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Treatment wetlands for removing phosphorus from agricultural drainage waters

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Abstract

As a treatment technology, wetlands face several challenges in providing effective phosphorus (P) removal from agricultural drainage waters (ADW). Wetland area requirements for P removal are typically higher than other ADW constituents, such as nitrate-nitrogen and oxygen demanding substances. Moreover, P cycling within wetlands is complex, with exchanges between dissolved and particulate P forms, and labile and refractory P forms, occurring in the treatment wetland on a spatial and temporal basis. The gradual accumulation of P-enriched sediments with time can affect biogeochemical P removal pathways and limit long-term P removal effectiveness of treatment wetlands. Despite these challenges, wetlands are capable of reducing P in ADWs to extremely low levels, in the range of 15 - 20 µg l^{-1}. However, because such low outflow concentrations are only attained at low mass P loading rates (< 1 - 2 g P m^{-2} yr^{-1}), wetland area requirements per unit mass of P removal can be extremely high. Unit area requirements appear to decline under higher mass P loading conditions, but this is achieved at the expense of higher outflow P concentrations. Several techniques have been evaluated for improving wetland P removal effectiveness and sustainability, including routine vegetation harvest, removal of accumulated sediments, and chemical immobilization of P in sediments. Such practices have been shown to work in pilot-scale systems, but their technical and economic feasibility for full-scale use remains to be demonstrated.

Keywords: phosphorus cycling, sediment accumulation, phosphorus biogeochemistry.

Introduction

In the past two decades, constructed wetlands have become increasingly popular as a technology for removing nutrients from point and non-point source flows (Reddy and Smith, 1987; Kadlec and Knight, 1996). A suite of compounds, including oxygen demanding substances and nitrogen, are removed effectively and sustainably by treatment wetlands (Kadlec and Knight, 1996) due to the complete or partial conversion of these constituents to gaseous forms. Phosphorus (P) removal in wetlands has proven to be particularly challenging, because soils are the only long-term sink for this element (DeBusk and DeBusk, 2000; DeBusk and Dierberg, 1999). In order to improve long-term P removal performance by constructed wetlands, a number of design approaches and management practices have been investigated, with varying levels of success.

In this paper, we discuss P cycling processes in agricultural watersheds and treatment wetlands, and review findings of some previous studies on the use of constructed wetlands for treating agricultural drainage waters (ADWs). Finally, we discuss some of the design and management aspects of wetlands that may improve their performance and sustainability of P removal.

Phosphorus forms and wetland removal processes

Particulate phosphorus

Many agricultural runoff and wastewater streams contain high concentrations of suspended solids. Soil erosion is a prominent source of such particulate matter, with export of particulate P most common during periods of heavy rainfall and/or irrigation in agricultural areas. There are a number of Best Management Practices (BMPs) that can be implemented for minimising soil erosion, and hence, P losses from agricultural fields. Despite on-farm control efforts, some particulate P is inevitably present in ADWs, and this fraction often comprises the dominant P form.

Particles exported in drainage waters contain P of varying concentrations, with the P content related to the origin of the particles. Sharpley (1999) noted that manures for pigs, sheep and cattle range from 6700 - 17,600 mg P kg^{-1}, which is markedly higher than the P content of most non-impacted soils. Hence, particulate-laden runoff from animal husbandry operations can exhibit very high TP concentrations. Autochthonous particulate P generation can also occur within water conveyance structures in agricultural regions. For example, particulate detritus from floating macrophytes that proliferated in south Florida agricultural drainage canals contained an average of 4227 mg P kg^{-1} (Stuck, 1996)

The tendency for particulate matter to be mobilised from farm fields and transported into surface waters is in part related to the particle size, charge and density, coupled with the velocity of the runoff stream. When particles mobilised by runoff encounter the relatively quiescent water column of a treatment wetland, much of the particulate matter can settle. The wetland vegetation is thought to contribute to particle removal through both sedimentation and filtration processes.

Particles removed in this fashion accrue in wetlands as sediments. A portion of the P associated with these sediments can be buried and permanently isolated from the water column. Depending on the nature of the particles, some P will likely be liberated from the settled particles as a result of desorption and/or decomposition processes. Sediment-water interface micro-environmental factors (e.g., electron acceptor availability, oxidation-reduction potential, and pH) and the chemical composition of the water and soil (e.g., sulphur, iron, calcium and aluminium contents) influence how effectively P in settled particles is retained in wetland sediments (Richardson, 1999).

Dissolved phosphorus

Particulate matter comprises only one component of the P in agricultural runoff and wastewaters. Dissolved chemical attributes of the soil are imparted to ADWs as they pass over or through the soil profile in farm fields and catchments. The complement of dissolved constituents in ADWs, including P containing compounds, is site-specific, a product of the catchment soil chemistry, topography, climate, and land management practices. For example, the P contained in inorganic fertilisers and even in manures can be exported in dissolved, bioavailable forms, particularly if application rates exceed crop requirements (Sharpley, 1999).

Dissolved P forms that enter a treatment wetland range from being quite labile to extremely recalcitrant. Soluble reactive P (SRP), operationally defined as the P fraction that passes through a 0.45 μm filter and is analytically detected by the molybdate blue method, is readily available for assimilation by bacteria, phytoplankton and macrophytes. Soluble reactive P can originate from fertilisers, or from decomposition of organic materials such as vegetation and manures. By contrast, dissolved organic compounds, which range from simple sugars to high molecular weight compounds, must first be broken down into more labile forms before their associated P can be assimilated by aquatic biota (Newman and Robinson, 1999). Some P is readily released from dissolved organic compounds following exposure to UV radiation or to enzymes (Wetzel *et al.*, 1995). In wetlands that successfully treat P to extremely low concentrations, recalcitrant DOP and particulate P compounds often comprise the bulk of the outflow P (Dierberg *et al.*, 2002a).

In wetlands, the labile dissolved P (the SRP) form is removed via biological uptake (by bacteria, phytoplankton, periphyton, and macrophytes), adsorption to chemical compounds (iron, aluminium and calcium) in soils and sediments, and chemical reactions in water columns (precipitation and/or co-precipitation). Phosphorus uptake rates and mass storages vary among ecological compartments, but regardless of the mechanism for SRP removal from the water column, the ultimate sink for P in wetlands is sediment.

The concentrations of constituents such as iron and aluminium in the water column may influence wetland P sequestration capabilities. In watersheds with little iron and aluminium, such as in the Florida Everglades, calcium can play a dominant role in P cycling. During photosynthesis, aquatic macrophytes can elevate surface water pH, thereby stimulating $CaCO_3$ precipitation. Precipitated calcium carbonate can provide sorption sites for dissolved phosphate ions (Dierberg *et al.*, 2002b). Thus, the influence of catchment water hardness on P retention in downstream treatment wetlands may be substantial.

Because wetlands generally are effective at removing particulate matter, it is possible that wetlands receiving P primarily in a particulate form exhibit higher mass P removal rates, at least on a short-term basis, than those dominated by dissolved P inputs. A complicating factor to such an assessment is that the cycling of P within wetlands is quite complex. Phosphorus can cycle among particulate, dissolved organic and dissolved inorganic compartments, on both a spatial and temporal basis, as water passes through a treatment wetland. For example, Dierberg *et al.* (in press) characterised the suspended algae entering and leaving a large 880 ha treatment wetland in South Florida and observed a change in algal density and speciation with passage through the wetland. Rather than simply "filtering" out the inflow algae, as evidenced by chlorophyll *a* reductions, the wetland was affecting species composition, which suggests cycling of P forms occurred between particulate and dissolved fractions.

Wetland phosphorus removal: design aspects

Several key parameters must be addressed in designing a treatment wetland for P removal. The most important of these are the expected flow rate (quantity and timing) of the ADW, the mean and range in ADW total P concentrations and the desired wetland outflow P concentration. Additional information that can facilitate treatment wetland design includes: climatic conditions at the site, since temperature can influence rates of microbial and macrophyte activity; the concentrations of P species (particulate vs. dissolved fractions) in the inflow ADW; and, the concentrations of other ADW constituents (e.g., nitrogen, oxygen demanding substances, total suspended solids, alkalinity, calcium, iron and aluminium contents).

Numerous treatment wetland design models are available, including steady-state and dynamic empirical models, many of which incorporate terms to address expected hydraulic characteristics of the treatment wetland (Kadlec and Knight, 1996). Mechanistic, process models also have been developed for treatment wetlands, but these invariably are too complex to have useful predictive capability. The simpler steady state models appear fairly effective at predicting either land requirements for a designated application, or the likely outflow P concentrations given a wetland parcel of known size. For predicting land area requirements, input parameters for such models typically include inflow P concentrations, outflow P concentrations, and a removal rate constant (K). Removal rate constant values were developed using historical performance data from other treatment wetland systems.

Another "rule of thumb" design approach is to evaluate previously developed relationships among mass P loading, outflow P concentrations, and mass P removal rates for treatment wetlands. Where historical data is available for wetlands that have operated in a similar climate and in a comparable inflow concentration range to the proposed treatment wetland, such relationships can be particularly relevant and useful for design. We compiled data from several sources to provide a range of potential scenarios encountered for wetlands used for removing P from ADWs around the world (Table 1). For each system, we identified mass P removal rates, inflow and outflow P concentrations, and hydraulic loading rates (HLR). To compare P removal among systems, we present performance parameters from these studies on a mean annual basis. An exception is the Braskerud (2002) study, where data was averaged across the entire period of operation (3-7 years).

Mass P loads for these ADW treatment wetlands vary widely, from about 1 g P m^{-2} yr^{-1} to over 100 g P m^{-2} yr^{-1} (Figure 1). Hydraulic loading rates also vary by about two orders of magnitude. These data suggest that mass P load is a better determinant of outflow P concentrations than HLR (Figure 1). Additionally, these data follow a commonly reported trend where wetland mass P removal rates increases with increasing P loads. While this is to be expected, since flow rate is a parameter embedded in both x- and y-axis terms, this relationship is useful in demonstrating that treatment wetlands operated at high mass P loads are capable of achieving quite high mass P removal rates (Figure 2).

With respect to design, the important factor to note is that interrelationships between mass P loading and outflow P concentrations dictate the amount of area required for the wetland. Wetland area requirements for P removal can be high, and they indeed are when compared to removal rates for other constituents. For example, using data reported for 15 treatment wetlands (see Kadlec, 2003), we calculate that the area required for the annual removal of 1 kg of P ranged from 1.4 to 1,378 m^2. The lowest area requirement for removing 1 kg P yr^{-1} was reported for systems receiving an extremely high mass P loading (1113 g P m^{-2} yr^{-1}). While mass P removal rates were impressively high, outflows from these systems contained high concentrations of P. By contrast, data from 18 systems described by Kadlec (2003) demonstrate

Table 1. Phosphorus loading and removal characteristics of wetlands used to treat agricultural runoff and wastewaters.

Location (source)	Treatment system	TP_{IN}* (mg P l^{-1})	TP_{OUT}* (mg P l^{-1})	TP load (g P m^{-2} yr^{-1})	Mass P removal		HLR (cm day^{-1})
					g P m^{-2} yr^{-1}	%	
• New Zealand (Tanner and Sukias, 2003)	Surface and subsurface wetlandsreceiving waste stabilization pond effluent	16.7 - 42.4	9.6 - 35.6	173 - 2278	-4 - 296	-2 - 45	2.5 - 16.0
• Maryland, USA (Jordan *et al.*, 2003)	Restored natural wetland receiving corn-soybean runoff	0.35 - 7.0‡	0.38 - 2.9‡	2.5 - 3.0	-0.28 - 1.8	-11 - 59	1.2 - 2.0
• Norway (Braskerud, 2002)	In-stream wetlands; fields in cereals with manure applied	0.17 - 0.43	0.10 - 0.27	91 - 191	18 - 71	21 - 44	66 - 181
• Finland (Koskiaho *et al.*, 2003)	Boreal wetlands receiving farm runoff	0.073 - 0.57‡	0.063 - 0.22‡	0.93 - 11.1	-0.5 - 2.4	-6 - 62	1.9 - 14.3
• Florida, USA (SFWMD, 2004)	Wetlands receiving stormwater from irrigation/drainage	0.067 - 0.277	0.017 - 0.136	0.90 - 4.2	0.6 - 2.7	39 - 69	3.7 - 7.4

* Range in reported mean TP concentrations

‡ Calculated from reported mass removals, hydraulic loading rate and % removal

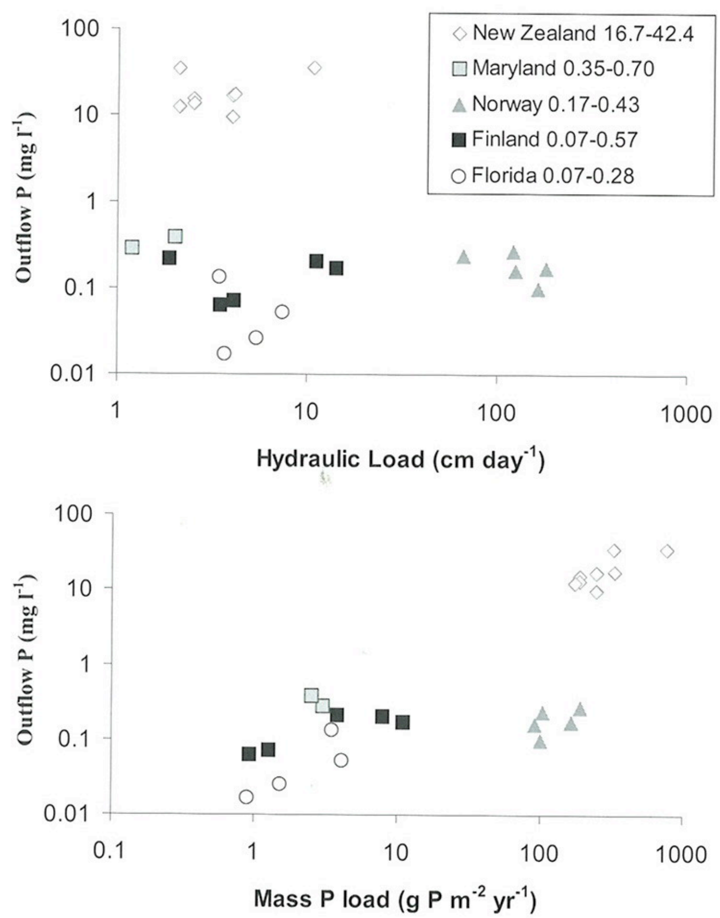

Figure 1. Outflow phosphorus (P) concentrations from treatment wetlands at five locations around the world, expressed as a function of (a) hydraulic loading rate and (b) mass P loading rate. The range of values given in the legend denotes annual mean ADW inflow TP concentrations (mg l^{-1}) for each respective wetland. Data sources for each wetland are provided in Table 1.

that the wetland area required for removing 1 kg of BOD_5 ranges from 0.5 to 70 m^2. Similarly, data from Kadlec and Knight (1996) demonstrate that an average of 76 m^2 of constructed wetland area is needed to remove 1 kg nitrate-N per year.

Case studies

We selected five ADW treatment wetland case studies from the literature, to illustrate performance under a range of inflow P concentration ranges and mass P loading rates.

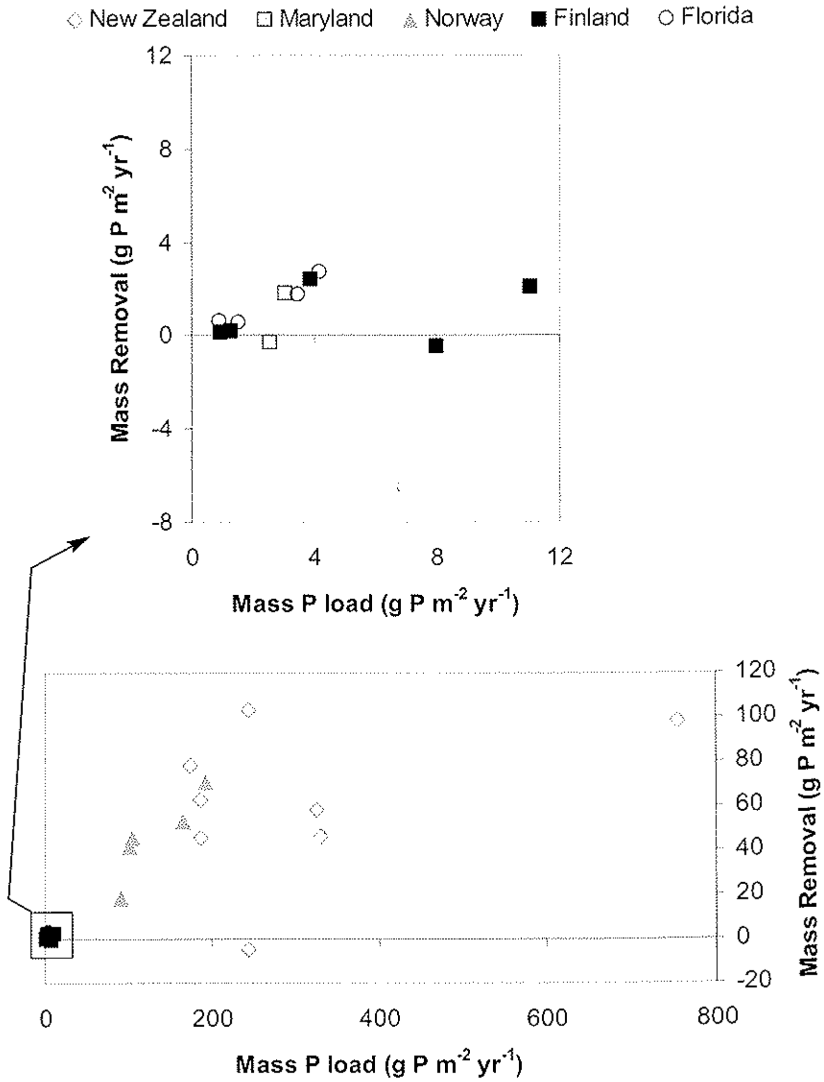

Figure 2. Mass P removal rate as a function of mass P loading for treatment wetlands at five locations. Panel on the top is presented at a finer scale to show differences among wetland systems operated at lower P mass loading rates. Data sources are presented in Table 1.

Florida, USA

Probably the most stringent application of wetlands for ADW P removal is the complex of Stormwater Treatment Areas (STAs) in South Florida. These are a group of six large treatment wetlands, totalling approximately 16,000 ha in area, that are being used to treat runoff from a 300,000 ha agricultural area prior discharge to the Everglades (SFWMD, 2004). The TP levels in runoff flowing into the wetlands typically range from 50 - 150 µg l^{-1}, and the target TP concentration is 10 μg l^{-1}. To date, several of the STAs have achieved outflow total P concentrations of 15-20 μg l^{-1} (SFWMD, 2004). At such low inflow concentration ranges, the resulting P loads are low (ca. 1- 3 g P m^{-2} yr^{-1}) as are the mass P removal rates (e.g., 0.8 - 1.3 g P m^{-2} yr^{-1}). Considerable wetland area therefore is needed, in this case ~1,000 m^2, to remove 1 kg of P annually.

New Zealand

At the other extreme, wetlands have been used to remove P from concentrated agricultural waste streams that contain much higher P concentrations. Tanner and Sukias (2003) describe wetland treatment of high P concentration (17 - 42 mg P l^{-1}) wastewaters from swine and dairy operations. Each wetland system was preceded by an anaerobic /facultative pond. Performance for three surface flow wetlands, two subsurface flow wetlands, and four surface-subsurface flow treatment wetlands is described by Tanner and Sukias (2003).

At moderately high HLRs of 2.5-16 cm d^{-1}, mass P removals exceeding 1000 g P m^{-2} yr^{-1} were achieved (Table 1). Such extraordinary load reductions were possible only under high P loading rates, which in this study resulted from both high P inflow concentrations and high hydraulic loading rates. While the mass P removal rates were high, it also should be noted that outflow P concentrations were an order of magnitude higher than wetlands at the other four locations (Table 1). This was a two-year study, so the long-term sustainability of wetlands receiving such high P loads is unknown.

Finland

Relationships between mass P loading rates and outflow P concentrations (Figure 1) suggest that increases in loading can lead to higher outflow P levels, and reductions in loading result in lower outflow TP concentrations. However, a potential problem with intermittent high P loads is that they may impair a wetlands ability to return to lower outflow P concentrations. In Finland, ADW was treated by three wetlands: the 0.6 ha Hovi demonstration wetland, the 0.48 ha Alastaro wetland, and a larger (60 ha), "semi-natural" Flyttrask wetland (Koskiaho *et al.*, 2003). The investigators monitored Hovi for one year, and Alastaro and Flyttrask for two years each. Agricultural fields covered 100%, 90% and 35% of the 12 ha, 90 ha and 2000 ha watersheds surronding the Hovi, Alastaro, and Flyttrask wetlands, respectively. Snowmelt and heavy rains during spring caused extremely high flow rates and a pulse of dissolved nutrients in wetland inflows. Koskiaho *et al.* (2003) observed P export from the Alastaro wetland when high nutrient loads (11.1 g P m^{-2} yr^{-1}) in the first year were followed in a second year by 28% lower P loading (8.0 g P m^{-2} yr^{-1}). The larger Flyttrask wetland received lower mass loading (1.3 g P m^{-2} yr^{-1}) and showed no P release the following year, despite an equivalent percentage reduction in loading (to 0.93 g P m^{-2} yr^{-1}).

Norway

Four small wetlands (0.03-0.09 ha) were created in Norway by widening first-order streams located in agricultural watersheds that ranged from 22-148 ha in size (Braskerud, 2002). Flows were measured at v-notch weirs installed in the outflow dams, behind which the wetland surface water was retained. Three of four catchments contained 14-27% arable land (oats, barley) with the remainder forested, while one catchment contained 99% pasture land used for dairy cattle grazing. Streams flowed year-round, but summer HLR to the wetlands was ~50% of flows during the remainder of the year. Performance data was summarized for all years of operation, which ranged from 3-7 years among the four systems.

Because of the small wetland footprints relative to the watershed, HLRs were quite high (> 100 m yr^{-1}) (Table 1) (Braskerud, 2002). The range of inflow TP concentrations were similar to many ADWs (0.17 - 0.43 mg P l^{-1}), and while outflow concentrations were not much lower, the mass P removal rate was quite high (18-71 g P m^{-2} yr^{-1}) due to the extremely high HLR. Short retention time, coupled with low temperatures and biomass P demand in spring probably contributed to the low observed removal efficiencies (21 - 44 % P mass removed), relative to the other wetland systems condidered (Table 1).

Maryland, USA

Jordan *et al.* (2003) presented two years of data from a restored natural wetland covering a contiguous 9% of its 14 ha watershed. Most (82%) of the watershed was cultivated (corn/soybean rotation), while the remainder was forested. Water entered the wetland from drainage leads, and exited the wetland through a standpipe outlet. Outflow P levels exceeded inflow P concentrations during the second year, presumably due to a two-fold higher HLR and lower inflow TP concentrations than the first year. These investigators suggest that a decrease in the inflow TP and PO_4-P concentrations in the second year may have caused release of P loosely sorbed to soil mineral components.

Enhancing long-term phosphorus removal performance

The case studies described above demonstrate several key trends related to P removal in treatment wetlands. First, wetlands that receive low P loadings, such as the 1- 2 g P m^{-2} yr^{-1} range of the South Florida STAs, are capable of achieving extremely low outflow P concentrations. Second, under variable P loading conditions, wetland outflow P concentrations do not necessarily respond (i.e., decline) immediately in response to load reductions. This phenomenon may be caused by some removal mechanisms (luxury uptake of P by biota and saturation of chemical adsorption sites during periods of high loadings) that do operate in proportion to mass loading rate. Finally, data from the New Zealand systems demonstrate that high mass P removal rates are attainable by treatment wetlands under high mass loading conditions. However, the sustainability of wetland P removal in these systems, particularly under prolonged, high P loads, is somewhat unknown.

Wetlands are thought to provide the most effective P removal performance during their first years of initial deployment. This is likely due to rapid vegetation growth and associated P assimilation upon initial flooding, coupled with ready availability of soil P sorption sites. However, as soil P sorption sites become saturated and vegetation reaches maximum standing crop levels, accrual of new sediment becomes the remaining pathway for long term P retention. Depending on the mass P loading rate and biogeochemical factors (e.g., renewal of sorption sites through inputs of calcium, iron and aluminium), declines in P removal performance may occur with time. Treatment wetlands that are highly loaded are the ones most likely to suffer from excessive sedimentation, which can not only impair P removal effectiveness, but also reduce overall water storage volume, particularly in the inflow regions of the system (Martinez and Wise, 2003).

Two techniques have been evaluated for enhancing sustainability of treatment wetland P removal. The first is periodic harvest of vegetation, and the second entails management of sediments. Wetland vegetation management for P removal has been assessed at various scales for at least three decades. The earliest work involved the use of the productive floating macrophyte, *Eichhornia crassipes* (water hyacinth) (Wolverton *et al.*, 1976). Extremely high mass P removal rates have been achieved through harvest of water hyacinths and other productive aquatic macrophytes (exceeding 100 g P m^{-2} yr^{-1}) (Reddy and DeBusk, 1985). Similarly, work has been conducted for approximately a decade on using attached algae cultures ("algal turf scrubbers" or "periphyton filters") for P removal. Removal rates up to 0.73 g P m^{-2} d^{-1} have been reported for such systems (Craggs *et al.*, 1996). While both attached algae and floating macrophytes such as *Eichhornia* and other species (e.g., *Lemna*) can provide effective P removal, this practice has never proven economically viable due to the high costs of plant harvesting, coupled with the low market value of the harvested biomass.

With respect to sediment management, it has long been recognised that wetlands receiving a high sediment load should be divided into at least two compartments, with a levee separating inflow from outflow regions. This is done to encourage the bulk of the allochthonous solids deposition to occur in the inflow region (Kadlec and Knight, 1996). There exists little information, however, on the effects of "front-end" sediment accumulation on wetland P removal performance, and whether or not pro-active management of such sediments can enhance P removal.

In 2003, our research team performed an *in situ* mesocosm study to evaluate the effects of sediment drydown and removal on overlying water column P concentrations of a Florida treatment wetland. This wetland was in operation for 16 years. The P content of the original mineral soil in the wetland was 48 ± 19 mg kg^{-1}, whereas the P content of accrued organic sediments near the inflow region was substantially higher, at 431 ± 170 mg kg^{-1} (Miner, 2001). We isolated portions of the water column and soil within 1.2 m diameter cylinders so that we could evaluate the effects of sediment drydown and organic sediment removal on P concentrations in the overlying water column. Measurements performed during 11 two-week batch incubations showed that sediment drydown alone provided a slight decrease in water column P levels, from 130 to 116 μg l^{-1}. By contrast, complete removal of the organic sediment layer sharply reduced water column TP levels, down to 62 μg l^{-1}. These data demonstrate that accrued wetland sediments indeed provide an internal contribution of P to the water column, and that their removal may contribute to improved performance. However, a problem with organic sediment removal is that it is expensive, and the technical effectiveness of this approach for full-scale wetlands has not yet been demonstrated. It is worth noting that removal of organic sediments from shallow lakes has had limited effectiveness in reducing water column TP concentrations (Moss *et al.*, 1996; Ruley and Rusch, 2002). As an alternative approach to sediment removal in treatment wetlands, it may be possible to use chemical amendments to immobilise sediment P. Ann *et al.* (2000) reported that soils amended with calcium, iron and aluminium prior to wetland flooding reduced export of sediment P. Such an approach may prove less costly than bulk removal of accumulated sediments.

Conclusions

Phosphorus cycling within treatment wetlands is complex, with exchanges between dissolved and particulate P forms, and labile and refractory P forms, occurring dynamically on a spatial and temporal basis. Wetlands are capable of reducing P in ADWs to extremely low levels, but area requirements per unit mass of P removal can be extremely high. Unit area requirements appear to decline under higher mass P loading conditions, but this is achieved at the expense of higher outflow P concentrations. The gradual accumulation of P-enriched sediments with time can affect internal P cycling and limit long-term P removal effectiveness of treatment wetlands. Several techniques have been evaluated for improving wetland P removal effectiveness and sustainability, including routine vegetation harvest, removal of accumulated sediments, and chemical immobilisation of P in sediments. Such practices have been shown to work in pilot-scale systems, but their technical and economic feasibility for full-scale use remains to be demonstrated.

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