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Phosphorus removal from storm water by biofilms (periphyton) in constructed wetland systems, Western Australia

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Introduction

The ability of natural wetlands to provide effective nutrient sinks for organic and inorganic pollutants and to absorb new nutrient loadings has been well documented (KADLEC 1997, LANTZKE et al. 1999). Constructed wetland systems (CWSs) operate by optimising the nutrient removal characteristics of natural wetlands, thereby aiming to achieve higher removal rates than in natural wetlands. While the nutrient removal potential of CWSs is well documented, the lack of knowledge on filterable reactive phosphorus (FRP) removal mechanisms has hampered their wider use (LANTZKE et al. 1999). Understanding of the internal wetland mechanisms has typically relied on CWS conceptual models of phosphorus removal.

Conceptual models of phosphorus removal for stormwater CWSs have been developed by KADLEC (1997), MOUSTAFA (1997), DLWC (1998) and LANTZKE et al. (1999), with a similar number of models developed for wastewater CWSs (see BUTCHBERGER & SHAW 1995). By estimating phosphorus removal by soils, vegetation and microbial communities (biofilms) over time, in relation to cumulative phosphorus removal, these models have been developed as a baseline tool for CWS design. The DLWC (1998) model suggests that in the long-term, the greatest proportion of phosphorus is removed by biofilm development, peat accretion and filtration. The present study aimed to quantify phosphorus removal of the biofilm component, by assessing the FRP removal rates of biofilms obtained from an established stormwater CWS.

Methods

Study site

The Hammond Road Experimental Wetlands system, located 22 km south of Perth, began operation in March 1998 and consists of three individual wetland ponds (15 × 5 × 1.5 m^3 (length × width × maximum depth)) that each receive influent storm water (see LUND et al. 2000). Biofilms were collected on vertically hung glass panes (200 × 100 mm^2 (length × width)) resting on the sediment. The panes were hung vertically to minimise any sedimentation that could smother the biofilm matrix (APHA 1995).

Biofilm biomass within the system was estimated using randomly located panes in open water and vegetated habitats for a 2-week period, as per APHA (1995), sampled monthly between October and January 1999–2000. Biofilms used for the FRP uptake experiments were collected from randomly located panes in the open water habitats left for 6 weeks in order to maximise biomass. During transit to the laboratory, the samples were submerged in dark, sealed containers containing water from the system.

Laboratory procedure

Filterable reactive phosphorus uptake was determined from a batch-culture experiment in glass chromatography tanks (cells), where FRP uptake was calculated as the loss of FRP from the surrounding water, standardised to the water volume and the biofilm biomass. Five FRP concentrations (<50, 50, 100, 200 and 400 µg L^{-1}), each with five replicate cells, were used to determine phosphorus uptake. The selected concentrations aimed to encompass the variability of FRP concentrations found in natural systems on the Swan Coastal Plain by DAVIS et al. (1993). A single 10-mL water sample was extracted from each replicate cell at 0, 5, 10, 20, 35, 55, 85 and 120 min to determine FRP loss from the water column. The first sample (0 min) was taken 3 min after the panes were inserted, in order to avoid recording any initially high uptake as a result of concentration change.

The FRP concentration of each sample was determined by the ascorbic acid method as per APHA (1995), with the extracted samples filtered through 0.45-µm GFC filter paper to remove particulate matter. Four-cm path-length cuvettes were used to reduce analytical error to within 3 µg L^{-1}. The criterion for assessing a significant result was therefore identified as uptake >3 µg L^{-1}. The FRP uptake rate for each concentration was calculated as the mean

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slope of regression for each cell. The uptake rate for each concentration was standardised to the mean biofilm organic biomass at each concentration, with the biofilm biomass in each cell determined as per APHA (1995).

Each tank contained four panes separated into pairs by plastic dividers (Fig. 1). A water pump was installed in each tank to reduce boundary layer formation by circulating the FRP solution evenly around the biofilms. Dye tests confirmed that the cells were fully circulated within 5 s (HAWKINS 2000). Each tank was filled to a total volume of 2 L, containing the appropriate volumes of FRP and Bold's Basal Medium (BBM), and then topped with wetland water to reach the desired volume. The wetland water was obtained from Loch McNess (50 km north of Perth) because of consistently low FRP concentrations at ~2 µg L^{-1} (SOMMER & HORWITZ 1999). The FRP stock solution was made using a combination of dipotassium hydrogen–orthophosphate (K_2HPO_4) and potassium dihydrogen–orthophosphate (KH_2PO_4) as per BISCCHOFF & BOLD (1963, cited in BOLD & WYNNE 1978), POLPRASERT et al. (1998) and PASTORELLI et al. (1999), with the relative proportions based on BISCCHOFF & BOLD (1963, cited in BOLD & WYNNE 1978). Bold's Basal Medium (BISCCHOFF & BOLD 1963, cited in BOLD & WYNNE 1978) was added as a nutrient supplement to ensure that the FRP uptake by the biofilms was not nutrient limited. Sodium chloride was excluded from the medium to prevent the water from becoming brackish. Phosphorus was also excluded, as this was the experimental nutrient.

Photosynthetically active radiation (PAR) was provided at 3.4 µmol m^{-2} s^{-1}. For operator safety in darkness, this was as close as practicable to the 0.2-µmol m^{-2} s^{-1} PAR intensity measured at the sediment surface in the Hammond Road Experimental Wetlands.

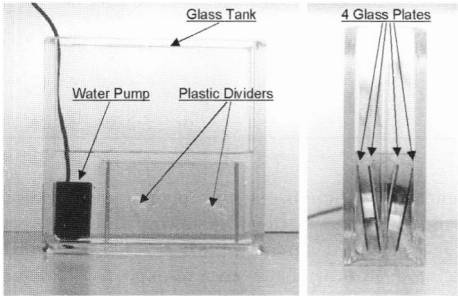

Fig. 1. FRP uptake tank design. Side and end views of the uptake tanks are shown in order to show the water pump and the division between plates that helped water circulation around and between the plates.

Results and discussion

The maximum potential FRP uptake by biofilm was ≥1.67 µg mg^{-1} h^{-1} at an FRP concentration of 400 µg L^{-1} (Fig. 2, Table 1). When this rate was extrapolated using the biofilm biomass data from the Hammond Road wetlands, the FRP uptake rates were estimated at 16.6 µg m^{-2} h^{-1} and 29.9 µg m^{-2} h^{-1} in the open water and vegetated habitats, respectively (Table 2).

On a weekly basis this would equate to 2.8–5.0 mg m^{-2} $week^{-1}$, similar to that recorded by MITSCH et al. (1995), who estimated the FRP uptake by biofilms (combined with water-column uptake) at 4–6 mg m^{-2} $week^{-1}$ from a stormwater CWS on freshwater riparian marshes in Illinois (US). CRONK & MITSCH (1994) estimated biofilm FRP uptake to be slightly lower, at 1–3 mg m^{-2} $week^{-1}$, for the same system. Despite the emphasis given to the maximum potential FRP uptake rate, it must also be considered that FRP uptake by biofilm may be negligible at low concentrations. Three of the concentrations in the FRP uptake experiments did not indicate FRP removal, and one concentration indicated a low FRP export. Therefore, given that the rate of uptake is concentration dependent (KADLEC 1997), FRP uptake at low concentrations may be negligible. It must also be considered that the biofilms used for the FRP uptake experiments may also have been FRP saturated prior to the commencement of the FRP uptake experiments, indicating that the potential FRP uptake rates may actually be higher than reported.

The FRP uptake rates obtained by MITSCH et al. (1995) and CRONK & MITSCH (1994) were similar to the FRP uptake rates found in the present study. However, in contrast, the biofilm biomass in this study was found to be lower, 5–9 mg m^{-2} $week^{-1}$ compared to 0.5–2.5 g m^{-2} $week^{-1}$ recorded by CRONK & MITSCH (1994), indicating that the potential uptake rate per gram of biofilm was found to be higher (no previously published data were available for comparison with Australian biofilm FRP uptake

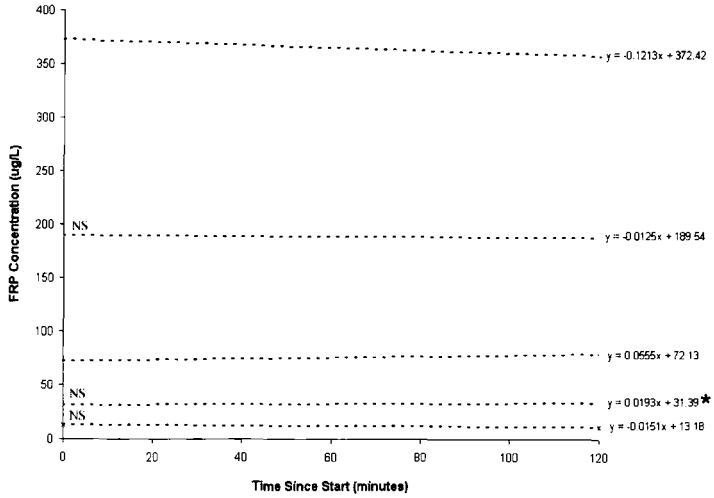

Fig. 2. FRP uptake kinetics of biofilm at five concentrations. The regression shown is the mean regression of all tanks in the given concentration. Two concentrations recorded uptakes that met the significance criteria. The remaining three concentrations did not meet the significance criterion (marked by NS). The 400-µg L^{-1} concentration had an FRP uptake, while the 100-µg L^{-1} concentration had a net FRP export (±SE, n = 5, *n = 4).

Table 1. Mean FRP uptake standardised to concentration biomass. The highest concentration had the highest FRP uptake rate standardised to biomass. NS indicates where the FRP uptake was not significant. FRP uptake occurred at the highest concentration (400 µg L^{-1}) at a rate of 14.56 µg h^{-1} (Fig. 2), 1.67 µg mg^{-1} h^{-1} when this rate was standardised to the mean tank biomass for the concentration. FRP export recorded in the 100-µg L^{-1} concentration had an export of 6.66 µg h^{-1}, 0.20 µg mg^{-1} h^{-1} when standardised to the mean tank biomass.

FRP concentration	Mean tank uptake rate (µg h^{-1})	Mean organic biomass (mg)	FRP uptake rate (µg mg^{-1} organic biomass h^{-1})
400 µg L^{-1}	14.56	8.7	1.67
200 µg L^{-1}	NS	–	NS
100 µg L^{-1}	–6.66	33.8	–0.20
50 µg L^{-1}	NS	–	NS
<50 µg L^{-1}	NS	–	NS

Table 2. The mean organic biofilm biomass and the extrapolated FRP uptake rates for open water and vegetated habitats in the Hammond Road Experimental Wetlands. The organic biomasses recorded for the open water and vegetated habitats were combined with the maximum FRP uptake rate, the extrapolated FRP uptake rates were shown to be 16.6 µg m^{-2} h^{-1} and 29.9 µg m^{-2} h^{-1} for the open water and vegetated habitats, respectively. The vegetated habitat had a greater mean organic biofilm biomass, thus resulting in a higher extrapolated FRP uptake rate.

Habitat type	Mean organic biofilm biomass (mg m^{-2} $week^{-1}$)	Extrapolated FRP uptake rate (µg m^{-2} h^{-1})
Open water	5.05 (n = 12)	16.6
Vegetated	8.95 (n = 12)	29.9

rates).

In relation to CWS conceptual model mechanisms, MITSCH et al. (1995) concluded that most influent phosphorus was retained through sedimentation and by macrophytes, with a lesser amount removed by biofilms. In contrast to this, higher potential biofilm FRP uptake and the diminished role of sedimentation on the Swan Coastal Plain (due to low particulate composition (DOUGLAS 1993, cited in WRC, 1997)) indicate that long-term phosphorus removal by biofilms may be highly significant if sufficient biomass is available.

In order to significantly increase FRP removal from CWSs in Western Australia, design criteria and wetland management must focus on mechanisms for maximising biofilm biomass. The higher biofilm organic biomass in the vegetated habitat may also indicate that maximising FRP removal from a system could be achieved by optimising the area of vegetated habitat. Additionally, the vegetated habitat would provide an increased area for biofilm development, and thus improve FRP removal.

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