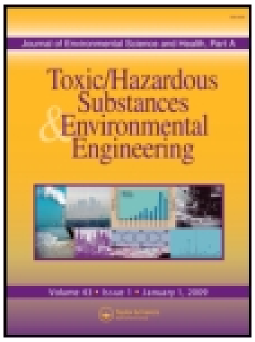

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DESIGNING CONSTRUCTED WETLANDS TO REMOVE PHOSPHORUS FROM BARNYARD RUNOFF: A COMPARISON OF FOUR ALTERNATIVE SUBSTRATES

Key Words: Constructed wetlands, stormwater management, phosphorus, substrates, agricultural wastewater, dairy barnyard runoff, calcium, LECA

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ABSTRACT

While constructed wetlands can be a cost-effective method for reducing the export of P from agricultural ecosystems, removal rates vary widely. The objective of this research was to evaluate substrates that could consistently improve P treatment in these wetlands. We built eight 55 m^2 subsurface wetland cells on an 800-head dairy farm in Newark, NY, USA, to test alternative substrates for removing soluble P from dairy barnyard runoff. The four media were (1) a fine loamy, mixed, mesic Glossic Hapludalf, (2) crushed limestone, (3) Norlite, lightweight coarse aggregates of fired shale, and (4) wollastonite (calcium metasilicate) mining tailings. Based on this research, we recommend Norlite for P removal in agricultural ecosystems. The native soil retained more soluble P but could not sustain subsurface flow. Wollastonite tailings warrant further research. They adsorbed 2 mg P/g in the laboratory but performed less well in the field, probably because of preferential flow.

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INTRODUCTION

Agricultural land use in the United States involves extensive land drainage and loss of wetlands (USEPA, 1990), which may be partially responsible for the declining health of freshwater streams and lakes in agricultural ecosystems. In the nine-county region surrounding Minneapolis-St. Paul, for example, lower wetland density is correlated with higher seasonal export of organic matter and inorganic soluble P in streams (Johnson et al., 1990). Phosphorus in surface runoff and the general degradation of surface water resources are both correlated with increasing proportions of agricultural to total land use in a watershed (Omernik, 1977).

Phosphorus can enrich freshwaters and cause significant shifts in the composition of aquatic communities because the primary productivity of many freshwater lakes is P limited (Schindler, 1974). Total P concentrations as low as 30 *ug*/L (Carlson, 1977) and inorganic P concentrations as low as 10 *ug*/L (Sawyer, 1947) stimulate algal blooms. Decomposition of algal blooms, in turn, can lead to anoxia and a loss of biodiversity.

An increasing number of farmers are choosing to restore or construct wetlands to mediate polluted water draining from their fields and barnyards (Kadlec and Knight, 1996). The technology is promising: An eleven-year study in western Pennsylvania showed that the establishment of wetlands is a cost-effective method for reducing the export of P from watersheds (Brenner et al., 1991). But, retention rates for P in agricultural wetlands and in constructed wetlands utilized for wastewater treatment range from only 12% to a high of 95%. After 3-4 years of operation, most remove less than 40% of the P (Mæhlum, 1998). Moreover, P concentrations in the treated effluent are often two orders of magnitude greater than concentrations that can stimulate algal blooms in freshwaters. Thus, there is an urgent need to find cost-effective mechanisms for improving the nutrient removal efficiency of constructed wetlands. The need is particularly urgent on American livestock farms because many farmers are rapidly expanding herds to1000 or more head, creating a wastestream that is more nutrient-rich than municipal sewage.

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Both natural and constructed wetlands adsorb and precipitate soluble P and trap P-rich eroded sediment. In addition, some wetlands bury organic P in aggrading layers of detritus. Whether these sinks exist at all, and whether they are permanent or temporary depends on the hydrology and the chemistry of the water flowing in and through the wetland. Also critical is the P adsorption capacity of the soil or other substrate relative to the P already sorbed.

Thus, in constructed wetlands adsorption and chemical precipitation control P removal, while plants have relatively little influence. Richardson and Davis (1987) cite the Listowel experimental study in Ontario (Ontario Ministry of the Environment, 1985) as evidence that aboveground plant assimilation, even with recurring harvests, is unimportant relative to chemical adsorption: aboveground biomass accounted for the removal of only 3.8 to 9.6% P and 5.7 to 9.1% N. The preferred method of optimizing P removal by constructed wetlands is either to add chemicals to help precipitate P or to use a substrate known to adsorb or precipitate P (Brix, 1994). Additional properties of a substrate that affect P removal include surface area and factors that influence the flow path of water through the material: porosity and particle size distribution.

Wollastonite tailings and coarse lightweight aggregate rock (Norlite) are two products that have properties favorable for removing P. As documented below, each has high P adsorption capacity and a high surface area. Both are available in NY. The objective of this research is to compare these two media with two more common and more readily available substrates, soil and limestone. Neither wollastonite tailings nor Norlite have been tested in the field. Based a combination of factors (P fixation capacity, expected flow pathways, and surface area), we expected Norlite to remove the most soluble P, followed by wollastonite tailings, limestone, and soil.

MATERIALS AND METHODS

Materials

Wollastonite tailings are the byproduct of a mining operation near Willsboro, NY, which produces wollastonite (calcium metasilicate) and garnet (a ferrous

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metasilicate). The tailings are approximately 15% wollastonite and 70-80% garnet, so they provide both calcium and iron as potential adsorption sites for P (Geohring et al., 1995). The particle size distribution is also favorable for P removal: 0.2% fine gravel, 4.3% coarse sand, 44.4% medium sand, 36.5% fine sand, and 14.6% silt and/or clay (Brooks, 1997). Laboratory experiments show that over a wide pH range, this material removes 90% of the P from influent solutions containing 5 mg/L. In general, its adsorptive capacity is 5 mg P/g substrate (Geohring, 1994), which is orders of magnitude higher than most soils. At lower ambient concentrations of P (1 mg/L), the tailings removed 2 mg P/g substrate in mechanically agitated laboratory tests (Geohring et al., 1999). Such tests overestimate the removal in a passive-flow wetland but do give an upper limit for performance. A retention time of at least 62 hours is necessary for optimal removal (Geohring et al., 1999). In addition, one must design for preferential flow: hydraulic overloading and variability in particle size of the wollastonite tailings each exacerbated preferential flow in a pilot study (Geohring et al., 1999). Preferential flow decreases contact with the wollastonite tailings and thus decreases P adsorption per gram of material.

Calcium metasilicate deposits exist in China, India, Finland, California (Hare, 1993), and Mexico, in addition to New York. Because each deposit is unique in terms of its crystalline nature and associated minerals, mining tailings from each site would have to be individually tested for potential use in constructed wetlands. In addition, engineers designing wetlands must consider that the tailings from a single plant have heterogeneous porosity, hydraulic conductivity, and chemical composition because grinding and separation processes vary over time.

Norlite is shale that has been crushed and fired. It is a construction material that is classified as a lightweight aggregate. Similar materials are manufactured in Virginia (Solite) and, as listed in Zhu et al., 1997, in Utah (Utilite), Oklahoma (Chandler), Virginia (Lehigh Cement), and Arkansas (Arkansas Lightweight Corp). Norlite may be compared to lightweight expanded clay aggregates (LECA), produced in Scandinavia and utilized in Norwegian residential treatment systems (Jenssen et al., 1994). Norlite is less effective in treating P than LECA, which removes 0.05 to

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0.6 mg P/g in laboratory tests (Jenssen, personal communication, and Zhu et al., 1997). According to the manufacturer, Norlite is 4.7% iron oxide, 3.6% magnesium oxide, 3.2% alkalies, 2.0% calcium oxide, 20.2% aluminum, and 64.2% silica. In this study we used the coarse aggregate (certified by Norlite corporation to be in accordance with ASTM C330 Table 1, which requires 95% ± 5% to be retained on a 19 mm sieve). Norlite has high surface area because each of the particles is rough and pitted.

The soil is a fine loamy, mixed, mesic Glossic Hapludalf that formed from calcareous and sulfur-rich glacial till. Glossic refers to tonguing of the E horizon into the argillic (top of the Bt) horizon. In this context the E horizon refers to a zone depleted of clay and Fe oxides. The parent material is rich in calcium carbonate but the top meter of soil is not calcareous, due to leaching. The soil used in this research was excavated from the top meter.

Most of the particles comprising the #1 limestone (one of the four treatments) are 0.6 to 1.3 cm in size. The #2 limestone used at the head and foot of each wetland cell has larger particles, most of which range from 1.3 to 2.5 cm.

Norlite has the greatest porosity (54.2%), followed by soil. Porosity of the soil was estimated from bulk density as 50.9% in the first soil bed and 49.3% in the second soil bed. We measured the porosity of the limestone and the wollastonite tailings used in this experiment as 47.1% and 46.7%.

Substrates with a more uniform particle size structure are less likely to clog and more likely to support uniform hydraulic flow, as opposed to preferential flow. Norlite and limestone have the most uniform particle size, followed by wollastonite and then soil.

Methods

This experiment involves treatment of runoff from an 800-head dairy barnyard in Newark, NY, USA. The wastestream includes runoff from a bunk silo, cowpaths, roofs, small pastures and an agricultural field. Most of the barnyard manure and milkhouse wastewater is treated separately and does not enter the constructed wetland system. The barnyard runoff flows through two small sedimentation basins

(208 m^2 x 1.2 m deep, 268 m^2 x 2.5 m deep) and one large retention basin (856 m^2 x 1.5 m deep) before entering the wetland cells. This pretreatment allows for the settling of solids, volatilization of ammonia, coupled nitrification and denitrification, and BOD (biological oxygen demand) removal. After additional treatment in the wetlands, the water flows into another retention basin for storage and aeration. The landowners periodically apply this stored effluent to a nearby field that is planted in a rotation of maize [Zea mays L.] and alfalfa [Medicago sativa].

The constructed wetland experiment utilized eight 55 m^2 subsurface wetland beds, two for each of the four substrates to allow replication of each treatment. The design for all beds included limestone (about 1.2 m in length of #2 limestone) and buried tile drains at the head and the foot to filter suspended matter and facilitate flow of wastewater into and out of the wetlands. The cells are each 1 m deep with 75 cm of substrate. The berms slope at a 45-degree angle. Water flows into the wetlands 64 cm above the floor of the cells and exits at 9 cm above the floor. The high water level fluctuates from about 45 to 55 cm, in accordance with design criteria for constructed wetlands (Weider et al, 1989).

We wanted to optimize the probability that the wollastonite tailings would support subsurface flow despite low porosity and potential clogging of pores. Therefore, we put wollastonite tailings only in the second half of the wollastonite beds; the first half we filled with fine limestone to act as a prefilter. In addition, to prevent crusting on the surface of the wollastonite, we added 10-15 cm of fine limestone (#1) on top of the wollastonite tailings. This strategy prevented sustained overland flow, but it complicated interpretation of results, since the volume of wollastonite used in the experiment was half the volume of Norlite, soil, or limestone in the other three treatments.

The wetland beds were not planted because we wanted to avoid confounding the experiment with variations in plant uptake of P. But, opportunistic vegetation such as Juncus sp., Ranunculus sceleratus, Trifolium repens, Poa palustris, Poa pratensis, and Agropyron repens grew in the soil beds. We periodically mowed the plants in the soil beds, without harvesting any biomass. Twice during the summer of 1998 we

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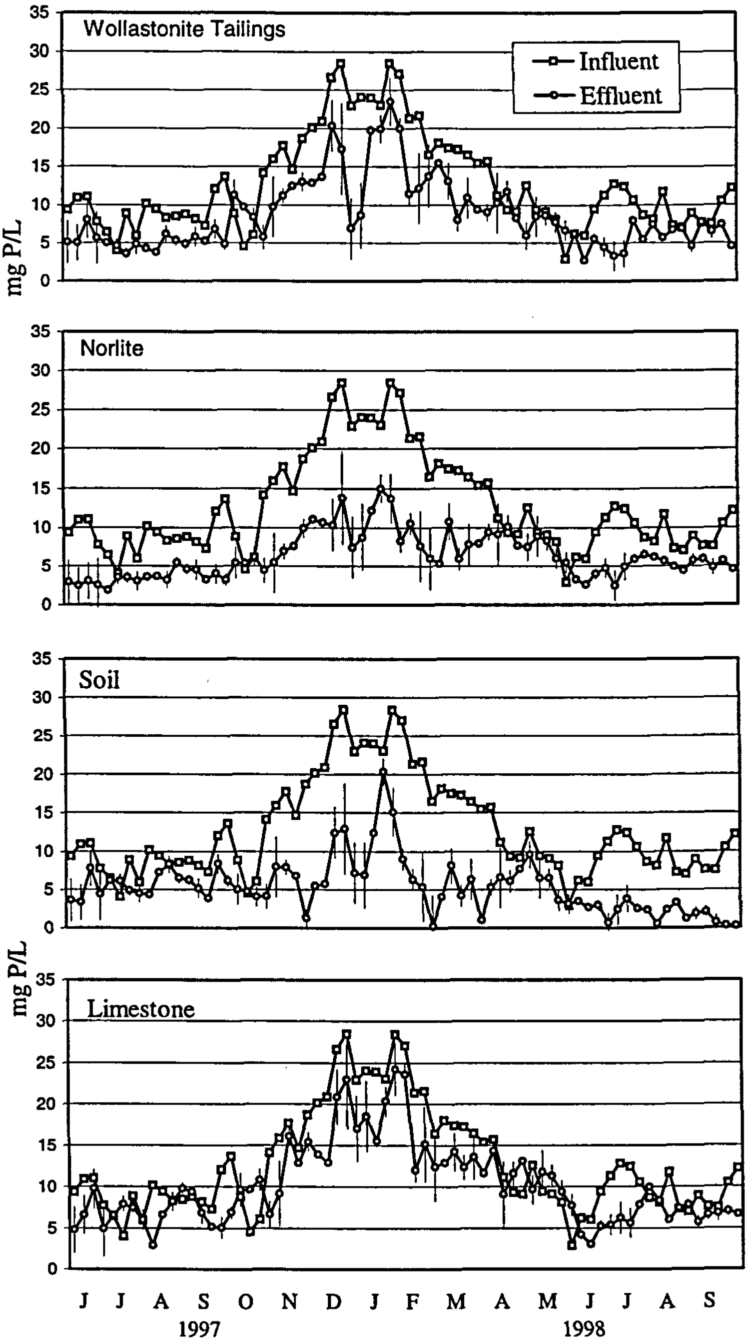

FIGURE 1
Concentration of Soluble P in The Influent and in the Effluent from the two Subsurface Wetland Cells Constructed with (A) Wollastonite Tailings, (B) Norlite, (C) Soil, and (D) Limestone.

killed the vegetation with glyphosate to ensure that the opportunistic plants did not jeopardize the integrity of the experiment.

Each bed is hydrologically self-contained because we lined each with a PVC liner. We strictly controlled hydrologic inputs and outputs to ensure uniform hydrology in each cell. Wastewater entered the cells for one or two pulses diurnally over 1.5 years (24 May, 1997 to 8 Oct, 1998) via a pumped distribution system. Each bed received an average of 691 L of wastewater per day, for a total of 347,530 L over 503 days.

The constructed wetland system was designed primarily to treat P, but the design constraints also considered nitrogen and BOD removal. For BOD removal, the goal was a retention time for wastewater of 7-10 days: this range was empirically derived from data on early surface flow systems (Kadlec and Knight, 1995). The range for subsurface flow systems was much lower, 2-4 days. In most surface flow systems this goal of an adequate retention time is met with influent delivery of 1.5-6.5 cm/day, while subsurface flow systems can treat 8-30 cm/day. The ELVI Farms subsurface system was designed for the worst-case scenario of overland flow, with a target of 3 cm of wastewater/day/bed. During the coldest months, however, when the pump had to run 24 hours per day to prevent pipes from freezing, the minimum input of wastewater was theoretically 2.4 cm/day/bed (the flow meters only measure correctly when flow exceeds 0.945 L/min). We were comfortable using previous studies for design criteria because we first established that nutrient levels in the wastestream were comparable to municipal sewage, which many of the early systems treated: Based on measurements of soluble P in surface runoff and in an underground tile drain that funneled barnyard runoff prior to construction, we expected the soluble P concentration to average 3-10 mg/L.

We sized the sedimentation and retention basins to accommodate the 24-hour precipitation event with a return period of 25 years (9.4 cm of precipitation), consistent with US Natural Resource Conservation Service requirements at the time of construction. We estimated the watershed area (7.2 ha) from USGS 24000:1 topographic maps, and used this number and a curve-number runoff model to estimate runoff associated with the 25-year storm.

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Measures taken to prevent freezing in the winter included use of underground distribution pipes, a subsurface-flow design, use of hay bales over meter boxes, and a light bulb to provide heat in the pumping station. An ice layer that formed on the soil beds insulated them. Input varied by day depending on the weather and depending on the condition of filters that sometimes impeded flow. We ran the pump for at least 4 hours each day but as long as necessary to prevent freezing of pipes and meters. The volumes of inflow and outflow were recorded on totalizing flow meters designed to function over a flow range of 0.8 to 94 L per minute. Outflow was controlled by siphons.

We installed a USGS precipitation gauge with a continuous recorder to measure rain and snowmelt. We used US Weather Service (USWS) data from the Newark station (0.4 km away) and the Geneva station to ensure reliability of the precipitation measurements. Total precipitation measured with our instrument and summed over the entire study period was essentially consistent with the USWS data, although the official data records snow when it falls, whereas we measured snowmelt.

Once per week we collected influent and effluent water samples and measured pH and soluble P (undigested, filtered with a 0.45 *u*m filter). We also measured ammonium, nitrate, and total P (total P only monthly), which we will report in future papers. We used the ascorbic acid method for soluble P (Murphy and Riley, 1962).

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RESULTS

Hydrology

The inflows and outflows of water balanced for the Norlite and limestone beds, with a maximum error over the life of the experiment of 3.3%. But, based on a comparison of hydrologic inflows and outflows, one of each of the two meters in the other four beds recorded too little flow. The outflow from the soil beds and from one wollastonite bed probably registered incorrectly because air entered the meters each time the siphons tripped. The recorded inflow to the other wollastonite bed was about 9% too low for an unknown reason. Because at least one meter worked correctly in each of these four beds, and because we are confident of the precipitation and

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evaporation data, we were able to use the measurements to model real volume. The measured outflow data were adjusted upward by a constant uniquely calculated for each of the two soil beds and the one wollastonite bed. The inflow data for the other wollastonite bed was adjusted in accordance with a computer program that calculated error by date. After adjustment, the maximum error in the hydrologic balance for these four beds was about 4%.

One might argue that we couldn't be sure which meters were accurate and which were not. First, we knew the error was from the meters because we tested the wetland cells to make sure they did not leak. Second, we are certain all the meters worked correctly as long as there was no air in them, because we tested them against a control meter every week at first and as often as necessary afterwards to establish accuracy within 2%. Meters that measured incorrectly in the field did so either because of sediment clogging the gears or because of air in the meters. After the first month of the project, filters that we installed in the meters prevented sediment from entering the gears, so we eliminated that potential problem. Although we correctly designed the siphons so that air would exit through vent pipes prior to entering meters, some air did enter the meters each time the siphons tripped. We know the siphons of the two soil beds and the one wollastonite bed tripped much more often than the other siphons, and it just happens that the raw hydrologic data from these three cells indicated undermeasurement of outflow in every case. Thus, for three of the beds, we have a theory of why the error occurred and consistent circumstantial evidence to support the theory. In the other wollastonite bed, we are less sure of the reason for the error in the hydrologic balance, and the data from this bed is therefore considered less robust than the data from the other seven beds. Our hypothesis is that air entered the inflow meter when the pump at the pump station shut off. This hypothesis is supported by visual evidence towards the end of the experiment that this meter (and no others) sometimes turned backwards when the pump stopped. This cell was the last in line to receive pumped water, so it makes sense that if any inflow meter recorded imperfectly, it would be this one. In summary, we adjusted flow data for each of 4 of the 16 meters because we knew there was error in the overall hydrologic balance for the associated wetland cells, we had theories as to why the errors occurred, and we had evidence from the field to support the theories.

The error in the outflow data was proportional to flow volume, so to correct for the error we multiplied the daily flow of water out of the soil beds by 1.2. The multiplier for the wollastonite bed was 1.3. The magnitude of these multipliers was chosen for each of the three beds to force the hydrologic budget to balance within at least 4%.

The computer program that was written to pinpoint and correct error in the hydraulic budget of the other wollastonite bed incorporates daily information on precipitation and evaporation, keeps track of the day that incoming water most likely exited the system (based on theoretical retention time and a reasonable margin of error), and calculates an empirical daily retention time based on inflows and outflows of water. The program does not account for changes in storage resulting from the rise and fall of the siphons because there was no data to separate volume changes from random error. The results of the program indicate on which dates there was too much outflow (measured outflow plus estimated evaporation) relative to inflow (precipitation and measured inflow of wastewater). It also indicates the volume of the discrepancy. We used this information to force the hydrologic inputs and outputs over the life of the experiment to balance within 4%. Adjustments were conservative and totaled only 5.2% of the total inputs for this wollastonite bed.

Corrected flow data were used to calculate effectiveness of the various substrates for P treatment. These adjustments were minor relative to the total hydraulic budget of the cells and do not change the outcome of the experiment, only the magnitude of differences in performance of the four substrates.

The theoretical median retention times of both wastewater and precipitation, estimated as a function of inputs, outputs, porosity and volume of the beds, were 14.7 (soil), 13.0 (Norlite), 13.0 (wollastonite tailings), and 13.4 days (limestone). Median retention times of the wastewater, as estimated by matching daily hydrologic inflow and outflow in a computer model, were 8.0, 7.5, 7.0, and 7.8 days for the soil, Norlite, wollastonite, and limestone cells.

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Chemistry

The influent pH averaged 7.6, while the effluent pH averaged 7.2 for the limestone beds, 7.3 for the soil beds, and 7.7 from the wollastonite and Norlite beds. During the first 7 months of the experiment the pH of the influent and the effluent were higher: 7.9 for the influent, 7.6 for the soil and limestone cells, and 8.0 and 8.2 for the wollastonite and Norlite beds, respectively.

Average soluble P in the influent was 14.2 mg/L. This influent concentration was much higher than the design concentration of 3-10 mg/L because (1) the farm expanded its operation significantly during the life of the experiment; (2) high-intensity rains and large precipitation events associated with El Nino increased the P load in stormwater; and (3) a greater percentage of the runoff than anticipated was bunk silo leachate.

The effluent from the soil, Norlite, wollastonite, and limestone beds contained 6.1, 7.2, 9.7, and 11.3 mg/L of soluble P, respectively. These results are each averages of the replicates, calculated with a one-week retention time.

Efficacy of Substrates

Over 1.5 years, incorporating data from all weekly samples, the soil beds removed the most P (52.7% ± 1.1%), followed by the Norlite beds (33.7% ± 3.6%). Soluble P retention in the wollastonite and the limestone cells averaged only 12.8% (± 9.5%) and 4.3% (± 4.3%), respectively. One-way ANOVA indicates a significant difference in treatment across substrates. Percent reduction in load varies significantly across each pair of substrate types except when wollastonite tailings are compared with the limestone treatment. Pairwise comparisons were conducted with an individual error rate of 0.05 (Fisher's pairwise comparisons) and a family error rate of 0.15 (justifiably high to balance probability of Type 1 and Type 2 errors).

The rank in the efficacy of the substrates does not change if one considers removal as percent reduction in concentration, assuming a one-week retention time and including all the weekly measurements of soluble P concentration as independent measurements; however, in this case the efficacy of Norlite and soil do not differ significantly at the family error rate of 0.05 (Tukey's pairwise comparisons), whereas

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all the other pairwise comparisons are significant. Mean reductions in concentrations over 1.5 years for each of the substrates were 53.6% ± 31.0% for soil, 45.5% ± 23.6% for Norlite, 27.5% ± 30.8% for wollastonite tailings, and 14.5% ± 30.4% for limestone. The high standard deviation figures reflect the influence of precipitation and abrupt changes in influent concentrations.

A third method of analyzing the data constrains each data point entering the analysis so that no single data point is unduly influenced by low flow or low concentration entering or exiting the bed. Again, the rank of substrates in terms of removing soluble P load did not change. Means and standard deviations are 42.0% ± 39.7% for soil, 28.1% ± 31.8% for Norlite, 2.9% ± 43.1% for wollastonite tailings, and –5.1% ± 40.36% for limestone (n ranges from 48 to 66, depending on the bed). All pairwise comparisons are significant at the family error rate of 0.05 (Tukey's pairwise comparisons) except for wollastonite tailings and limestone.

Adding a variable representing either the dormant or growing season improves the fit of a general linear model primarily designed to predict reduction in load from substrate type; this result, however, is misleading. If one removes soil and considers the other substrates, the seasonal factor is no longer significant at the 0.05 level. The apparent effect of seasonality on treatment in the soil bed reflects increased treatment as the soil pores clogged and overland flow developed. There is no convincing seasonal pattern within the 1.5 years of the study.

Table 1 indicates removal of soluble P per mass and volume of substrate. Note that by weight (but not volume) Norlite removes more P per day than soil because it is less dense. The density of soil is oven-dried bulk density (median of 82 samples) and does not include particles over 1 mm in size. All other densities are averages of three to five air-dried subsamples of the porous media.

Occasionally, negative treatment occurred: more P left the wetland cells than entered the cells during the median one-week retention time. Norlite and soil had fewer periods of negative treatment than wollastonite and limestone. The data for the first 1.5 years of operation are inconclusive in comparing Norlite and soil in this respect: one of the Norlite beds performed more consistently than the soil beds, but

TABLE 1
Average Daily Removal of Soluble P from Wastewater

Substrate	mg P/g substrate	mg P/m^3 substrate	Substrate density (g/cm^3)
Wollastonite Tailings	6.7E-05	1.2E-1	1.9
Norlite	2.3E-04	1.8E-1	0.8
Soil	1.8E-04	2.4E-1	1.3
Limestone	1.3E-05	2.1E-2	1.7

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the other Norlite bed did not. Apparent negative treatment occurred primarily when the influent P concentration dropped significantly while the corresponding outflow P concentration remained relatively steady.

If Norlite removed as much P as LECA, under the conditions of this experiment, the Norlite in the wetland cells at ELVI farms would need to be replaced every 6 to 7 years. Similar calculations for soil are irrelevant because of overland flow across the surface of the wetland cells. Likewise, for wollastonite tailings, the calculation is not useful for designers because of preferential flow. Limestone didn't remove P adequately even in the first year.

DISCUSSION

We were surprised by the performance of the soil relative to the other media because we expected biofilm on the soils to gradually reduce hydraulic conductivity and clog the beds, thus reducing treatment of P. Indeed, overland flow occurred consistently at the head of the soil beds after the first month of the experiment, and horizontal hydraulic conductivity throughout the length of the beds continued to decline. After the first year water was flowing overland for the entire length of one of the soil beds. But, performance improved rather than deteriorated.

One possibility for this improvement is that intermittent overland flow, followed by slow seepage into the soil profile, increased rather than decreased contact between

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the wastewater and soil particles, allowing for greater adsorption of phosphorus onto iron and aluminum oxides and hydroxides in the soil. Another possibility is that greater exposure to air raised the redox potential and oxygen content of the wastewater flowing overland relative to the wastewater that previously flowed only underground. Soluble ferrous iron, in the presence of oxygen, oxidizes to ferric iron, which precipitates. This oxidation reaction can pull phosphorus out of the wastestream either as ferric phosphate or as phosphorus sorbed to ferric hydroxide. Thus, greater aeration of the wastewater may explain why soil performed better over time and, also, why soil outperformed the other substrates. Unlike soil, the other substrates all flawlessly supported subsurface flow.

One piece of evidence supports the hypothesis that aeration aided phosphorus removal in the soil beds. In December, 1997, a precipitate became visible on the filters in the influent pumping station. The precipitate was significantly denser on the part of the filter above the surface of the water compared to below, where the oxygen concentration was only about 1.0 mg/L (1.2 mg/L was measured in the field on Oct., 98, while 1.6 mg/L was measured in the lab on Nov., 1997). Inductively coupled plasma (ICP) analysis of this precipitate yielded high concentrations of P, S, Ca, Fe, and Mg in proportions suggesting that the anions associated with the precipitated cations may have included sulfate and phosphate.

The pH of the wastewater in the soil beds in the winter ranged from 6.3 to 7.0, which would suggest precipitation of calcium phosphates. ICP analysis of influent and effluent water samples from 17 Jan., 1998, indicates significant removal of calcium from the water column in both the wollastonite and the soil beds.

CONCLUSION

The soil beds removed the most soluble P for two reasons: (1) greater adsorptive surface area (finer texture with an abundance of iron and aluminum oxides and hydroxides), and (2) greater precipitation of Fe, Mg, and Ca and associated P. Norlite was the second most effective substrate, followed by wollastonite tailings. Limestone performed poorly, as expected.

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Based on this research, despite our findings that soil removes more soluble P than Norlite in the field, we recommend Norlite for use in agricultural systems. More land would be required if Norlite were used, and there would be an added cost of the material and its shipment. But, for four reasons, we are more confident of extrapolating the results of this study to predict consistent, long-term performance of Norlite.

First, declining hydraulic conductivity in the soil beds will eventually lead to a lower retention time, which would decrease treatment of phosphorus during precipitation events (and hinder treatment of other elements, such as C and N). Second, during subfreezing temperatures, subsurface treatment of P is more predictable. Third, we carefully pretreated the wastestream, but the farmer might be less fastidious about keeping suspended matter out of the media. If so, the Norlite, coarser in texture, would outlast soil. Finally, because the wastewater often contains algal blooms, when the temperature is above freezing, we recommend that the water be applied to the beds vertically via pipes laid over the surface of the beds. This distribution system, originally proposed by Seidel (Laber et al., 1997 and Seidel, 1978) and well accepted in Europe by 1990, would decrease maintenance required in operating the system and likely would improve N removal without hindering P removal. Vertical flow would work well in the Norlite beds, assuming that the farmer installed an easily-maintained prefilter with a large surface area. In the soil cells, however, the hydraulic conductivity of the soil surface is too low for a vertical application of the wastewater.

While recommending Norlite, we believe that wollastonite tailings warrant more research. We originally added a limestone prefilter to the wollastonite beds to prevent clogging: laboratory studies showed declines in hydraulic conductivity over time, and we wanted to minimize this problem. In the field, however, while there was evidence of preferential flow, water continued to flow through rather than over the wollastonite tailings. Based on this result, the limestone prefilter was oversized. Without it, we could have doubled the volume of wollastonite tailings and potentially increased removal of soluble P to 23%. While this treatment seems low, wollastonite is an inexpensive resource, and in certain locales where the farmer can allocate additional land to compensate for lower treatment per m^2, wollastonite might be more economical than Norlite. Wollastonite tailings also warrant more research as a polishing media. Pilot studies at a residential wastewater treatment facility indicate that wollastonite tailings may be able to reduce concentrations of P in wastewater from 6 mg/L to 0.8 mg/L (Geohring et al., 1999).

In summary, we recommend coarse aggregate Norlite for use as a substrate in wetlands constructed in agricultural ecosystems, where influent nutrient concentrations are high relative to optimal effluent concentrations, and where the concentration of suspended matter is high. If wollastonite tailings are used to reduce costs, the size of the constructed wetlands must be larger than comparable Norlite cells.

This research may also serve as documentation that subsurface flow wetlands are appropriate components of stormwater management systems on farms in cold climates. The US Department of Agriculture (USDA) typically recommends surface flow as opposed to subsurface flow wetlands.

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