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Research Article

Study of Seasonal Phosphorus Dynamics in Vegetated and Non-vegetated Wetland Sediment Affected by Long-term Agricultural Productions

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Abstract

Backgroun and Objective: Phosphorus in runoff from agricultural land area is an important component of non-point source of pollution and can accelerate eutrophication processes in downstream lakes and rivers. Phosphorus inputs to the streams depend on land use and phosphorus management within the catchment. **Methodology:** Using phosphorus adsorption-desorption experiments, Equilibrium Phosphorus Concentration (EPC) was calculated as a measure of the phosphorus adsorption capacity of wetland sediments in vegetated and non-vegetated pond. When phosphorus concentration of porewater is greater than the EPC, then the sediment will adsorb phosphorus and vice versa. The EPC values were lower in vegetated pond than in non-vegetated pond, indicating greater phosphorus adsorption capacity of vegetated pond sediment than non-vegetated pond sediment. **Results:** Phosphorus fractionation of the sediments showed that the inorganic forms of phosphorus (loosely sorbed-P, Ca/Mg-P and Fe/Al-P) and the Fe-P was consistently higher in vegetated pond than in non-vegetated pond. The ferric ion complexes adsorb phosphorus, reducing the amount of phosphorus available for diffusion to the overlying water. **Conclusion:** Therefore, it appears oxygen release by macrophytes in vegetated pond may promote phosphorus storage in sediments with greater phosphorus adsorption capacity in vegetated pond than in non-vegetated pond.

Key words: Phosphorus, eutrophication, sediment, wetland, equilibrium phosphorus concentration

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Phosphorus was recognized as the primary limiting nutrient for the occurrence of harmful algal bloom phenomenon[1,2]. Extensive replacement of native vegetation by agricultural crops and application of fertilisers, phosphorus inputs along with other nutrients from surrounding landscape have increased, which leading to eutrophication problem toward freshwater ecosystems[3,4]. In particular, the land use in the Cox Creek sub-catchment is dominated by horticulture, which commonly practiced inorganic fertilisers in order to increase vegetable production[5]. According to Fisher[5], one of four vegetables producers in the Cox Creek area were applied more phosphorus than required by crops for their growth. Subsequently excess phosphorus in soils washed to the receiving water bodies.

Once in receiving water bodies, the process of adsorption and desorption of nutrients at the water column and sediment interface plays an important role in regulating nutrient concentration. Thus, the overall function of constructed wetlands prior nutrient discharge to receiving water body is extremely important for adsorption and desorption of phosphorus by the sediment[6]. Sediment plays a significant role in constructed wetlands acting as substrate to retain or release nutrients as well as media to support rooted macrophytes[6,7]. The process of adsorption and desorption involves weak atomic and molecular interactions or stronger ionic-type bonds[8]. Given the high ability of wetland sediments to retain phosphorus is likely to be an important process resulting in the retention of phosphorus in the Cox Creek wetland.

During high flow conditions, the movement of organic matter and phosphorus into the system is driven by the flow (Fig. 1). Fractions of both phosphorus and organic matter are deposited into the sediment through sedimentation. Higher sedimentation was observed at the inlet sites as water enters the wetlands, leading to settling of suspended particles and associated nutrients. Further into the downstream, lower sedimentation was observed due to less suspended particles in the water. Since, agricultural soils of the Cox Creek may contain high organic matter, their complexion with phosphorus binding cations (Ca, Fe and Al) can also reduce phosphorus concentrations.

Laboratory adsorption experiments were applied for many years to qualify and predict retention capacity of phosphorus onto sediments[9]. Equilibrium Phosphorus Concentration (EPC) and phosphorus adsorbed by sediment obtained from the adsorption experiments were used to represent phosphorus adsorption capacity by standard sorption isotherms as developed by Langmuir and Freudlich[9,10]. It has been shown that inorganic phosphorus added at concentrations considerably greater than those present in the pore water of soil will be retained by oxides and hydroxyoxides of iron, aluminum and calcium carbonate. On the other hand, during low loading, sediment was found to release phosphorus rather than retain phosphorus. In general, phosphorus removal in constructed wetlands can be initially perform well, but declines as the system "ages" due to saturation of finite adsorption sites.

To determine the role of sediment in phosphorus dynamics in the constructed wetland, it is important to distinguish the various phosphorus pools in wetland sediment. Sediment phosphorus fractionations method has been widely used to characterize phosphorus binding to various organic and inorganic sediment components[11-13]. It is believed that some phosphorus forms in sediment are sensitive to environmental conditions, thus under certain circumstances, they may be released to overlying water

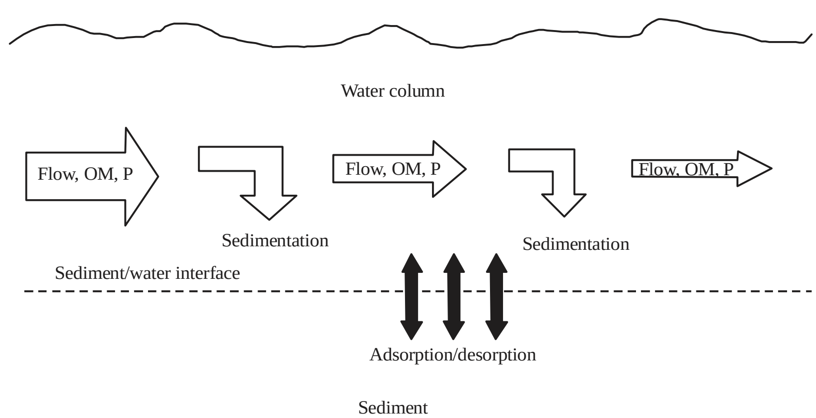

Fig. 1: Conceptual diagram of phosphorus sedimentation and sorption process in the wetland sediment of the Cox Creek wetland, OM: Organic matter and P: Phosphorus

column. For instance, the iron associated phosphorus is sensitive to low redox potential, when the sediment becomes anoxic due to bacterial respiration or stratification, it has the potential to be mobile. In other cases, the calcium bound phosphorus is sensitive to low pH value. The most frequently used method in sediment studies is the sequential extraction technique of Hieltjes and Lijklema[11], which was modified from Williams *et al.*[14] and Kurmies[15] or its modifications.

This study was conducted in order to understand phosphorus dynamics at the sediment-water interface of the Cox Creek wetland. Sediment nutrient contents, phosphorus fractionation and phosphorus sorption isotherms of the vegetated and non-vegetated wetlands were analysed and compared between seasons. It was hypothesized that sediment nutrient contents and EPC were higher in the non-vegetated pond as compared to vegetated pond because it will receive greater continuous flow, organic matter and phosphorus deposition and has therefore, a high phosphorus retention capacity. Sediment core samples were seasonally collected and the phosphorus adsorption-desorption experiments were conducted in the laboratory.

MATERIALS AND METHODS

Collection of sediment samples: The sediment samples were collected from the vegetated pond and non-vegetated pond of the Cox Creek wetland in spring 2008, summer 2009, autumn 2009 and winter 2009. Both vegetated and non-vegetated ponds were divided into five equal longitudinal cells with a randomly selected transect chosen in each cell (Fig. 2 and 3). In each transect, 1 m^2 quadrats containing 25 cells (20×20 cm) were constructed at each end and in the middle of the transect line. In each quadrat, a sediment core sampler (a 30 cm length and 5.5 cm internal diameter Plexiglas cylinder tube) was used to collect sediment cores up to 10 cm in depth. After collection, all fresh sediment cores were stored in dark at 3°C and brought back to the laboratory in sealed plastic bags for analysis. A total of 15 sediment samples were collected in each pond.

In the laboratory, the sediment cores were divided into two sub-samples for further analysis (Fig. 4). One sub-sample remained fresh and was used for phosphorus adsorption-desorption experiments and phosphorus fractionations. The fresh sediment samples were kept in a cool room at 4°C and brought back to room temperature condition prior the experiments. The second sub-sample was used for organic matter, total phosphorus, total nitrogen and total carbon analysis. The drying procedure was conducted in an oven at 60°C for 48 h. Sediments were then finely ground using a mortar and pestle and sieved using a standard 2 mm-mesh[6,16].

The organic matter contents were measured from loss of volatile solids upon igniting at 550°C following standard method 2540E[17]. The total phosphorus contents were measured using a Technicon Autoanalyser after nitric-perchloric acid digestion[18] at 160°C for 6 h. The total nitrogen and toal carbon contents were measured with a LECO CNS-2000 using the high temperature combustion in an atmosphere of oxygen technique[19].

Phosphorus fractionations: Phosphorus forms in soil sediments are characterised by their specific solubilities in various chemical extractants[20]. In order to quantify the phosphorus forms within the sediments, sequential phosphorus fractionations were carried out following the

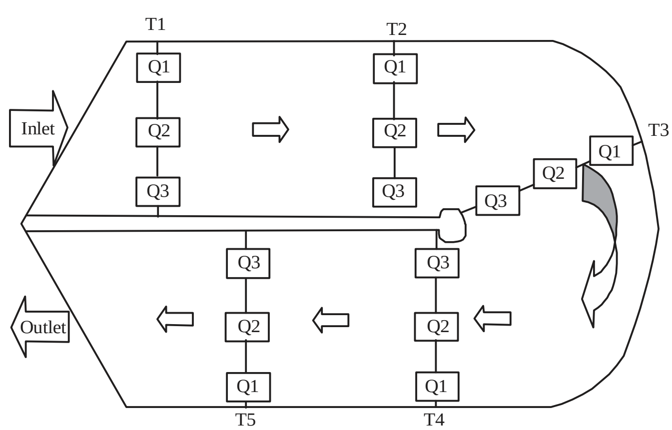

Fig. 2: Sediment soils sampling strategy for the vegetated pond of the Cox Creek wetland system. Arrow denoted flow direction of water, T1: Transect 1, T2: Transect 2, T3: Transect 3, T4: Transect 4, T5: Transect 5, Q1: Quadrat 1, Q2: Quadrat 2 and Q3: Quadrat 3

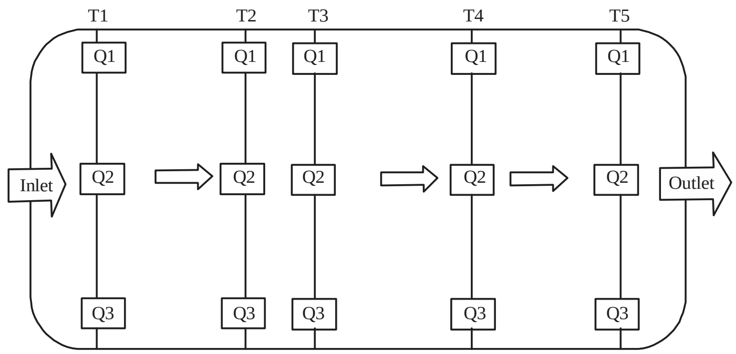

Fig. 3: Sediment soils sampling strategy for the non-vegetated of Cox Creek wetland system. Arrow denoted flow direction of water, T1: Transect 1, T2: Transect 2, T3: Transect 3, T4: Transect 4, T5: Transect 5, Q1: Quadrat 1, Q2: Quadrat 2 and Q3: Quadrat 3

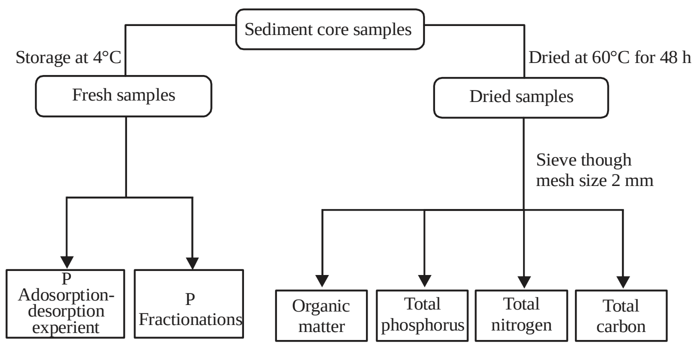

Fig. 4: Schematic protocol for analysis of sediment core samples collected from the reed bed and pond 1 of the Cox Creek wetland

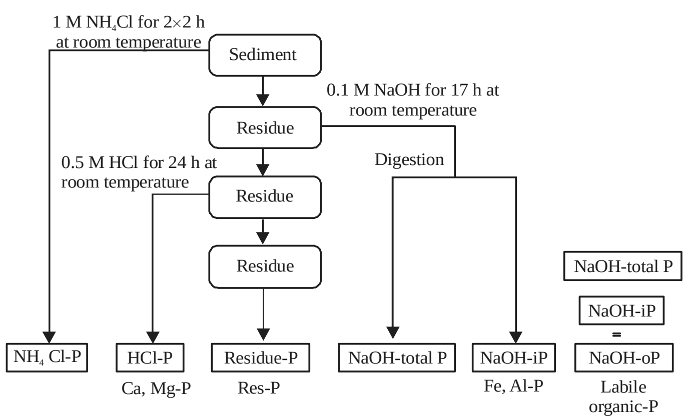

Fig. 5: Sequential phosphorus fractionations scheme used to differentiate phosphorus forms in the sediment samples collected from the Cox Creek wetland, NH_4Cl: Ammonium chloride, HCl: Hydrochloric acid, NaOH: Sodium hydroxide, NH_4Cl-P: Ammonium chloride bound phosphorus, HCl-P: Hydrochloric acid bound phosphorus, Ca, Mg-P: Calcium, manganese bound phosphorus, Res-P: Residual phosphorus, NaOH-total P: Sodium hydroxide bound total phosphorus, NaOH-iP: Sodium hydroxide bound organic phosphorus, Fe, Al-P: Iron, aluminium bound phosphorus and NaOH-oP: Sodium hydroxide bound organic phosphorus

procedure reported by Penn *et al.*[21] and Rydin[13]. This separates phosphorus in the sediments into five pools: (1) NH_4Cl-P (loosely sorbed phosphorus), (2) HCl-P (Ca/Mg-phosphorus), (3) NaOH-iP (Fe/Al-phosphorus), (4) NaOH-oP (labile organic-phosphorus) and (5) residual phosphorus (res-P) as shown in Fig. 5. The loosely sorbed phosphorus represents adsorbed phosphorus potentially bioavailable. The HCl-P represents phosphorus associated with calcium (Ca) and manganese (Mg) that is relatively stable and not readily bioavailable. The NaOH-iP represents inorganic phosphorus associated with iron (Fe) and aluminium (Al) and represents phosphorus readily not bioavailable. The labile organic phosphorus is an intermediate pool between readily available and unavailable phosphorus and represent those phosphorus compounds affected by mobilisation and immobilisation processes. The res-P are the highly resistant organic phosphorus or unavailable mineral bound phosphorus, which not extracted with either alkali or acid.

The phosphorus fractionations were conducted by adding 25 mL of 1 M NH_4Cl solution to wet sediment (0.5 g dry weight equivalent) in centrifuge tubes. Formaldehyde solution (1 mL) was added to inhibit microbial activity followed by shaking in an over-end shaker for 2 h. This step was repeated, resulting in loosely sorbed phosphorus (NH_4Cl-P). Following this step, 0.1 M NaOH (25 mL) was added to the residue followed by shaking in an over-end shaker for another 17 h, resulting in NaOH-total P (digested) and NaOH-iP (undigested). The labile organic phosphorus (NaOH-oP) was calculated from the difference of NaOH-total P and NaOH-iP. The remaining residue from 0.1 M NaOH extractions was then added with 0.5 M HCl acid solution (25 mL) followed by shaking for another 24 h, resulting in HCl-P. The phosphorus remaining in the final residue (res-P) was calculated from the difference of total phosphorus and the sum of all extractable phosphorus fractions. All the extractants were filtered through 0.45 μm Milipore® membrane filter and filtrate was used for filterable reactive phosphorus following the ascorbic acid method[22], using a Hitachi U-2000 spectrophotometer (Hitachi Ltd., Tokyo, Japan).

Phosphorus adsorption-desorption experiments: Phosphorus adsorption-desorption experiments were conducted to estimate phosphorus sorption capacity of wetland sediments. These experiments were carried out by adding a known amount of dissolved inorganic phosphorus (as KH_2PO_4) to wet sediment (0.5 g dry weight equivalent) of each sediment sample. Initial concentrations of 0, 0.2, 0.5, 1, 2, 5, 10, 50 and 80 mg L^{-1} P were used, resulting in total volume of 25 mL. In order to inhibit microbial activity during the experiments, 1 mL of formaldehyde was added to each centrifuge tube. The centrifuge tubes were placed in an over-end shaker for 24 h to reach equilibrium[6]. After 24 h, the solutions were centrifuged for 15 min at 3000 rpm and filtered through 0.45 μm Milipore® membrane filter. Filtrate was analysed for FRP following ascorbic acid method[22], using a Hitachi U-2000 spectrophotometer (Hitachi Ltd., Tokyo, Japan).

The phosphorus sorbed onto sediment (in mass, mg kg^{-1}) was calculated by multiplying the difference of phosphorus concentrations between initial and after 24 h equilibrations in 25 mL solution over 0.5 g sediment. The phosphorus sorbed onto sediment was regressed against initial phosphorus concentration (phosphorus sorption isotherm) to determine the Equilibrium Phosphorus Concentration (EPC). Finally, the EPC was recorded as the x-intercept[23].

Statistical analysis: All data were tested for normality using a Shapiro-Wilk test followed by two-way analysis of variance in order to compare the differences between sediment nutrient (e.g., total phosphorus, total nitrogen and total carbon) and organic matter contents, phosphorus fractionation forms and EPC value, with wetland pond and season as the fixed effects. Statistically significant differences were accepted with α of 0.05. All statistical analysis were performed using JMP-IN (Version 4.0.3, S.A.S Institute Inc., Cary, USA).

RESULTS

Chemical characteristics of the Cox Creek wetland sediments: Sediment nutrient and organic matter contents varied seasonally between vegetated and non-vegetated pond (Table 1). Overall, total phosphorus, total nitrogen and total carbon contents in sediment were higher in non-vegetated pond than in the vegetated pond. In the both ponds, total phosphorus, total nitrogen and total carbon contents in sediment were highest in autumn 2009 and winter 2009 and were lowest in spring 2008 and summer 2009.

Table 1: Sediment Total Phosphorus (TP), Total Nitrogen (TN), Total Carbon (TC) and Organic Matter (OM) contents of the vegetated and non-vegetated pond of the Cox Creek wetland in spring 2008, summer 2009, autumn 2009 and winter 2009

Parameters	Season	Vegetated pond	Non-vegetated pond
TP (mg kg^{-1})	Spring (2008)	115.08±24.85	212.28±107.91
	Summer (2009)	112.65±27.91	276.88±118.74
	Autumn (2009)	122.22±47.71	449.35±116.19
	Winter (2009)	180.53±110.73	436.09±152.88
TN (mg kg^{-1})	Spring (2008)	615.52±166.79	2015.97±800.01
	Summer (2009)	569.61±191.0	1790.57±302.69
	Autumn (2009)	1556.97±138.19	2552.94±485.68
	Winter (2009)	1363.00±156.30	2702.55±540.74
TC (mg kg^{-1})	Spring (2008)	785.24±183.86	3912.81±901.23
	Summer (2009)	691.47±164.95	2917.32±586.0
	Autumn (2009)	3590.43±470.86	6810.21±372.34
	Winter (2009)	2040.46±103.0	7280.52±299.89
OM (mg m^{-2})	Spring (2008)	2.46±1.17	19.48±8.68
	Summer (2009)	2.58±2.41	18.17±6.78
	Autumn (2009)	11.52±6.16	58.63±35.41
	Winter (2009)	8.91±4.82	44.51±28.81

Mean±Standard Deviations, n = 15

For total phosphorus, there was a significant difference found between wetland and season, since there was a seasonal effect on the wetland pond (Table 2, $p<0.0001$). This was possibly due to sediment total phosphorus contents in the vegetated pond almost similar in spring 2008 and summer 2009, but lower than in autumn 2009 and winter 2009. In the non-vegetated pond, sediment total phosphorus contents was significantly higher than in the vegetated pond and was lowest in spring 2008 than in summer 2009, autumn 2009 and winter 2009. For total nitrogen and total carbon, there were also shown significant differences between wetland pond and season (Table 2, $p<0.0001$), but no interactions were found (Table 2, TN: $p = 0.8972$ and TC: $p = 0.0787$).

Table 2: p-values obtained for the effects of wetland pond and season (and interaction) on Total Phosphorus (TP), Total Nitrogen (TN), Total Carbon (TC) and Organic Matter (OM)

Effect	TP	TN	TC	OM
Wetland	<0.0001	<0.0001	<0.0001	<0.0001
Season	<0.0001	0.0018	<0.0001	<0.0001
*Wetland×season	<0.0001	0.8972	0.0787	0.2831

*Interaction effects between wetland and season

The organic matter contents ranged between 2.46±1.17 and 11.52±6.16 mg m^{-2} and 18.17±6.78 and 58.63±35.41 mg m^{-2} for the vegetated pond and non-vegetated pond, respectively (Table 1). The organic matter contents of sediments in non-vegetated pond were significantly higher than that in the vegetated pond (Table 2, $p<0.0001$). As for total phosphorus, total nitrogen and total carbon, the organic matter contents were highest during autumn 2009 and winter 2009 and lowest during spring 2008 and summer 2009. The results also revealed statistically significant difference between wetland pond and season ($p<0.0001$) and interactions was found between wetland pond and season (Table 2, $p = 0.0007$).

Sediment phosphorus fractions: The sediments from the vegetated pond had significantly lower phosphorus contents than the sediments from non-vegetated pond (Fig. 6). Loosely sorbed phosphorus (NH_4Cl-P) was significantly higher in non-vegetated pond than in the vegetated pond sediment (Fig. 6, Table 3, $p<0.0001$). This fraction was highest during

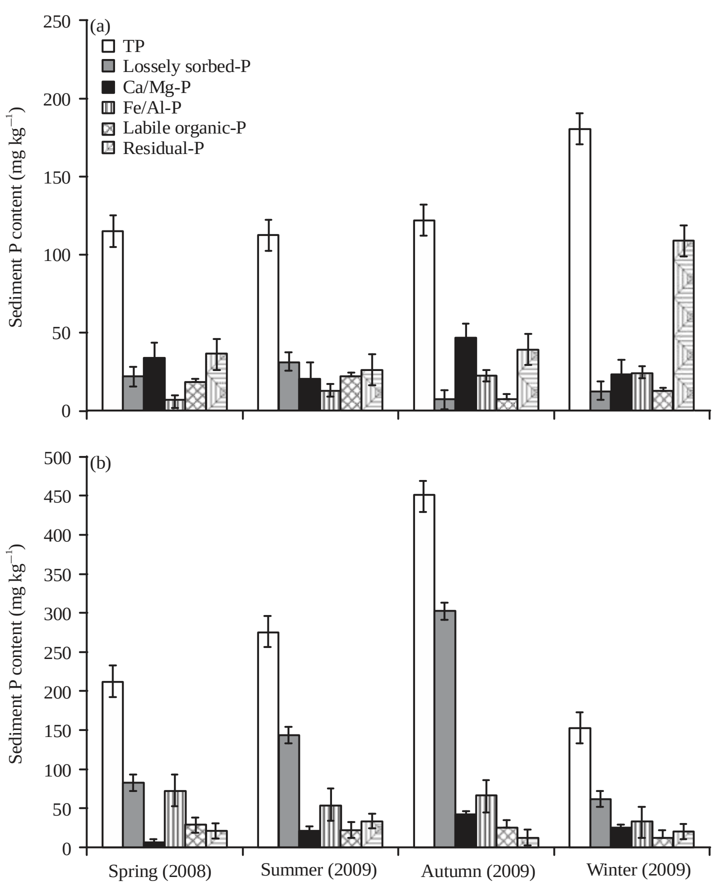

Fig. 6(a-b): Sediment phosphorus content of different fractions for the (a) Vegetated pond and (b) Non-vegetated pond of the Cox Creek wetland in spring 2008, summer 2009 autumn 2009 and winter 2009 Mean±Standard Errors (n = 15)

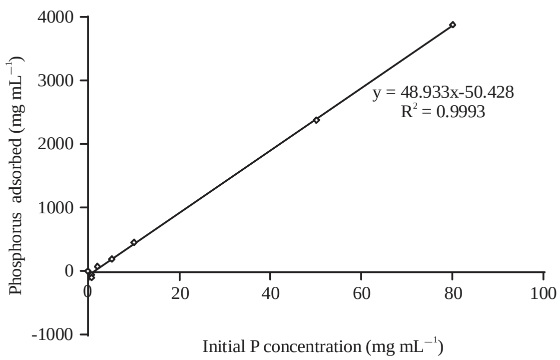

Fig. 7: Fitted phosphorus adsorption isotherms for the wetland sediments of the Cox Creek wetland. The graph shows the phosphorus sediment sorbed (in mass, mg kg^{-1}) regressed against initial phosphorus concentration (mg L^{-1}), EPC was calculated as the x-intercept, dots represent the measured data and lines are the fitted linear lines

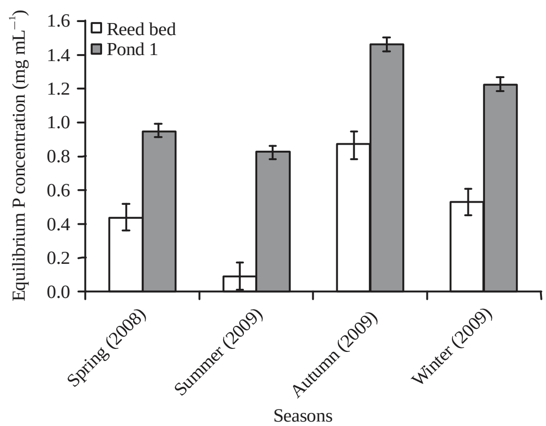

Fig. 8: Measured Equilibrium Phosphorus Concentration (EPC) for the vegetated pond and non-vegetated pond of the Cox Creek wetland in spring 2008 (Spr 08), summer 2009 (Sum 09), autumn 2009 (Aut 09) and winter 2009 (Win 09). Mean$\pm$Standard Error (n = 15)

summer 2009 in the vegetated pond and during autumn 2009 in non-vegetated pond, respectively. These response were supported by the interactions of wetland$\times$season (Table 3, p<0.0001). The HCl-P (Ca/Mg-P) fractions varied seasonally (5.15-45.83 mg kg^{-1}) between the vegetated pond and non-vegetated pond sediments (Fig. 6). The NaOH-iP form was highest during autumn 2009 for both ponds and was lowest during summer 2009 and winter 2009 in the vegetated pond (Fig. 6a) but during spring 2008 in non-vegetated pond (Fig. 6b). Statistically, there was an interaction between wetland and season (Table 3, p<0.0001). The labile organic phosphorus (NaOH-P) was highest in autumn 2009 for both ponds and was significantly different between seasons. In the vegetated pond, residual phosphorus (res-P) accounted the highest phosphorus forms in winter 2009, whereas non-vegetated pond was highest in summer 2009. In addition, the effect of wetland was also dependent upon the effect of season.

Sediment phosphorus adsorption-desorption characteristics: The phosphorus sorption isotherm experiments were successfully conducted to enable calculations of Equilibrium Phosphorus Concentration (EPC). The amount of phosphorus sorbed after equilibrium for 24 h, where the positive values depicted adsorption of phosphorus into sediment and negative values depicted desorption of phosphorus from sediment into solution. The x-intercept of fitted linear regression represents the EPC (Fig. 7). The sediments from the vegetated pond exhibited lower EPC value, indicated greater potential for phosphorus adsorption from the water column as compared to non-vegetated pond (Fig. 8). In general, the EPC was significantly lower during spring 2008 and summer 2009 than autumn 2009 and winter 2009.

Table 3: p-values obtained for the effects of wetland pond and season (and interaction) on loosely sorbed phosphorus (NH_4Cl-P), hydrochloric acid bound phosphorus (HCl-P), sodium hydroxide bound inorganic phosphorus (NaOH-iP), labile organic phosphorus (NaOH-oP) and residual phosphorus (res-P)

Effect	NH_4Cl-P	HCl-P	NaOH-iP	NaOH-oP	Res-P
Wetland	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Season	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
*Wetland$\times$season	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

*Interaction effects between wetland and season

DISCUSSION

The nutrients and organic matter concentrations in the sediment of non-vegetated pond were higher than in the sediment of the vegetated pond (Table 1). The higher total phosphorus concentrations were found in the non-vegetated pond was might be due to continuous external phosphorus loadings driven by the flow since past decades and less uptake of nutrient by macrophytes. The lower sediment nutrient concentrations in the vegetated pond seems to be influenced by its intermittent flow during high flow events and the uptake of nutrient by macrophytes for their growth.

The study also found that sediment nutrient and organic matter concentrations changed significantly between the seasons. The seasonal patterns showed that the nutrient and organic matter concentrations were lower during the growing seasons (spring 2008 and summer 2009) as compared to the non-growing seasons (autumn 2009 and winter 2009). During the growing seasons, emergent macrophytes utilise nutrients in the sediment for their growth and nutrient release from sediment into water column is likely to happen. This observation suggested that during the growing seasons the sediment may act as nutrient source but act as nutrient sink during the non-growing season, as indicated by higher nutrients in sediments. During growing season, the sediments may act as total phosphorus source for macrophytes uptake and potentially to be released into the water column due to anaerobic conditions. In contrast, during the non-growing seasons the sediment will act as total phosphorus sink and phosphorus will be retained in the sediment, indicated with higher total phosphorus content in the sediments (Table 1).

Similar seasonal patterns of total nitrogen and total carbon were observed in both ponds (Table 1). Unlike sediment total phosphorus contents, total nitrogen underwent different pathways in order to release nitrogen from the wetland (e.g., nitrification, denitrification and ammonification). During the growing seasons, the sediment was believed to function as nitrogen source for the macrophyte community and the denitrification process by the microbial activity will transform N (as NO^{3-}) to N_2 and N_2O under anaerobic conditions[10]. The higher total nitrogen contents in the sediment during the non-growing seasons might be attributed to leaching of nitrogen during senescence of macrophytes and external inputs from catchment runoff. As for the total carbon contents in the sediment, lower concentration were found during growing season probably due to utilisation of organic carbon by microorganism[24]. Decompositons of carbon due to senescence of macrophytes during the non-growing seasons contributed to the total organic carbon in the wetland.

The differences of phosphorus forms in the sediments can be used as indicator to identify a potential mobilisation of phosphorus pools and its impact on water quality. The higher phosphorus concentration can be a possible reason that enhanced pools of organically bound phosphorus which suggesting that a large part of this forms will be mobilised and eventually will be mineralised and released. In the non-vegetated pond, loosely sorbed phosphorus contributed the most for the phosphorus pools followed by the Fe/Al bound phosphorus which on average constitutes about 41-67 and 15-35% of the total phosphorus, respectively. The lowest phosphorus pools were Ca/Mg bound phosphorus which on averaged of 2-9% of the total phosphorus. The results indicated that the sediment in non-vegetated pond was considered as bioavailable, where it can be sufficiently mobilised to enter sediment porewater and potentially flux into overlying water column. However, this study also indicated that the Fe/Al bound phosphorus dominated the phosphorus pools (Fig. 6), which can be temporarily immobilised in the wetland sediment[12,25]. Therefore, this suggest that the manipulation of iron to wetland sediments may be a useful restoration tool to increase the permanent deposition of phosphorus pools in the sediment.

The ability of wetland sediments to retain phosphorus regulates the productivity of many aquatic system through adsorption of phosphorus from water column onto sediments[26,27]. Thus, improved understanding is needed of interactions between phosphorus in overlying water column and wetland sediment governed by the phosphorus sorption capacity or buffer intensity. The results of phosphorus retention capacity vary considerably over the season as clearly indicated by the seasonal variation in EPC value between the vegetated pond and non-vegetated pond (Fig. 8). In the vegetated pond, the phosphorus adsorption capacity were highest during spring 2008 and summer 2009 than autumn 2009 and winter 2009, indicated by lower EPC value. This characteristics were not solely dependent upon the phosphorus loads, as shown by lower phosphorus content during spring and summer seasons (Table 1) but also caused by the seasonal changes in the interactions between the sediment and the water phase[12]. The difference of phosphorus adsorption capacity during growing seasons and the non-growing seasons were also corresponds to the available sorption sites[10], suggesting that during growing seasons the sediment have higher available sorption sites.

In the non-vegetated pond, almost a similar seasonal pattern of phosphorus adsorption capacity were investigated as in the vegetated pond sediment, which were highest during spring 2008 and summer 2009 than autumn 2009 and winter 2009 (Fig. 8). This result showed that the decreasing sorption potential of phosphorus from the water column onto the non-vegetated pond sediment, suggesting that sediment in the non-vegetated pond possibly have fewer available sorption sites. In conclusion, by investigating the sediment nutrient contents and EPC in the vegetated and non-vegetated pond sediment cores, the vegetated pond sediment had higher potential to absorb phosphorus than non-vegetated pond sediment. Therefore, these findings dictated valuable information onto the adsorption status of the wetland sediments.

CONCLUSION

Sediments are the key components of wetlands for phosphorus retention. Strong interactions between phosphorus and wetland sediments determine the fate and mobility of phosphorus in the wetlands. The nature and type of sediment, the chemical composition and the cation exchange capacity of the sediment play important roles in the retention and conversion of phosphorus and other pollutants. The results from the laboratory batch experiments revealed that sediments of non-vegetated pond had higher phosphorus contents but had less capability to adsorb phosphorus from the water column than sediments of the vegetated pond. Therefore, it can be concluded that vegetated pond sediments have a higher phosphorus adsorption capacity than the non-vegetated pond sediment. Implications of this are that sediment characteristics may vary depending upon the position of the basin in the wetland complex and the vegetation that it contains. When wetland sediments exceed their capacity to adsorb additional phosphorus, the wetland becomes less effective as a barrier to phosphorus transport. Continual renewal of sediment from inflows may increase the phosphorus binding capacity but removal of sediment may be necessary to increase the longevity of the wetland as a phosphorus removal system.

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