowering the redox potential of leachate by consuming the available oxygen from soil pore water in the mesocosms with FGD liner (Hao, 1998). No significant difference was found for the parameters mentioned above in surface outflow among the treatments except pH in the second-year experiment (Table 3).

Most of the leachate redox was below 100 mV in the second year, indicating the sediment was reduced enough for the reduction of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}) (Boström *et al.*, 1982). Iron reduction influences phosphorus (P) dynamics in anaerobic sediments because the inorganic P adsorbed with iron and aluminum oxyhydroxide can be released back to the water in waterlogged soils and underwater sediment (Patrick *et al.*, 1973; Mitsch and Gosselink, 2000). One way to control the release of sediment P in anaerobic wetland sediments is to reduce its solubility by precipitation with other elements such as calcium, iron and aluminum. FGD by-products are the sources of these elements that can precipitate phosphorus in soil.

Effects on phosphorus retention

The use of coal combustion by-products to immobilize phosphate from the water column was previously investigated (Theis and McCabe, 1978; Hishashi *et al.*, 1986). Stout *et al.* (1998) reported that FGD by-products could be successfully used to reduce the release of soil P to runoff from the soil, which exceeded P levels, needed for plant production. The reduction resulted from the conversion of readily desorbable soil P to less soluble Ca-, Al- and Fe-bound pools. FGD was the most effective in reducing water-extractable P out of the several coal combustion by-products tested in their research. In our mesocosm experiment, orthophosphate was more effectively removed from leachate in mesocosms with FGD liner material than in mesocosms without liners in the first year ($p<0.01$) (Table 3) although there was no difference in terms of total phosphorus. Most of the orthophosphate of leachate remained under the detection limit in the second year, resulting in more than 90% of removal regardless of treatment scheme (Table 3).

During the second-year experiment, both total phosphorus and orthophosphate were more effectively removed from P-spiked surface water passing through wetland mesocosms lined with FGD by-product than through those with no FGD material ($p<0.05$) (Table 3). More effective phosphorus precipitation with elements contained in FGD material may have been stimulated since the FGD material provides the elements that can immobilize phosphorus in soil (Stout *et al.*, 1998). The same tendency was observed in mesocosms with river water inflow, but the difference in phosphorus removal between lined and unlined mesocosms was not significant (Table 3). Fig. 2 provides a phosphorus budget of lined mesocosms fed by P-spiked water in the second year to show all the pathways of the supplied phosphorus. Most of the phosphorus was retained in the wetland sediment (75%). Of that amount 6.3% was bound in the liner and 9.4% taken up by plants. Substrate adsorption has been suggested as a significant mechanism in phosphorus removal in constructed wetlands as observed in this study (Kadlec, 1985; Richardson, 1985; Steiner and Freeman, 1989; Kadlec and Knight, 1996). Phosphorus loss as leachate was negligible (0.06%). The high phosphorus loading through phosphorus fertilization is assumed to have also increased soluble phosphate in the soil solution, inducing higher phosphate sorption in the sediment (Patrick and Khalid, 1974). Anaerobic soils release more phosphate to soil solutions low in soluble phosphate (Patrick and Khalid, 1974), a fact which may explain higher concentrations of total phosphorus in the leachate from mesocosms fed by river water with low phosphorus compared to mesocosms with phosphorus-spiked inflow in the second year (Table 3).

Table 3. Water quality and nutrient measurements in the mesocosm FGD liner experiments, 1997–1998[a]

Year and parameter	Surface outflow			Percentage change, inflow to outflow[b]		Result of t–test[c]	Leachate		Percentage change inflow to leachate[b]		Result of t-test[c]
	Inflow	Liner	No-liner	Liner	No-liner		Liner	No-liner	Liner	No-liner	
First year (1997)											
Riverwater											
Temperature, °C	23.92 ± 0.7 (10)	22.67 ± 0.16 (57)	22.40 ± 0.15 (63)	− 5.2	− 6.4	NS	23.93 ± 0.28 (98)	23.51 ± 0.18(93)	+ 0.1	− 1.7	NS
Turbidity, NTU[d]	27.8 ± 5 (9)	9.4 ± 1.2 (53)	7.7 ± 1.1 (59)	− 66	− 72	NS					
Dissolved oxygen, mg L^{-1}	6.19 ± 0.69 (10)	7.11 ± 0.50 (57)	6.2 ± 0.32 (63)	+ 15	+ 0.2	NS	0.44 ± 0.13 (98)	0.33 ± 0.04 (93)	− 93	− 95	NS
pH	8.72 ± 0.14 (10)	9.34 ± 0.07 (57)	9.08 ± 0.07 (63)	+ 7.1	+ 4.2	NS	9.79 ± 0.23 (98)	7.85 ± 0.1 (93)	+ 12	− 10	*
Conductivity, μS cm^{-1}	503 ± 19 (10)	548 ± 11 (57)	557 ± 12 (63)	+ 9	+ 11	NS	934 ± 65 (98)	902 ± 64 (93)	+ 86	+ 79	NS
Redox potential, mV	448 ± 11 (10)	409 ± 5 (57)	415 ± 3 (63)	− 9	− 7	NS	169 ± 28 (98)	211 ± 15 (93)	− 62	− 53	NS
Orthophosphate, μg L^{-1}	62 ± 5 (10)	10 ± 2 (53)	8 ± 2 (61)	− 85	− 86	NS	8 ± 1 (90)	12 ± 2 (88)	− 88	− 81	*
Total phosphorus, μg L^{-1}	140 ± 7 (10)	62 ± 11 (55)	65 ± 9 (62)	− 56	− 53	NS	226 ± 35 (90)	201 ± 35 (88)	+ 61	+ 44	NS
Nitrate, mg L^{-1}	1.39 ± 0.12 (10)	0.58 ± 0.06 (55)	0.52 ± 0.01(62)	− 58	− 62	NS	0.75 ± 0.07 (81)	0.58 ± 0.04 (79)	− 46	− 58	NS
Second year (1998)											
Riverwater											
Temperature, °C	25.01 ± 0.65 (9)	24.09 ± 0.15 (43)	23.83 ± 0.19 (43)	− 3.7	− 4.7	NS	23.75 ± 0.18 (55)	23.19 ± 0.18 (47)	− 5.0	− 7.3	NS
Turbidity, NTU[d]	11.66 ± 3.5 (9)	5.9 ± 1.0 (43)	5.4 ± 1.0 (43)	− 49	− 54	NS					
Dissolved oxygen, mg L^{-1}	4.90 ± 0.19 (9)	2.40 ± 0.54 (43)	2.14 ± 0.58 (43)	− 51	− 56	NS	0.57 ± 0.25 (55)	0.54 ± 0.17 (47)	− 88	− 89	NS
pH	7.41 ± 0.07 (9)	7.67 ± 0.09 (43)	7.52 ± 0.07 (43)	+ 3.6	+ 1.6	*	7.60 ± 0.15 (55)	6.81 ± 0.03 (47)	+ 2.6	− 8.0	*
Conductivity, μS cm^{-1}	513 ± 31 (9)	505 ± 11 (43)	490 ± 13(43)	− 2	− 5	NS	1719 ± 310 (55)	847 ± 157 (47)	+ 235	+ 65	*
Redox potential, mV	341 ± 20 (9)	199 ± 12 (43)	201 ± 11 (43)	− 41	− 41	NS	− 10.3 ± 44 (55)	61.3 ± 13 (47)	− 103	− 82	*
Orthophosphate, μg L^{-1}	57 ± 10 (9)	11 ± 4 (42)	11 ± 4 (43)	− 80	− 82	NS	2 ± 2 (55)	1 ± 1 (52)	− 97	− 98	*
Total Phosphorus, μg L^{-1}	126 ± 10 (9)	116 ± 31 (43)	157 ± 56 (43)	− 8	+ 25	NS	840 ± 321 (55)	717 ± 246 (51)	+ 568	+ 470	NS
Nitrate plus nitrite, mg L^{-1}	1.96 ± 0.35 (9)	0.89 ± 0.30 (43)	0.74 ± 0.23 (43)	− 54	− 62	NS	0.25 ± 0.11 (55)	0.23 ± 0.08 (50)	− 87	− 88	NS
P-spiked water					−						
Temperature, °C	25.56 ± 0.59 (9)	24.23 ± 0.26 (35)	24.13 ± 0.2 (40)	− 5.2	− 5.6	NS	23.76 ± 0.23 (44)	23.55 ± 0.12 (55)	− 7.0	− 7.9	NS
Turbidity, NTU[d]	17.44 ± 3.9 (9)	5.4 ± 1.5 (35)	6.4 ± 1.2 (41)	− 69	− 63	NS					
Dissolved oxygen, mg L^{-1}	4.79 ± 0.29 (9)	2.99 ± 0.63 (35)	2.30 ± 0.48 (40)	− 37	− 52		0.60 ± 0.29 (44)	0.30 ± 0.08 (55)	− 87	− 94	NS
pH	7.25 ± 0.08 (9)	7.59 ± 0.09 (35)	7.48 ± 0.08 (40)	+ 4.7	+ 3.2	NS	7.46 ± 0.16 (44)	6.88 ± 0.04 (55)	+ 2.8	− 5.2	*
Conductivity, μS cm^{-1}	520 ± 30 (9)	533 ± 10 (35)	529 ± 11 (40)	+ 3	+ 2	NS	1720 ± 323 (44)	677 ± 55 (55)	+ 231	+ 30	*
Redox potential, mV	346 ± 25 (9)	228 ± 7 (35)	231 ± 7 (40)	− 34	− 33	NS	19 ± 39 (44)	43 ± 10 (55)	− 94	− 88	NS
Orthophosphate, μg L^{-1}	2169 ± 120 (9)	1082 ± 272 (34)	1506 ± 197 (41)	− 50	− 31	*	0 ± 1 (44)	0 ± 0 (55)	− 100	− 100	NS
Total phosphorus, μg L^{-1}	2850 ± 80 (9)	1472 ± 324 (35)	2032 ± 164 (41)	− 48	− 29	*	313 ± 109 (44)	324 ± 97 (54)	− 89	− 89	NS
Nitrate plus nitrite, mg L^{-1}	2.11 ± 0.35 (9)	0.66 ± 0.31 (35)	0.88 ± 0.33 (41)	− 68	− 58	NS	0.27 ± 0.15 (44)	0.33 ± 0.18 (55)	− 87	− 84	NS

[a] Data are presented as mean ± SE (number of samples).

[b] Increase is indicated by plus symbol, decrease by minus symbol.

[c] Liner vs. no-liner; NS, no significant difference; * significant difference at $\alpha = 0.05$.

[d] NTU, nephelometric turbidity units.

Plant growth

When waste by-products such as FGD residue are used in any soil–plant system in a beneficial manner, questions are raised about potential detrimental effects to the environment. No difference was found in the biomass production of wetland vegetation *Schoenoplectus tabernaemontani* between lined and unlined mesocosms in either river water (first year) or phosphorus-spiked (second year) experiments (Fig. 3). *S. tabernaemontani*, however, did show lower average stem length, fewer stems, and fewer stems bearing flowers in mesocosms using FGD by-product as a liner in the first growing season ($p < 0.01$). This trend lessened in the second year, but still resulted in lower average stem length and fewer stems bearing flowers in the lined mesocosms (Table 4). There was no difference in the number of stems between lined and unlined mesocosms in the second year (Table 4), indicating the plants had overcome any potentially detrimental effects from the FGD materials applied.

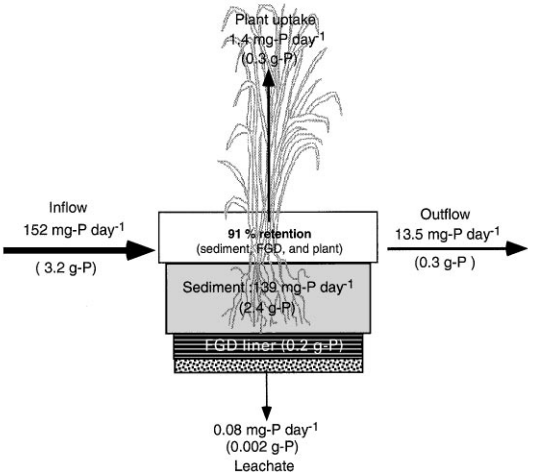

Fig. 2. Phosphorus budget of mesocosm wetland with P-spiked inflow. Numbers in parentheses indicate the total amount of phosphorus flux in the mesocosm (1 m^2) during the second-year experiment.

Trace metals in plants

B concentrations were not significantly ($p > 0.05$). different in the plant tissues of aboveground biomass among the treatments (Fig. 4). However, the B content of the plant tissues of belowground biomass was significantly higher in FGD-lined mesocosms relative to unlined mesocosms when they both were fed by riverwater ($p < 0.05$). B is an essential micronutrient for plant growth, but it can become phytotoxic to some plants (Nable *et al.*, 1997; Crews and Dick, 1998; Clark *et al.*, 1999). Serious problems have occurred to plants grown on soils irrigated with high-boron water (Gupta *et al.*, 1985), and to plants grown on pulverized fuel ash (PFA or "fly ash") (El-Mogazi *et al.*, 1988). B toxicity has been well studied in agricultural crops and fruit trees, but research on wetland plants is rare (Sposito, 1988). McLeod and Ciravolo (1998) tested bottom-

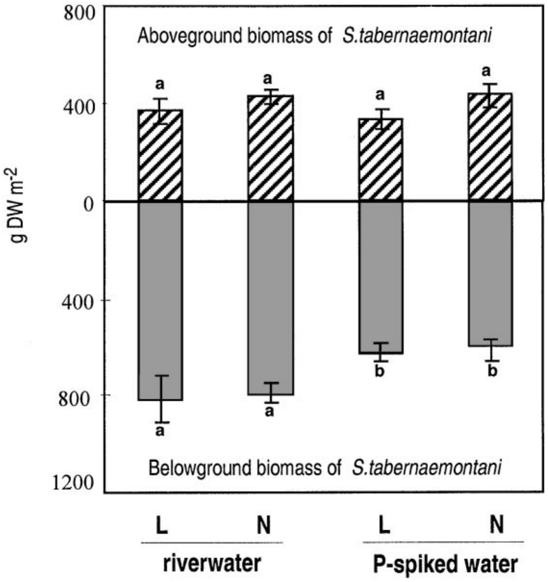

Fig. 3. Biomass production of *Schoenoplectus tabernaemontani* in mesocosms after two growing seasons. The same letters among the treatments indicate no statistical difference. Bars denote the standard error of the mean ($n = 5$). L = FGD liner; N = no liner.

Table 4. Number of stems, number of stems bearing flowers and stem length of *S. tabernaemontani* under various treatment regime after two growing seasons' experiments[a]

	Treatment[b]			
Variable	L + R	N + R	L + P	N + P
No. of stems	282 ± 20a	304 ± 22a	255 ± 17b	289 ± 9a
No. of stems (w/flowers)	266 ± 17b	299 ± 19a	232 ± 15c	284 ± 8ab
Stem length (cm)	102 ± 2c	112 ± 2a	108 ± 4b	113 ± 3a

[a] Values are mean ± SE.

[b] L + R = FGD liner + river water; N + R = no-liner + river water; L + P = FGD liner + P-spiked water; N + P = no-liner + P-spiked water. Means in each row followed by the same letter are not significantly different across the treatments at the $p < 0.05$ level.

land tree seedlings for B tolerance and found decreased growth of the plants tested at the highest boron treatment applied. The higher B content of belowground biomass from the lined mesocosms did not seem to affect biomass production negatively because there was no difference in the aboveground ($p = 0.094$) or belowground biomass ($p = 0.68$) of plants between lined and unlined mesocosms (Fig. 3).

The higher B content found in the belowground biomass is probably not related to the morphometric growth retardation of wetland vegetation observed through this experiment since the amount of plant-available B of the FGD by-product used was very low (29 mg kg^{-1}) (Table 1). Generally, B above ~50–100 mg kg^{-1} has been considered high for many plants (Clark *et al.*, 1999). B is also readily adsorbed to soil particles, and its availability decreases as soil pH increases (Clark *et al.*, 1999). Thus, the high alkalinity of the wetland mesocosm sediments, reflected in the high pH of leachate, can reduce plant uptake of B even when B levels applied to soils are relatively high. B is also highly soluble in water and may readily leach (Sposito, 1988; Clark *et al.*, 1999). Any potential phytotoxicity of B may disappear or be mitigated over time through mechanisms such as immobilization, leaching, and plant uptake (Ransome and Dowdy, 1987; McLeod and Ciravolo, 1998). The lower morphometric values observed in the mesocosms containing FGD material as a liner (Table 4) may be due to initial high pH of sediments induced by highly alkaline FGD by-products applied, which could be detrimental to early growth of the plants (Stehouwer *et al.*, 1996). Relatively lower redox potential that developed in the sediments with FGD by-product may also have affected plant growth (Brix and Sorrell, 1996). The lower concentrations of water-soluble phosphorus in lined mesocosms (Table 3) might also limit the amount of plant-available phosphorus, inducing lower growth of plants. FGD by-products also contain higher amounts of many elements essential for plant growth such as Mo, Zn, P, and K relative to the topsoil (Table 1). But, the alkaline characteristics of FGD by-products may make these elements increasingly unavailable for plant uptake because the higher soil pH will probably immobilize most metals (El-Mogazi *et al.*, 1988), this effect may also have contributed to lower morphometric growth of wetland vegetation in the mesocosms with a FGD liner.

Mesocosm artifacts and study limitations

There were some mesocosm-scale artifacts found during the experiments. The 1 m^2 mesocosms became "pot-bound" with plants after two years. This leads us to conclude that wetland mesocosms older than two years with emergent plants are not sufficient analogs of large-scale wetlands. Potentially phytotoxic impacts which can be indirectly induced by FGD material being applied have not been tested on other species of wetland plants, so the observed results cannot be extrapolated with confidence to other plant species that may colonize treatment wetlands being built with FGD liners. It was not possible to see the effects of FGD material on other aquatic life, e.g. amphibians and benthic invertebrates, at this small mesocosm scale. Moreover, the implications of season and long-term loading of high-nutrient water were not evaluated.

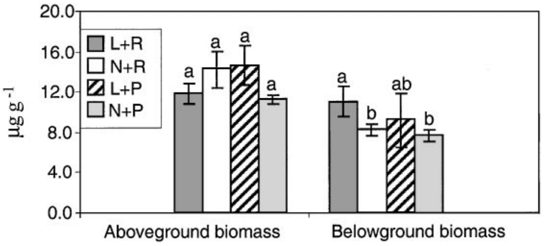

Fig. 4. Boron content of plant tissue in mesocosms after two growing seasons. Bars denote standard error of the mean ($n = 5$). The same letters among the treatments indicate no statistical difference. L = FGD liner; N = no-liner; R = river water; P = phosphorus-spiked water.

The composition and the amount of FGD material being used as liners, and the method of application of the material will also affect the quantity and quality of water (leachate and surface outflow) (Ransome and Dowdy, 1987; Crews and Dick, 1998) and wetland ecosystem development.

CONCLUSIONS

FGD by-products appear to assist in retaining phosphorus from water with no detrimental impact on biomass production of macrophytes in the constructed wetland system over two growing seasons. FGD by-products may offer a good substrate material as well as a liner material for phosphorus retention in constructed wetlands for water treatment. However, the susceptibility of other components of wetland ecosystem to the FGD material is currently unknown. Long-term chronic effects of FGD on biomass production may not be ascertained through this relatively short two-year study. A larger-scale, longer-term wetland experiment closer to full scale should be conducted to better predict the effects, both positive and negative, of using FGD by-products to seal constructed wetlands.

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