



# Phosphorus Release due to Decomposition of Wetland Plants

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**Abstract** Agricultural activities are major sources of non-point pollutants causing eutrophication. Vegetated constructed wetlands are used as a best management practice for sequestration of nutrients from agricultural runoff. However, plants release nutrients back into the system as they decompose after senescence, affecting the nutrient removal efficiency of a constructed wetland. This information is important for a focused selection of plants and for improving the effectiveness of a constructed wetland. A greenhouse experiment was conducted to study the release of phosphorus by common freshwater macrophytes - *Juncus effusus*, *Carex lurida* and *Dichantherium acuminatum* var. *acuminatum* during plant decomposition. Microcosms with the mixed culture of these three species showed higher phosphorus retention rates compared to monoculture microcosms. Results indicate that plant species differ in their nutrient removal efficiencies when grown in the mixed culture compared to monoculture treatments, indicating that nutrient removal efficiencies vary with plant species composition. Thus, plant species may play an important role in determining the phosphorus removal rates of vegetated constructed wetlands.

**Keywords** Decomposition · Phosphorus · Constructed wetlands · *Dichantherium acuminatum* · *Juncus effusus* and *Carex lurida*

## Introduction

Nutrient fluxes to coastal areas have risen in recent decades because of high concentrations of nutrients in agricultural runoff deposited into surface waters (Howarth et al. 2011). Due to their nutrient retention characteristics, plants are used to solve eutrophication problems of freshwater bodies (Aoi and Hayashi 1996) and to remove pollutants in constructed wetlands (Delgado et al. 1993; Maine et al. 2004). Despite the advances in understanding eutrophication, it still remains one of the foremost problems in protecting freshwater and coastal marine ecosystems (Schindler 2006). Agricultural runoff is a major source of non-point pollution contributing to eutrophication (Carpenter et al. 1998). Phosphorus inputs to freshwater can accelerate eutrophication; hence, control of P inputs and their subsequent transport in runoff is critical to reduce eutrophication (Sharpley et al. 1997). One of several best management practices recommended for the removal of nutrients and pesticides from agricultural runoff is the use of constructed wetlands (Cooper et al. 2004; Bouldin et al. 2005).

Constructed wetlands are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater (Hammer and Bastian 1989). Removal of phosphate in wetlands is known to be mediated by precipitation, adsorption, plant uptake and microbial assimilation (Moshiri 1993; Kadlec and Knight 1996; Reddy et al. 1999). Phosphorus storage in vegetation can range from short- to long-term, depending on type of vegetation, litter decomposition rates, leaching of P from detrital tissue, and translocation of P from above- to belowground biomass (Garver et al. 1988). Phosphorus uptake by wetland macrophytes is usually highest during the beginning of the growing season (in most regions during the early spring) before maximum growth rate is attained (Boyd 1969). The concentration of phosphorus in plant tissue of

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these macrophytes varies among species, sites and by season (Brix and Schierup 1989). Phosphorus storage in above-ground biomass of emergent wetland macrophytes is usually short-term with a large amount of P being released during the decomposition of litter (Vymazal 1996). The aboveground portions of wetland macrophytes return P to the water, while belowground portions returns P to the soil (Reddy et al. 1999).

Wetland plants are capable of retaining nutrients in high concentrations, but decomposition of macrophytes may lead to the release of the retained nutrients and, thus, become another source of nutrients to the water column or any part of the system (Kröger et al. 2007). Hence, while considering the nutrient retention capacity of a vegetated constructed wetland, it is important to take into consideration the amount of nutrients released back into a system following plant senescence (through leaching and decomposition) in order to estimate the actual effectiveness of the system. In most mitigation studies, this concept is not taken into consideration while calculating the net retention rate of the system and, hence, might lead to the failure of the system to mitigate nutrients efficiently (Kröger et al. 2007). Therefore, it is important to know the phosphorus release rate of plants during decomposition for planning an efficient constructed wetland system. The main objective of this study was to examine the release of phosphorus by *Juncus effusus*, *Carex lurida* and *Dichanthelium acuminatum* var. *acuminatum* following plant senescence in constructed wetland systems.

## Materials and Methods

A greenhouse experiment was conducted to study the phosphorus retention rates of *Juncus effusus* (*J. effusus*), *Carex lurida* (*C. lurida*) and *Dichanthelium acuminatum* var. *acuminatum* (*D. acuminatum*) by studying the amount of phosphorus released following plant senescence. These species are native macrophytes used in constructed wetlands belonging to the Juncaceae, Cyperaceae, and Poaceae families, respectively (USDA 2007; Zazo et al. 2008; Brisson and Chazarenc 2009; White et al. 2012). The experiments were conducted in the greenhouse at the University of Mississippi Field Station (UMFS) as described previously (Menon et al. 2013). In brief, 16 plastic barrels (volume=105 l) were filled with sediment (mixture of sand and clay) taken from unused ponds at the UMFS, Abbeville, MS, USA and were filled with groundwater to 10 cm depth above the sediment surface. After 2 weeks, young plant ramets were collected from UMFS wetlands and planted into the barrels in June (hereafter called mesocosms) as described previously (Menon et al. 2013). Each vegetated mesocosm was planted with 33 individual plant ramets, with four replicate mesocosms for each of the monocultures (four each per plant species) and four replicate mesocosms with the mixed culture (11 plants from each

species). The mesocosms were maintained until the end of the experiment without replantation.

Monocultures and the mixed culture of all the three plants, *C. lurida*, *J. effusus*, *D. acuminatum*, were dosed with a total of 108 l of 2.5 mg/L of phosphorus over a period from June to November (each dose consisted of 18 l of 2.5 mg/l) in 2008 and 2009 as described earlier in a previous experiment to study the phosphorus retention capacity of the above plants (Menon and Holland 2013). The dose was added six times each year and the last dose was added on November 22nd (both in 2008 and 2009). The aboveground tissue of 12 plant stems (three from each replicate mesocosm) of each species from monoculture and the mixed culture was clipped above the sediment surface and placed into each litter bag (mesh size: 5 mm mesh diameter) in December for both years. Four replicate litter bags were set up for each species from monocultures (each bag with 12 plants) and for plants from the mixed cultures (each bag with 12 plants, 4 each from three species). All the bags were weighed using a weighing scale before they were placed in the tubs. There was no difference in the weights between the litterbags and they all weighed approximately 10 g. The litter bags were weighted using a small pebble and placed in 18 l plastic tubs (hereafter called microcosms) filled up to the 18 L mark with ground water from the University of Mississippi Field Station (Fig. 1). Baseline phosphorus concentration of UMFS ground water was 0.002 mg P/L. A control treatment with only UMFS ground water and litterbags was also established in order to determine if the phosphorus concentration in the water fluctuated over the course of the experiment.

The experiments were initiated on 1st December in both 2008 and 2009. Water samples were collected from the tubs beginning on 15 December in each experiment, and thereafter samples were collected on the 15th day of each month through March of the following year. In total, samples were collected four times for each experiment. The water column was mixed before sampling and a single sample was collected at 10 cm depth from the water surface. Water samples (250 ml) collected were analyzed for total phosphorus. Immediately before the decomposition experiment, the total phosphorus



**Fig. 1** Microcosms with litterbags at the start of the experiment in December 2008

concentration in a subsample (1 g) of the aboveground plant tissue from each plant stem placed in the litter bags was also determined. The total phosphorus in water and plant samples were determined using a Dionex ion chromatograph and the ammonium per sulfate digestion method (Murphy and Riley 1962; American Public Health Association APHA 1998).

The total phosphorus concentration values were all normalized to per gram of plant tissue or to the number of plants to avoid the variation in the biomass due to difference in height and in the number of plants. Difference between the total phosphorus in the water column in the treatment tubs were statistically analyzed using repeated analysis of variance and Tukey's posthoc test. The percent rate of phosphorus released into the water column in each treatment was calculated as the ratio of average TP in water to TP in initial plant biomass multiplied by 100. The differences in the percent rate of phosphorus released in 2008 and 2009 for all treatments were analyzed using repeated analysis of variance and Tukey's posthoc test. The mean percentage of P released for all treatments for both years were compared using a one way analysis of variance.

## Results

All the treatment microcosms had a floating film towards the end of the experiment in both years. The chemistry of the film was not determined due to time constraints. The total phosphorus (TP) content in the aboveground tissue in December 2008, before the start of the decomposition experiment, indicates *J. effusus* and *C. lurida* had higher concentrations of TP compared to *D. acuminatum* in both monoculture and the mixed culture treatments (Table 1). In 2008, the total phosphorus concentrations in the water showed a significant treatment by time interactive effect and a difference in the amount of phosphorus released by the different treatments over time ( $F=12.19$ ,  $p<0.001$ , Fig. 2a). The total phosphorus concentration in the water column was highest in January for *J. effusus* and *C. lurida* and then decreased over time. Water column total phosphorus concentration in the *J. effusus*

treatment was significantly greater (Tukey's HSD test,  $p<0.05$ ) than that in other treatments in December 2008. Also, the total phosphorus concentration in the water column for the mixed treatment was significantly lower than other treatments in January 2009 (Tukey's HSD test,  $p<0.05$ ). Moreover, *D. acuminatum* showed significantly higher phosphorus concentrations from all the treatments in February 2009 and March 2009 (Tukey's HSD test,  $p<0.05$ ).

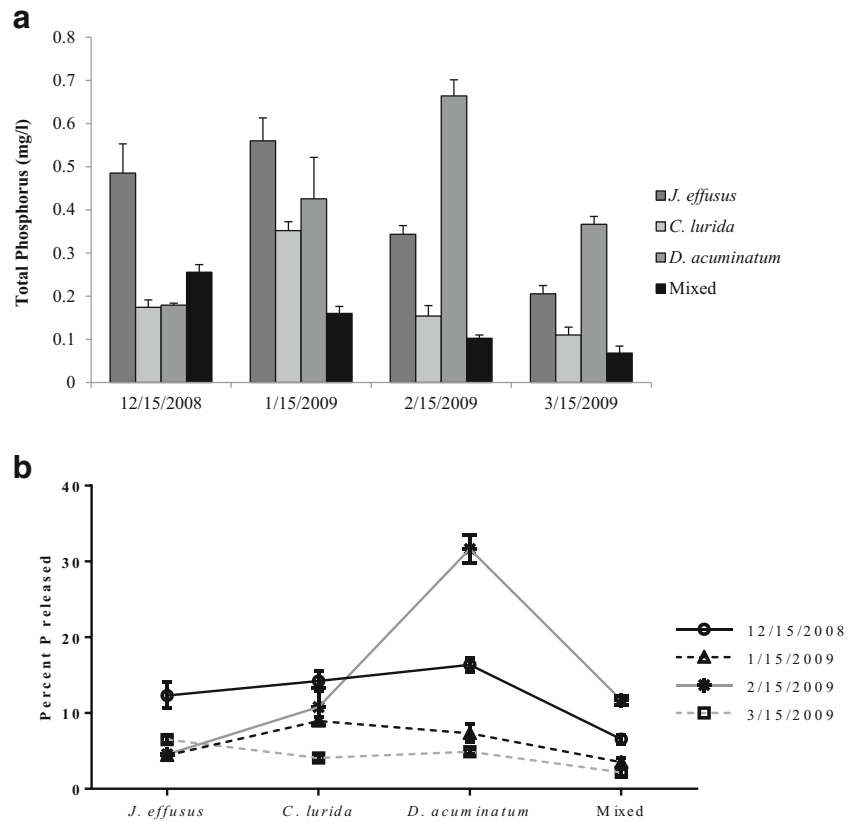
The total phosphorus release rate (mean of the difference between final and initial concentrations) in 2008 was highest in *D. acuminatum* treatments; lowest release rates were found for mixed and *C. lurida* treatments (Table 2). However, the temporal patterns in the percent rate of P released varied among the treatments in 2008 (Fig. 2b). While the highest percent rate of P was released in December for *J. effusus* and *C. lurida*, it was the highest in February for *D. acuminatum* and the mixed treatment. In addition, for *J. effusus* the release rates did not differ significantly between the months of January, February and March ( $p>0.05$ ). This pattern was not observed for the other treatments. *D. acuminatum* and the mixed treatment exhibited similar temporal pattern but the rates were significantly lower for the mixed treatment compared to *D. acuminatum* ( $p<0.05$ ). Interaction effects of the percent P release rates with respect to treatment (species) and time were significant ( $F=23.52$ ,  $p<0.0001$ ). The percent P release rates differed significantly between all the treatments except *J. effusus* and the mixed treatment ( $p>0.05$ ).

Repeated measures ANOVA results for 2009 indicates that there was a significant difference in the amount of phosphorus released into the water column between the different treatments over time ( $F=4.7$ ,  $p<0.05$ , Fig. 3a). TP in the water column for *C. lurida* was significantly lower in December while it differed significantly in January for *J. effusus* and *C. lurida* (Tukey's HSD test,  $p<0.05$ ). However, there was no difference in the TP in the water column in February and March for all the treatments. *C. lurida* had the highest TP concentration in the tissue before the experiment began (Table 1) and released relatively lower rates of P into the water column (Table 2). Apparently *C. lurida* and the mixed culture treatment released similar amounts of P into the water column in both experiments. Moreover, *J. effusus* showed the least amount of TP release (mean) from its aboveground plant tissue (Table 2). A temporal variation in the percent rate of P released was found for all treatments except for the mixed culture treatment (Fig. 3b). The pattern of the temporal variation was similar for *J. effusus* and *C. lurida*. Unlike the 2008 experiment, the highest percent rate of P was released in March for all the treatments in the 2009 experiment. Interaction effects of the percent P release rates with respect to treatment (species) and time were significant ( $F=4.3$ ,  $p<0.0001$ ). Similar to the 2008 experiment, the percent P release rates differed significantly between all the treatments except *J. effusus* and the mixed culture treatment ( $p>0.05$ ).

**Table 1** Total phosphorus concentration (Mean±SD) in the plant tissue at the start of the decomposition experiment in 2008 and 2009

	2008 (mg P/g)	2009 (mg P/g)
<i>C. lurida</i>	3.94±0.32	5.08±0.06
<i>D. acuminatum</i>	2.10±0.45	1.40±0.03
<i>J. effusus</i>	3.94±0.17	2.80±0.20
<i>C. lurida</i> in mixed culture	3.39±0.07	3.60±0.07
<i>D. acuminatum</i> in mixed culture	1.94±0.16	4.20±0.14
<i>J. effusus</i> in mixed culture	4.06±0.20	2.20±0.10

**Fig. 2 a** Total phosphorus concentrations (mean±SE,  $n=4$ ) in the water column as a result of plant decomposition for 2008–2009 **b** Percent phosphorus released from the 2008 decomposition experiment (mean±SE,  $n=4$ )



A significant difference was found in the mean percent P released by *J. effusus* and *D. acuminatum* in both the experiments ( $p < 0.05$ , Table 2). The rates were lower in the second experiment compared to the first experiment for *J. effusus* and *D. acuminatum*. The percent rates for *C. lurida* and the mixed culture treatment did not differ significantly between the two experiments. The control treatment indicated that the TP concentrations of the background (UMFS ground water) did not change significantly throughout the course of the experiment ( $p = 0.824$ ).

## Discussion

Wetland plants are an integral part of constructed wetland systems, but there is little quantitative information available

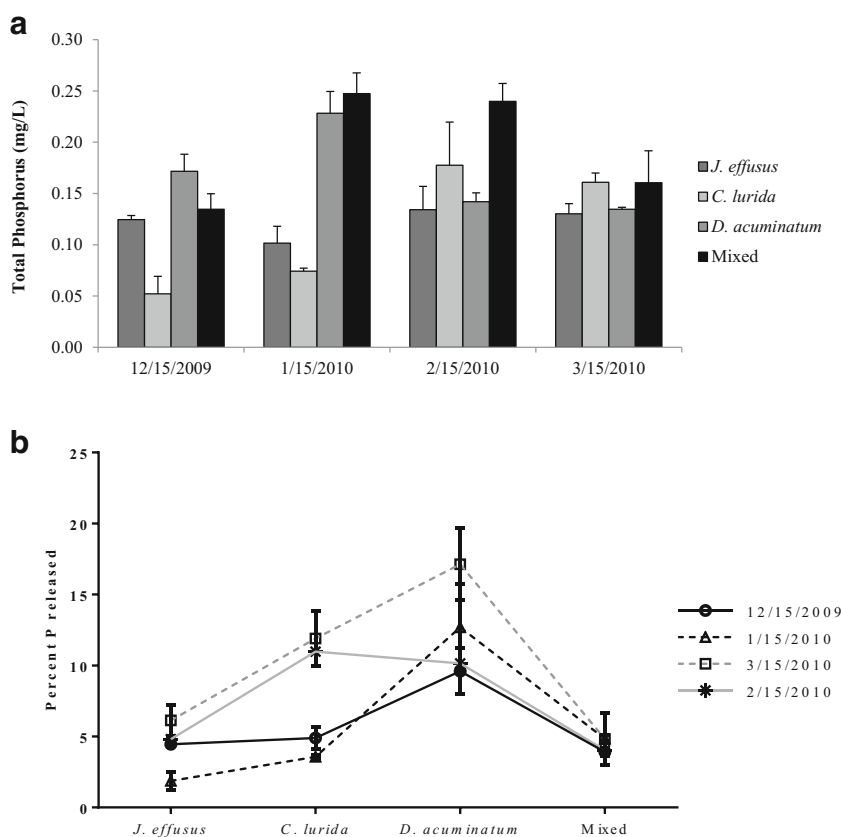
**Table 2** Percent rate of total phosphorus released (mean±SD) into the water column in 2008 and 2009

	2008–2009	2009–2010
<i>J. effusus</i>	10 %±0.3	4 %±0.4
<i>C. lurida</i>	5 %±0.6	6 %±0.2
<i>D. acuminatum</i>	20 %±0.3	12 %±0.4
Mixed	5 %±0.1	6 %±0.1

comparing their growth characteristics and treatment performance in constructed wetland systems (Tanner 1996; Vymazal 2007). Selection of plants is a crucial factor for the efficient functioning of constructed wetlands since storage in plant biomass is a saturable process, meaning plants release nutrients back into the ecosystem during decomposition. By using a microcosm study, we were able to examine the differential release rates of phosphorus due to decomposition of above-ground biomass of three wetland plants that are commonly used in constructed wetlands. Our results indicate that the plant species differed in the amount of total phosphorus released into the system. These variations in the amount of phosphorus released suggest that plant species exhibit different nutrient removal efficiencies.

Wetland plants are known to differ in their capacity to assimilate nutrients from wastewater (Kadlec and Knight 1996). For instance, the nutrient uptake capacity of *Phragmites australis* was higher than that of *Cyperus papyrus* (Brix and Schierup 1989). However, Richardson and Marshall (1986) found that plant dieback resulted in a 5-fold increase in P flux in the water column. Kröger et al. (2007) studied the leaching of nutrients after plant senescence of *Leersia oryzoides* and found that it retained N and P during the growing season but released the nutrients back into the water column after plant senescence, which would create eutrophic conditions in receiving waters during the winter months (December to January). Therefore, while it is important to

**Fig. 3 a** Total phosphorus concentrations (mean±SE,  $n=4$ ) in the water column as a result of plant decomposition for 2009–2010 **b** Percent phosphorus released from the 2009 decomposition experiment (mean±SE,  $n=4$ )



consider how well certain plant species can retain the nutrients initially from wastewater, it is equally important to study the retention rates during decomposition (Tyler et al. 2012). However, the release of accumulated nutrients by emergent wetland macrophytes during decomposition has received much less attention compared to the ability of plants to sequester nutrients (Boyd and Hess 1970; Vymazal 2007). In this study, we found a difference in the TP concentrations between different time points and also found that the plant species differ in their responses (release of phosphorus) over time. This could be due to the difference in the decomposition rates between the treatments which could be due to the differences in the plant tissue structures and morphology. *D. acuminatum* has round hollow stems while *C. lurida* have triangular stems and *J. effusus* has round stout soft stems (USDA 2007).

In the 2008 experiment, the percent P released decreased as the experiment progressed for all treatments except *J. effusus*. However, in the 2009 experiment, this trend was reversed for all treatments. This complimentary trend could be due to the fact that the plants harvested in the 2009 experiment stayed longer in the mesocosms before they were harvested. This could have led to the development of secondary tissue structures or lignin deposits in the cell walls, thereby delaying decomposition rates in the 2009 experiment. Although *C. lurida* was the most efficient at retaining phosphorus

among monoculture treatments in 2008, *J. effusus* was the most efficient in 2009 (Table 2).

Moreover, compared to monoculture treatments, the mixed culture treatment released lower amounts of phosphorus in both 2008 and 2009. The effectiveness of the mixed culture treatment over monoculture treatments in retention of phosphorus may be due to more diverse plant structures holding phosphorus, which could have led to a difference in the surface area available to store phosphorus. There was also a year effect on the phosphorus release rates among all the treatments and this could be due to the difference in the phosphorus concentration in the plant tissues at the start of the experiment or due to differential decomposition. The allocation and storage of nutrients in the aboveground and belowground tissue varies with plant species (Kao et al. 2003). Differences in release rates between treatments may therefore be due to species differences in nutrient storage capacity. However, we did not measure final plant biomass, examine phosphorus storage in belowground tissues, or determine storage differences between stems and leaves. A difference in bacterial communities in the phyllosphere or on other aboveground tissues of the species studied may have resulted in the differences in phosphorus utilization that were identified among the treatments. Therefore, there is a need for further studies examining the link between tissue structural differences and nutrient storage and release, as well as the effect

of microbial community structure on phosphorus release during decomposition.

It is important to study nutrient immobilization by different plant species as they differ in their morphology and physiology. In conclusion, our results lead us to recommend the use of *J. effusus* and *C. lurida* (either grown as monoculture or mixed culture) as plants that could be used for the efficient removal of phosphorus in constructed wetlands due to the low phosphorus release rates during decomposition. However, since *D. acuminatum* released almost 20 % of the phosphorus initially retained in the plant tissue, this may not be a suitable plant for use in constructed wetlands designed for phosphorus retention. This information indicates that a focused selection of plants can improve the effectiveness of constructed wetlands. The results obtained from this research are useful for designing efficient constructed wetlands and also contribute information to the database on the phosphorus retention capacity of different plants. Thus, plant species used may play an important role in determining the phosphorus removal rate of constructed wetlands.

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