

## Chemistry and Ecology

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/gche20>

### Influence of varying nutrient and pesticide mixtures on abatement efficiency using a vegetated free water surface constructed wetland mesocosm

Richard E. Lizotte Jr<sup>a</sup>, Martin A. Locke<sup>a</sup> & Sam Testa III<sup>a</sup>

<sup>a</sup> USDA-ARS National Sedimentation Laboratory, Oxford, USA

Published online: 17 Jan 2014.

To cite this article: Richard E. Lizotte Jr, Martin A. Locke & Sam Testa III , Chemistry and Ecology (2014): Influence of varying nutrient and pesticide mixtures on abatement efficiency using a vegetated free water surface constructed wetland mesocosm, Chemistry and Ecology, DOI: [10.1080/02757540.2013.861823](https://doi.org/10.1080/02757540.2013.861823)

To link to this article: <http://dx.doi.org/10.1080/02757540.2013.861823>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

# Influence of varying nutrient and pesticide mixtures on abatement efficiency using a vegetated free water surface constructed wetland mesocosm

Richard E. Lizotte, Jr\*, Martin A. Locke and Sam Testa III

*USDA-ARS National Sedimentation Laboratory, Oxford, USA*

*(Received 25 February 2013; final version received 8 October 2013)*

The nutrient and pesticide abatement efficiency of varying mixtures was examined in a vegetated free water surface constructed wetland. Three different agricultural chemical pollutant mixture conditions were assessed: nutrients only (N and P); pesticides only (atrazine, *S*-metolachlor and permethrin); and a mixture of nutrients and pesticides. With nutrients only, 672 h nutrient mitigation of 77–91% total phosphorous (TP) and 74–98% total nitrogen (TN) was associated with distance from the injection point and rainfall, whereas with nutrient and pesticide mixtures, 672 h nutrient mitigation of 11–71% TP and 84–98% TN were associated with distance and time. With pesticides only, 672 h pesticide mitigation of 50–99% was associated with distance and time, whereas with nutrients and pesticide mixtures, 672 h pesticide mitigation of 48–99% was associated primarily with distance. Dissipation half-lives were 2–10 times greater for P and 1.5–5 times greater for N when pesticides were present. Pesticide dissipation half-lives showed no clear differences with or without nutrients. While vegetated free water surface constructed wetlands can be effective best management practice tools to trap and abate agricultural run-off during rainfall events, efficiencies can be affected by different types of complex pollutant mixtures and wetland design and implementation should accommodate varying efficiencies.

**Keywords:** best management practices; mitigation; nitrogen; phosphorus; atrazine; *S*-metolachlor; permethrin

## 1. Introduction

Mechanised modern agricultural techniques have allowed us to maximise row-crop productivity to feed and clothe an ever increasing global population, a need that will intensify as global demand for agricultural products continues to increase. [1] However, these techniques can come at a potentially high ecological cost by posing a significant increased risk to aquatic ecosystems and drinking water resources. [2,3] Such risks originate from the growing use of man-made fertiliser (N, P) and pesticides to control and maintain high agricultural row-crop production. Tilman et al. [4] estimated an increase of 2.4–2.7-fold in global fertiliser (N, P) and pesticide use by 2050, with a concomitant impact on downstream aquatic ecosystems via eutrophication and habitat destruction. As a result, there is a need for effective conservation management strategies to be implemented.

One strategy to mitigate downstream impacts due to global increased fertiliser and pesticide use has been to implement constructed wetlands to intercept run-off from intensively cultivated

\*Corresponding author. Email: [richard.lizotte@ars.usda.gov](mailto:richard.lizotte@ars.usda.gov)

landscapes. Use of free water surface constructed wetlands has increased globally in the last decade in countries such as China,[5–7] South Africa,[8,9] France,[10] Norway,[11] Spain,[12] and the USA.[13–17] Although constructed wetlands are recognised as reliable technology for wastewater treatment,[18,19] the technology has only recently begun to be widely implemented for mitigation of non-point source pollution such as agricultural run-off.[10,11,15,17,20] Previous research has addressed the use of vegetated free water surface constructed wetlands to remove nutrients of various types including N [6,12,17,21] and P.[11,15,17,21–23] In addition, other research has focused on the use of free water surface constructed wetlands to remove pesticides of various types including herbicides and insecticides either singly or in mixtures.[10,13,16,24] However, more complex mixtures of nutrients and pesticides in combination, as well as comparisons between nutrient only and pesticide only conditions have been less well studied.[8] Such mixtures can occur under various scenarios such as primarily nutrients in early spring, nutrients and pesticides in late spring to early summer, and primarily pesticides in mid- to late summer. Issues of the effectiveness of constructed wetlands in abating such complex agricultural pollutant mixtures have become increasingly important as constructed wetlands are more frequently used as conservation practices to mitigate agricultural contamination, a leading cause of increased eutrophication, ecological impacts from pesticides and overall degradation of habitat in rivers, lakes and streams.

The focus of this study was to assess the abatement efficiency of a prototypical vegetated free water surface constructed wetland receiving three different simulated agricultural pollutant mixture conditions: nutrients only (N and P); pesticides only (two herbicides and one insecticide); and a combination of both nutrients and pesticides. It is hypothesised that pollutant entrapment and dissipation from the water column will be unaffected by the presence or absence of nutrients or pesticides entering a vegetated free water surface constructed wetland.

## 2. Materials and methods

### 2.1. Constructed wetland mesocosm design

An experimental vegetated free water surface wetland mesocosm was constructed at the University of Mississippi Field Station (34°25'55"N, 89°24'00"W) in Lafayette County, Mississippi, USA. The wetland mesocosm was evenly divided and hydraulically isolated along its north–south axis with a 6 mil plastic liner placed 0.3 m below the sediment surface and standing 1.2 m above the sediment surface. The partition divided the wetland mesocosm into two sections (227 m<sup>2</sup> each) to the east and west. Both sections were naturally vegetated with emergent aquatic plants, predominantly common rush (*Juncus effusus*) and common reed (*Phragmites australis*) (Table 1) with similar species distribution and plant densities based upon Kruskal–Wallis one-way analysis of variance (ANOVA) on ranks (*J. effusus*,  $p = 0.434$ ; *P. australis*,  $p = 0.555$ ). The east section had a minimum and maximum water-holding capacity of 110,880 and 258,720 L, respectively, with a wetland slope of 9.2 mm m<sup>-1</sup> (0.92% grade). The west section had a minimum and maximum water-holding capacity of 99,330 and 247,170 L, respectively, with a wetland slope of 7.9 mm m<sup>-1</sup> (0.79% grade). Prior to the first treatment exposure, wetland hydrology was near mid capacity (east: ~ 180,000 L, west: ~ 170,000 L).

To simulate a variety of possible agricultural run-off event scenarios with differing contaminant inputs, we assessed three different mixture conditions: nutrients (N and P) only; pesticides (two herbicides and one insecticide) only; and a combination of both nutrients and pesticides. A fourth control condition (no amended contaminants) was included as a baseline comparison. To do this in a constructed wetland mesocosm with only two sections, the experiment was divided into two briefly temporally separate treatment exposures. During the first treatment exposure, conducted from 29 July 2009 to 26 August 2009, the east wetland section was amended over a 4-h period on

Table 1. Plant species and densities (ramets m<sup>-2</sup>) in east and west sections of a constructed wetland mesocosm used to mitigate varying nutrient and pesticide mixtures.

Plant species	Distance from inflow (m)			
	0	10	20	40
East section <sup>a</sup>				
<i>Juncus effusus</i>	286 (153)	85 (32)	223 (171)	171 (296)
<i>Phragmites australis</i>	24 (25)	27 (35)	37 (64)	12 (15)
<i>Lythrum salicaria</i>	4 (6)	0 (0)	0 (0)	0 (0)
<i>Osmunda cinnamomea</i>	5 (8)	0 (0)	0 (0)	0 (0)
<i>Acer rubrum</i>	2 (4)	0 (0)	0 (0)	0 (0)
<i>Leersia oryzoides</i>	0 (0)	5 (8)	0 (0)	17 (29)
Total	325 (163)	117 (30)	260 (172)	199 (274)
West section <sup>b</sup>				
<i>Juncus effusus</i>	113 (19)	124 (106)	40 (69)	159 (144)
<i>Phragmites australis</i>	44 (21)	36 (41)	51 (44)	0 (0)
<i>Acer rubrum</i>	1 (2)	0 (0)	0 (0)	0 (0)
<i>Leersia oryzoides</i>	0 (0)	20 (35)	0 (0)	0 (0)
Total	158 (13)	180 (102)	91 (26)	159 (144)

<sup>a</sup>Nutrients only and pesticides only treatments.

<sup>b</sup>No treatment (control) and pesticides + nutrients treatment.

29 July 2009 at a continuous flow rate of 103 L min<sup>-1</sup> using a submersible groundwater well pump located at the study site with an aqueous 20 L stock solution mixture of ammonium nitrate (total of 357 g N) and triple superphosphate (total of 409 g P) delivered via piston pump (Fluid Metering Inc., Syosset, NY, USA) at 85 L min<sup>-1</sup> to a 121 L mixing chamber simultaneously receiving groundwater; the west wetland section was amended over the same 4-h period at the same flow rate with only water (control). At the conclusion of the first treatment and prior to the start of the second treatment, the wetland was drained, flushed with fresh unamended water from the same source as the first treatment for 48 h, and allowed to refill to mid capacity (east: ~ 185,000 L, west: ~ 173,000 L) per the hydrologic conditions previous to the first treatment exposure. During the second treatment exposure, conducted from 2 to 30 September 2009, the east wetland section was amended over a 4-h period on 2 September 2009 at a continuous flow rate of 103 L min<sup>-1</sup> with an aqueous mixture of atrazine [total of 0.5 kg active ingredient (a.i.)], S-metolachlor (total of 0.5 kg a.i.) and permethrin (total of 0.133 g a.i.) as commercial field formulations Bicep II Magnum<sup>®</sup> (atrazine + S-metolachlor) and Hi-Yield 38<sup>®</sup> (permethrin). Concomitantly, the west wetland section was amended over the same 4-h period and same flow rate with an aqueous mixture of ammonium nitrate (total of 357 g N), super triple phosphate (total of 409 g P), atrazine (total of 0.5 kg a.i.), S-metolachlor (total of 0.5 kg a.i.) and permethrin (total of 0.133 g a.i.) as commercial field formulations Bicep II Magnum<sup>®</sup> (atrazine + S-metolachlor) and Hi-Yield 38<sup>®</sup> (permethrin). Both treatments were amended from 20 L mixture stock solutions delivered via piston pump (Fluid Metering Inc) at 85 L min<sup>-1</sup> to a 121 L mixing chamber simultaneously receiving groundwater as previously described. Simulated run-off volume was based upon what would be expected from a 2.5 mm run-off from a 0.9-ha agricultural field generating a total inflow volume of 24,777 L of run-off in each section. All target nutrient and pesticide loads amended to the constructed wetland were determined from previously reported concentrations of these agricultural pollutants in row-crop agricultural run-off.[25,26]

## 2.2. Nutrient and pesticide analysis

Water samples (1 L) were collected every 30 min within the first 4 h; every 4 h until 48 h; and on days 5, 7, 14, 21 and 28 post amendment at distances of 10, 20 and 40 m from the

injection point within both sections of the wetland mesocosm. Samples were collected during the study using an automated pumping sampler (ISCO Model 3700, Teledyne ISCO, Omaha, NE, USA) modified from Smith.[27] Sample containers were 1 L fluorine-coated polyethylene plastic bottles fitted with a Teflon-lined screw cap, to minimise pesticide sorption. Samples were placed on ice, transported to the USDA-ARS National Sedimentation Laboratory, and stored at 4°C (typically < 24 h) for target constituent analysis. In addition, bulk surface sediments (5 cm) were collected during pesticide treatments (pesticide only and nutrient + pesticide) at 10, 20 and 40 m from the injection point on days 1, 5, 12 and 22. Although a total of ~162 and 193 mm rainfall occurred during both monitoring periods (28 July to 26 August 2009 and 1 to 30 September 2009), no wetland inflow or outflow occurred from either section during the study following any storm event. Thus the wetlands functioned as retention systems.

Analyses for P and N were conducted according to methods described by Eaton et al. [28] In brief, total  $\text{PO}_4^-$ -P (TP) involved persulfate digestion and analysis with an ascorbic acid colourimetric method; for soluble reactive  $\text{PO}_4^-$ -P (SRP), samples were filtered through a 0.45  $\mu\text{m}$  cellulose nitrate filter and analysed using the ascorbic acid colourimetric method;  $\text{NH}_4^+$ -N, filtered samples were analysed using a phenate method;  $\text{NO}_3^-$ -N, filtered samples were analysed using a cadmium reduction colourimetric method;  $\text{NO}_2^-$ -N, filtered samples were analysed using a potassium permanganate colourimetric method; and total N (TN) [ $\text{NO}_3^-$ -N +  $\text{NO}_2^-$ -N + total Kjeldahl N (TKN)] involved block digestion in sulfuric acid and flow injection analysis. Colourimetric analyses were performed using a ThermoSpectronic Genesys™ 10 ultraviolet (UV) spectrophotometer (Spectronic Instruments, Inc., Rochester, NY, USA). Method detection limits were: 0.01  $\text{mg L}^{-1}$ , TP, SRP,  $\text{NO}_3^-$ -N and  $\text{NO}_2^-$ -N; and 0.02  $\text{mg L}^{-1}$ ,  $\text{NH}_4^+$ -N and TKN.

Aqueous and sediment pesticide analyses were conducted according to Smith et al. [29] and Bennett et al. [30] In brief, pesticides were extracted using pesticide-grade ethyl acetate, dried over anhydrous  $\text{Na}_2\text{SO}_4$  and concentrated to near dryness by rotary evaporation. The extract was then subjected to silica gel column chromatography cleanup, and concentration to 1 mL volume under high purity dry nitrogen for GC analysis. Pesticide recoveries and extraction efficiencies, based on fortified samples, were  $\geq 90\%$  for targeted pesticides.[29,30] Two Agilent HP model 6890 gas chromatographs (Agilent Technologies, Inc., Waldbronn, Germany) equipped with dual Agilent HP 7683 ALS autoinjectors, dual split-splitless inlets, dual capillary columns, an Agilent HP Kayak XA Chemstation, and the autoinjector set at 1.0  $\mu\text{L}$  injection volume fast mode were used for all targeted pesticide analyses, according to Smith et al. [29,30] The first of the two Agilent HP 6890 GCs was equipped with two micro-electron capture detectors ( $\mu\text{ECDs}$ ) and the second 6890 with one  $\mu\text{ECD}$ , one N-P detector (NPD) and an Agilent HP 5973 mass selective detector (MSD). The primary analytical column was an Agilent HP 5MS capillary column, 30 m  $\times$  0.25 mm i.d.  $\times$  0.25  $\mu\text{m}$  film thickness. Column oven temperatures were: initial at 85°C for 1 min; ramp at 25°C to 190°C; hold at 190°C for 25 min; ramp at 25°C to 230°C and hold for 30 min. The carrier gas used was ultra-high purity (UHP) helium at 28  $\text{cm s}^{-1}$  and inlet temperature at 250°C. The  $\mu\text{ECD}$  temperature was 325°C with a constant make up gas flow of 40  $\text{mL min}^{-1}$  UHP nitrogen. Method detection limits were: 0.1  $\mu\text{g L}^{-1}$ , aqueous atrazine, *S*-metolachlor, *cis*-permethrin and *trans*-permethrin; 1  $\mu\text{g L}^{-1}$ , sediment atrazine, *S*-metolachlor, *cis*-permethrin and *trans*-permethrin.

In addition, water quality parameters of temperature, pH, conductivity and dissolved oxygen were measured *in situ* in each section of the constructed wetland mesocosm from 28 July 2009 to 26 August 2009 and again from 1 to 30 September 2009 at 10 and 40 m using four calibrated Yellow Springs Instruments (YSI) 6290 multi-parameter water quality monitoring systems (Yellow Springs, OH, USA). Water quality monitoring systems were recalibrated weekly to ensure proper working conditions and data integrity. Measurements were collected hourly during treatment days 1–6 (week 1), 7–13 (week 2), 14–20 (week 3) and 21–28 (week 4).

### 2.3. Data analysis

Weekly means and standard deviations ( $\pm$ SD) were determined for all four *in situ* parameters and overall means  $\pm$ SD were determined for all nutrients and pesticides under control section conditions. Forward stepwise linear regressions were performed according to Berenson et al. [31] for each of the three different mixture conditions to assess multiple independent variables that could influence observed changes in concentrations of amended agricultural chemicals. Standardised dimensionless regression coefficients and coefficients of determination were computed from amended nutrients and pesticides as dependent variables and values of sampling time (time), distance from inflow (distance), *J. effusus* plant density (*Juncus*), *P. australis* plant density (*Phragmites*) and total daily precipitation (rain) as independent variables. Independent variables were added or removed using *F*-to-enter of 4.0 and *F*-to-remove of 3.9. Aqueous exponential dissipation models for each nutrient species and pesticide at 10, 20 and 40 m were constructed, when possible, using non-linear exponential decay rate regression models modified from Reddy et al. [32] for each of the three different mixture conditions. The resulting equations were used to determine aqueous dissipation half-lives ( $T_{1/2}$ ) within the wetland. All statistical analyses were conducted using SigmaPlot® v.12.0 (Systat Software Inc., Chicago, IL, USA) statistical software.[33] Statistical significance level for all models was set at 5% ( $p \leq 0.05$ ) for all analyses.[34]

## 3. Results and discussion

### 3.1. Wetland *in situ* water quality and control conditions

Monitored *in situ* water quality of the vegetated free water surface constructed wetland mesocosm was typical of shallow freshwater wetland habitats in the south-eastern USA (Table 2) with hypoxic conditions (dissolved oxygen < 2.0 mg L) [35,36] and slightly acidic water.[37,38] Water temperatures were indicative of climatic conditions of the study site (north Mississippi) during summer, with means ranging from 22.4 to 27.3°C.[36,39] No outflow occurred from the wetland at any time during the study periods (28 July to 26 August 2009 and 1 to 30 September 2009) despite ~ 162 mm total precipitation occurring from 28 July to 26 August and 188 mm total precipitation occurring from 1 to 30 September. Prior to both the first and second treatment periods, east and west section baseline pretreatment (27 July 2009 and 31 August 2009) nutrient and pesticide concentrations indicated low levels of N and P and very low to below detection limit concentrations of atrazine, *S*-metolachlor and permethrin (Supplemental Table 1 available online at <http://dx.doi.org/10.1080/02757540.2013.861823>). In addition, during the first study period (29 July to 26 August), control section baseline nutrient and pesticide concentrations again indicated low levels of N and P, and very low to below detection limit levels of atrazine, *S*-metolachlor and permethrin. The control section was used to assess the degree of hydraulic isolation between divided wetland sections. Results indicated good hydraulic isolation with minimal diffusion ( $\leq 6\%$  of amended P and N) of sections containing higher gradient agricultural pollutant concentrations leaching into sections containing low to no concentrations only observed at 10 m (Table 3).

### 3.2. Wetland nutrients

Wetland P concentrations during nutrients only treatment peaked within 8 h at all sites, ranging from 2.83 mg TP L<sup>-1</sup> at 10 m to 9.42 mg TPL<sup>-1</sup> at 40 m and 2.02 mg SRPL<sup>-1</sup> at 10 m to 6.87 mg SRPL<sup>-1</sup> at 40 m, indicating P loading at the downstream portion of the wetland (Figure 1). Aqueous TP dissipation ranged from 49 to 79% within 48 h and 77 to 91% by 672 h. Aqueous



Table 2. Mean (SD) weekly *in situ* water quality measurements within east and west sections of the constructed wetland mesocosm from 28 July 2009 to 26 August 2009 (nutrients only and control) and from 1 to 30 September 2009 (pesticides only and nutrients + pesticides).

Week	Temperature (°C)		Conductivity ( $\mu\text{S cm}^{-1}$ )		Dissolved oxygen ( $\text{mg L}^{-1}$ )		pH	
	10 m	40 m	10 m	40 m	10 m	40 m	10 m	40 m
Nutrients only (east section)								
1	25.5 (1.9)	24.9 (1.7)	65.9 (20.2)	216.1 (186.0)	1.7 (2.0)	3.1 (2.0)	5.8 (0.2)	5.4 (0.3)
2	27.3 (1.2)	26.9 (0.5)	84.4 (9.3)	93.1 (12.0)	0.4 (0.4)	1.2 (1.5)	6.2 (0.1)	6.0 (0.1)
3	26.9 (2.1)	25.6 (0.6)	69.7 (6.1)	93.0 (15.3)	0.5 (0.2)	0.5 (0.1)	6.0 (0.1)	6.1 (0.1)
4	23.9 (2.1)	23.6 (1.5)	52.6 (7.2)	65.3 (12.3)	0.6 (0.4)	0.4 (0.2)	5.9 (0.1)	5.9 (0.1)
Control (west section)								
1	25.2 (1.8)	25.0 (1.3)	49.5 (20.0)	66.7 (24.3)	1.0 (1.7)	0.3 (0.4)	5.9 (0.2)	6.0 (0.3)
2	27.0 (1.2)	26.6 (0.7)	92.5 (15.1)	108.1 (18.1)	0.3 (0.1)	0.3 (0.0)	6.2 (0.1)	6.3 (0.1)
3	25.8 (1.5)	25.5 (0.9)	71.5 (6.4)	95.0 (9.0)	0.4 (0.1)	0.3 (0.0)	6.0 (0.1)	6.1 (0.1)
4	24.0 (2.5)	23.5 (1.7)	58.4 (4.9)	73.4 (5.4)	0.7 (0.7)	0.4 (0.2)	5.9 (0.1)	6.0 (0.1)
Pesticides only (east section)								
1	22.7 (1.9)	22.5 (1.0)	37.9 (5.3)	54.8 (3.0)	0.8 (1.4)	0.4 (0.3)	5.8 (0.1)	5.8 (0.1)
2	23.9 (0.9)	23.9 (0.4)	43.1 (5.8)	56.1 (7.4)	0.5 (0.3)	0.4 (0.2)	5.9 (0.1)	5.8 (0.1)
3	23.3 (0.5)	23.4 (0.5)	59.3 (20.3)	66.7 (22.4)	0.5 (0.2)	0.4 (0.3)	6.1 (0.2)	6.1 (0.2)
4	22.5 (1.6)	22.5 (1.5)	39.5 (15.8)	46.8 (19.9)	0.5 (0.5)	0.5 (0.5)	5.9 (0.2)	5.9 (0.2)
Nutrients + pesticides (west section)								
1	23.0 (2.4)	22.8 (1.4)	274.9 (158.4)	67.0 (3.9)	1.2 (0.9)	0.4 (0.2)	5.9 (0.3)	6.0 (0.0)
2	24.0 (1.3)	23.9 (0.7)	120.0 (29.4)	74.0 (6.0)	0.6 (0.5)	0.3 (0.2)	6.5 (0.1)	6.1 (0.1)
3	23.4 (0.6)	23.3 (0.5)	84.7 (32.9)	81.5 (22.3)	0.4 (0.4)	0.3 (0.5)	6.4 (0.2)	6.5 (0.3)
4	22.5 (1.7)	22.4 (1.6)	55.2 (32.1)	66.6 (27.0)	0.4 (0.4)	0.4 (0.6)	6.1 (0.3)	6.3 (0.3)

Table 3. Mean (SD) measured nutrient ( $\text{mg L}^{-1}$ ) and pesticide ( $\mu\text{g L}^{-1}$ ) concentrations in the control (west section) of the constructed wetland mesocosm from 28 July 2009 to 26 August 2009. Adjacent east section received nutrients only.

Nutrient or pesticide	10 m	20 m	40 m
TP	0.47 (0.30)	0.37 (0.17)	0.29 (0.17)
SRP	0.21 (0.27)	0.07 (0.06)	0.05 (0.04)
$\text{NH}_4^+$ -N	0.03 (0.04)	0.01 (0.02)	0.01 (0.02)
$\text{NO}_3^-$ -N	0.68 (0.77)	0.08 (0.09)	0.04 (0.04)
$\text{NO}_2^-$ -N	0.01 (0.01)	<0.01 <sup>a</sup>	<0.01 <sup>a</sup>
TN	2.10 (1.09)	1.61 (1.44)	1.33 (0.46)
Atrazine	0.5 (0.7)	<0.1 <sup>b</sup>	<0.1 <sup>b</sup>
S-Metolachlor	< 0.1 <sup>b</sup>	<0.1 <sup>b</sup>	<0.1 <sup>b</sup>
Cis-Permethrin	0.2 (0.5)	<0.1 <sup>b</sup>	<0.1 <sup>b</sup>
Trans-Permethrin	<0.1 <sup>b</sup>	< 0.1 <sup>b</sup>	<0.1 <sup>b</sup>

<sup>a</sup>Below detection limit of 0.01  $\text{mg L}^{-1}$ .

<sup>b</sup>Below detection limit of 0.1  $\mu\text{g L}^{-1}$ .

SRP dissipation ranged from 45 to 77% within 48 h and 98 to 99% by 672 h. Forward stepwise regression models showed that P was influenced by plant density, precipitation and time (Table 4). Aqueous dissipation half-lives of P ranged from 13 to 34 h (Table 5). By contrast, during nutrients + pesticides treatment, aqueous P concentrations peaked at 3–44 h post amendment, ranging from 1.28  $\text{mg TP L}^{-1}$  at 40 m to 8.47  $\text{mg TP L}^{-1}$  at 10 m and 0.38  $\text{mg SRP L}^{-1}$  at 40 m to 7.24  $\text{mg SRP L}^{-1}$  at 10 m, indicating P loading in the upstream portion of the wetland (Figure 1). Aqueous TP dissipation during this treatment ranged from 13–34% within 48 h and 11–71% by 672 h. Aqueous SRP dissipation with this treatment ranged from 25 to 68% within 48 h and 79 to 99% by 672 h. Forward stepwise regression models indicated that TP during this treatment was

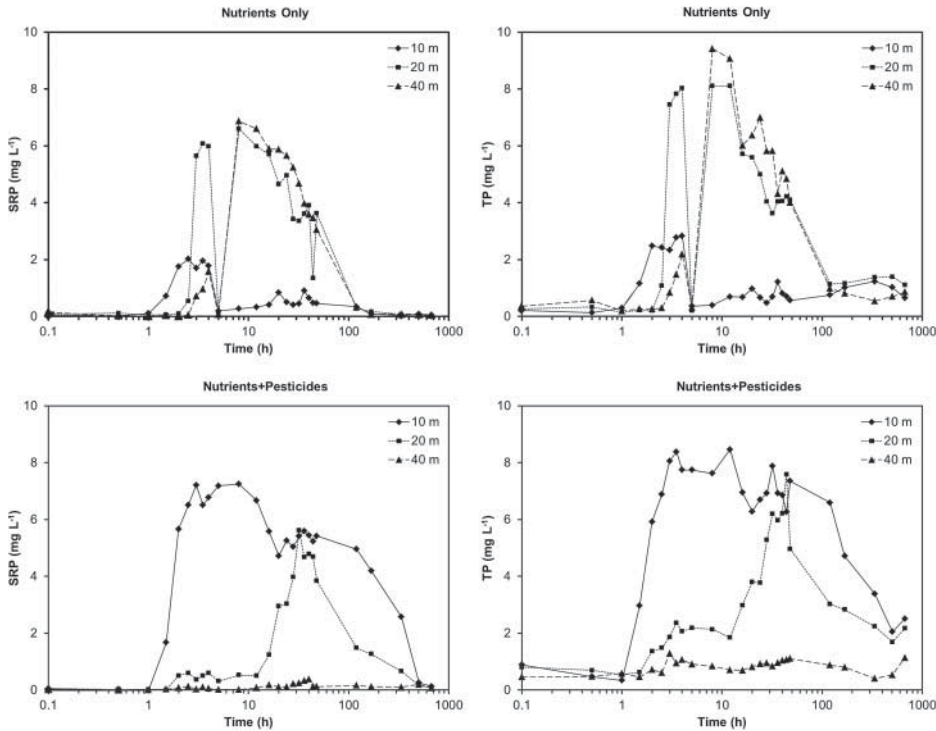


Figure 1. Phosphorus aqueous concentrations, total phosphorus (TP) and soluble reactive phosphorus (SRP), under nutrients only or nutrients + pesticides conditions in a free water surface constructed wetland mesocosm.

influenced by distance, time and rain, whereas SRP was influenced by distance, plant density and time (Table 4). Dissipation half-lives of P during nutrients + pesticides treatment were 2–10 times greater than nutrient only treatment ranging from 67 to 300 h (Table 5). Our dissipation results for P were comparable with other free water surface constructed wetlands receiving agricultural run-off during summer, showing aqueous SRP and TP dissipation ranging from < 30% [22] and 47% [23] to ~ 80%. [17] Observed associations of SRP and TP with *Juncus* sp. plant density during the summer nutrients only treatment are indicative of biological uptake of P by emergent aquatic macrophytes, [15,22,23] whereas the lack of association with plant density during the nutrients + pesticides treatment would indicate potential inhibition of biological uptake of P via growth inhibition in the presence of herbicides atrazine and *S*-metolachlor. [40,41] This, in turn, would affect the rate at which P dissipates from the water column and increase P half-life in the presence of herbicides at concentrations < 200  $\mu\text{g}$  atrazine  $\text{L}^{-1}$  and < 300  $\mu\text{g}$  *S*-metolachlor  $\text{L}^{-1}$ .

Aqueous N concentrations in the wetland during nutrients only treatment peaked at various times across the sites. In general, concentrations peaked within 3 h at 10 m and within 16–44 h at 40 m. Peak dissolved inorganic N (DIN) concentrations were 0.82–0.92  $\text{mg}$   $\text{NH}_4^+$ -N  $\text{L}^{-1}$ , 3.42 – 43.83  $\text{mg}$   $\text{NO}_3^-$ -N  $\text{L}^{-1}$  and 0.06–1.69  $\text{mg}$   $\text{NO}_2^-$ -N  $\text{L}^{-1}$ , whereas TN was in the range 7.58–116.91  $\text{mg}$   $\text{L}^{-1}$  (Figure 2). Similar to P, the greatest N loading during nutrients only treatment occurred at downstream wetland sites (Figure 2). DIN dissipation values at 48 h were in the range 4–8, 38–80 and 33–90%, and dissipation at 672 h were 100, 99–100 and 100% for  $\text{NH}_4^+$ -N,  $\text{NO}_3^-$ -N and  $\text{NO}_2^-$ -N, respectively. Dissipation of TN ranged from 27 to 62% at 48 h and 74 to 98% at 672 h. Forward stepwise regression analysis indicated that nutrients only treatment DIN and TN were influenced by rain, plant density and distance (Table 4). Aqueous dissipation half-lives for DIN during nutrient only treatment ranged from 146 to 187 h for  $\text{NH}_4^+$ -N and 22 to 58 h



Table 4. Forward stepwise linear regressions ( $n = 78$ ) with standardised dimensionless regression coefficients and coefficients of determination computed using amended agrichemicals as dependent variables and values of sampling time (Time), distance from inflow (Distance), *J. effusus* plant density (*Juncus*), *P. australis* plant density (*Phragmites*) and total daily precipitation (Rain) as independent variables.

Agrichemical	Time	Distance	<i>Juncus</i>	<i>Phragmites</i>	Rain	$R^2$	$p$
Nutrients only (east section)							
TP <sup>a</sup>	0.260 <sup>a</sup>		0.291 <sup>a</sup>		<b>0.292</b>	0.256	<0.001
SRP	-0.226		<b>0.369</b>		0.336	0.332	<0.001
NH <sub>4</sub> <sup>+</sup> -N	0.201 <sup>a</sup>		<b>0.347</b>		0.344	0.296	<0.001
NO <sub>3</sub> <sup>-</sup> -N			<b>0.425<sup>a</sup></b>		0.389	0.332	<0.001
NO <sub>2</sub> <sup>-</sup> -N		0.332			<b>0.394</b>	0.266	<0.001
TN		0.270	0.259		<b>0.452</b>	0.408	<0.001
Nutrients + pesticides (west section)							
TP <sup>a</sup>	0.378 <sup>a</sup>	<b>-0.723<sup>a</sup></b>			0.231	0.645	<0.001
SRP	-0.21	<b>-1.015</b>		-0.430		0.551	<0.001
NH <sub>4</sub> <sup>+</sup> -N	-0.192	<b>-0.624<sup>a</sup></b>				0.426	<0.001
NO <sub>3</sub> <sup>-</sup> -N	-0.239	<b>-0.884<sup>a</sup></b>		-0.398		0.426	<0.001
NO <sub>2</sub> <sup>-</sup> -N		<b>-0.454</b>				0.206	<0.001
TN <sup>a</sup>	-0.358	<b>-0.645</b>				0.545	<0.001
Pesticides only (east section)							
Atrazine	0.205 <sup>a</sup>	<b>-0.527<sup>a</sup></b>				0.320	<0.001
S-Metolachlor <sup>a</sup>	0.393 <sup>a</sup>	<b>-0.662<sup>a</sup></b>				0.593	<0.001
Cis-Permethrin	-0.260 <sup>a</sup>		<b>-0.433<sup>a</sup></b>			0.254	<0.001
Trans-Permethrin	-0.261 <sup>a</sup>		<b>-0.425<sup>a</sup></b>			0.249	<0.001
Nutrients + pesticides (west section)							
Atrazine	0.296 <sup>a</sup>	<b>-0.489<sup>a</sup></b>				0.327	<0.001
S-Metolachlor	-0.189	<b>-0.690</b>	0.334			0.411	<0.001
Cis-Permethrin	-0.216 <sup>a</sup>	<b>-0.361<sup>a</sup></b>				0.177	<0.001
Trans-Permethrin		<b>-0.645</b>		-0.434		0.150	0.001

<sup>a</sup>Log<sub>10</sub> transformed variable. Bold font indicates the largest standardised coefficient in each regression and blank cells indicate variables were dropped from stepwise regression due to a lack of significance.

for NO<sub>3</sub><sup>-</sup>-N and NO<sub>2</sub><sup>-</sup>-N, whereas TN ranged from 60–70 h (Table 5). In comparison, during nutrients + pesticides treatment, wetland aqueous N concentrations peaked within 8 h at 10 m and within 40–44 h at 40 m. Peak DIN concentrations during this treatment were 0.03–0.57 mg NH<sub>4</sub><sup>+</sup>-N L<sup>-1</sup>, 0.80–33.76 mg NO<sub>3</sub><sup>-</sup>-N L<sup>-1</sup> and 0.02–0.29 mg NO<sub>2</sub><sup>-</sup>-N L<sup>-1</sup>, whereas TN ranged from 6.31 to 79.53 mg L<sup>-1</sup> (Figure 2). Greatest N loading during nutrients + pesticides treatment occurred at the 10 m site, again similar to patterns of P loading during this treatment. DIN dissipation values at 48 h during this treatment were 16–67, 29–64 and 27–55%, and dissipation values at 672 h were 100, 88–100 and 100% for NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N and NO<sub>2</sub><sup>-</sup>-N, respectively. Dissipation of TN ranged from 34 to 59% at 48 h and 84 to 98% at 672 h. During nutrients + pesticides treatment, forward stepwise regression models revealed NH<sub>4</sub><sup>+</sup>-N was influenced by distance and time, NO<sub>3</sub><sup>-</sup>-N was influenced by distance, plant density and time, NO<sub>2</sub><sup>-</sup>-N was influenced by distance only, and TN was influenced by distance and time (Table 4). During nutrients + pesticides treatment, dissipation half-lives of aqueous N were 1.5–5 times greater than in the nutrients only treatment. DIN nutrients + pesticides treatment half-lives were 146–230 h for NH<sub>4</sub><sup>+</sup>-N, 32–65 h for NO<sub>3</sub><sup>-</sup>-N and NO<sub>2</sub><sup>-</sup>-N, and TN half-lives ranged from 44 to 408 h (Table 5).

Nitrogen dissipation from a wetland water column can occur via complex processes of several biogeochemical pathways including nitrification, denitrification and organism uptake (animal, plant, algae, bacteria). [6,18,41] Dissipation of wetland water column DIN in this study was comparable with other studies assessing free water surface constructed wetland vegetated with emergent aquatic macrophytes. [6,14] Díaz et al. [14] showed 85–99% dissipation of NO<sub>3</sub><sup>-</sup>-N from the water column during the growing season (April–September) in wetlands having 50–60%

Table 5. Aqueous exponential dissipation model coefficients and calculated aqueous dissipation half-lives for nutrients in east and west sections of a constructed wetland mesocosm.

Distance	TP	SRP	NH <sub>4</sub> <sup>+</sup> -N	NO <sub>3</sub> <sup>-</sup> -N	NO <sub>2</sub> <sup>-</sup> -N	TN
Nutrients only (east section)						
10 m						
Coefficient ( <i>b</i> )	0.0013	0.0523*	0.0022	0.0311*	0.0025	0.0013
Half-life (h) <i>T</i> <sub>1/2</sub>	NC <sup>a</sup>	13	NC	22	NC	NC
20 m						
Coefficient ( <i>b</i> )	0.0203*	0.0210*	0.0047*	0.0197*	0.0053	0.0115*
Half-life (h) <i>T</i> <sub>1/2</sub>	34	33	146	35	NC	60
40 m						
Coefficient ( <i>b</i> )	0.0196*	0.0202*	0.0037*	0.0120*	0.0128*	0.0099*
Half-life (h) <i>T</i> <sub>1/2</sub>	35	34	187	58	54	70
Nutrients + pesticides (west section)						
10 m						
Coefficient ( <i>b</i> )	0.0023*	0.0035*	0.0030*	0.0218*	0.0053*	0.0158*
Half-life (h) <i>T</i> <sub>1/2</sub>	300	197	230	32	130	44
20 m						
Coefficient ( <i>b</i> )	0.0032*	0.0103*	0.0047*	0.0126*	0.0080*	0.0083*
Half-life (h) <i>T</i> <sub>1/2</sub>	216	67	146	55	86	84
40 m						
Coefficient ( <i>b</i> )	0.0005	0.0011	0.0040*	0.0105*	0.0090*	0.0017*
Half-life (h) <i>T</i> <sub>1/2</sub>	NC	NC	173	65	77	408

\*Statistically significant model coefficient of determination ( $R^2$ ) < 0.05.

<sup>a</sup>NC, not calculated due to insignificant model coefficient of determination ( $R^2$ ).

vegetation coverage of *Typha latifolia* or *Echinochloa crus-galli* compared with only 22% dissipation with only 5% vegetation. Lu et al. [6] observed a broader range of NO<sub>3</sub><sup>-</sup>-N dissipation reporting an average of 60.9 ± 132.7% during summer (June–September) in a wetland vegetated with *Phragmites australis* and *Zizania caduciflora*. In addition, Lu et al. [6] in the same study, measured dissipation of NH<sub>4</sub><sup>+</sup>-N during summer reporting an average of 63.6 ± 49.5%, which is comparable with the results of the current study. Dissipation of TN is considered a valuable metric because it incorporates both inorganic and organic forms of N and is most consistently associated with the eutrophication of aquatic systems. Previous studies of TN dissipation in free water surface constructed wetlands receiving agricultural run-off during the growing season (April–September) range from as low as 20% to as much as 90%, and varied greatly [6,12,14,17] with greater dissipation percentages occurring with greater coverage of emergent aquatic macrophytes.[14] The results of the current study had comparable TN dissipation (74–98%) and showed that TN dissipation was associated with emergent aquatic plant density (*Juncus* sp.) during nutrients only treatment. By contrast, TN dissipation during nutrients + pesticides treatment was not associated with emergent aquatic plant density and might indicate the potential inhibition of plant uptake of N via growth inhibition in the presence of the herbicides atrazine and *S*-metolachlor,[41,42] which would account for the slightly longer half-lives (1.5–5-fold) during this treatment. Lytle and Lytle [43] showed *J. effusus* growth to be significantly inhibited by atrazine concentrations as low as 96 µg L<sup>-1</sup>, specifically new shoot development. Similarly, Moore and Locke [44] observed that mixtures of atrazine and *S*-metolachlor significantly reduce radicle development in *Typha latifolia* seedlings at concentrations as low as 31 µg L<sup>-1</sup> of the mixture, noting that *S*-metolachlor is a long-chain fatty acid inhibitor.[44] If plant growth and possibly plant metabolism slow in the presence of both atrazine and *S*-metolachlor, N metabolism will also be inhibited and concomitantly reduce N uptake rates. This would, in turn, affect the rate at which N dissipates from the water column and increase agricultural run-off storage time needed for a wetland to process and remove N before exiting into a river or stream.

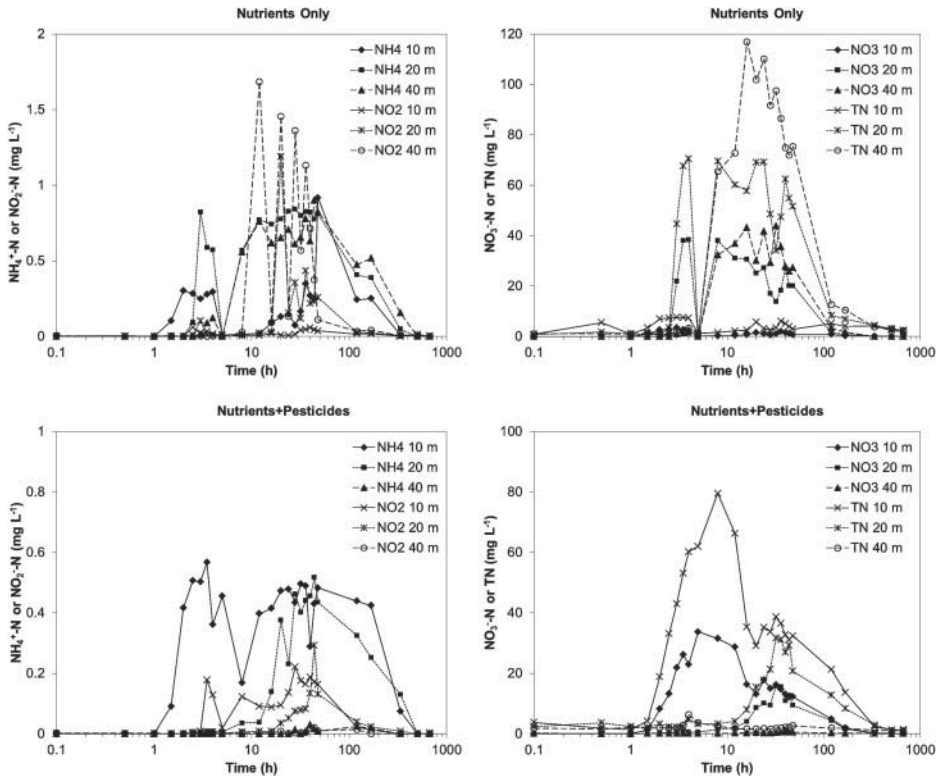


Figure 2. Nitrogen aqueous concentrations,  $\text{NH}_4^+$ -N,  $\text{NO}_2^-$ -N,  $\text{NO}_3^-$ -N and total nitrogen (TN), under nutrients only or nutrients + pesticides conditions in a free water surface constructed wetland mesocosm.

### 3.3. Wetland pesticides

Patterns of wetland herbicide concentrations during pesticides only treatment showed that peak concentrations occurred within 8–16 h at 10 m ranging from  $196.9 \mu\text{g atrazine L}^{-1}$  to  $287.5 \mu\text{g S-metolachlor L}^{-1}$  and within 168 h at 40 m ranging from  $8.3 \mu\text{g S-metolachlor L}^{-1}$  to  $14.9 \mu\text{g atrazine L}^{-1}$ , indicating loading in the first 10 m of the wetland (Figure 3). Herbicide dissipation during pesticides only treatment at 48 h ranged from 19 to 49% for atrazine and 56 to 58% for *S-metolachlor*, whereas at 672 h dissipation ranged from 50 to 97% for atrazine and 67 to 99% for *S-metolachlor*. Surface sediment herbicide concentrations peaked within 24–120 h at 10 m ranging from  $16 \mu\text{g S-metolachlor kg}^{-1}$  to  $21 \mu\text{g atrazine kg}^{-1}$  and within 120–288 h at 40 m with concentrations of  $20 \mu\text{g S-metolachlor kg}^{-1}$  to  $36 \mu\text{g atrazine kg}^{-1}$  (Figure 4). Forward stepwise regression analysis revealed that atrazine and *S-metolachlor* were influenced by distance and time variables (Table 4). Dissipation half-lives of herbicides during pesticides only treatment were 154–204 and 62–265 h for atrazine and *S-metolachlor*, respectively (Table 6). During nutrients + pesticides treatment, patterns of herbicide distribution similar to those in pesticides only treatment were observed. Peak herbicide concentrations occurred within 3–12 h at 10 m, ranging from  $191.8 \mu\text{g atrazine L}^{-1}$  to  $315.5 \mu\text{g S-metolachlor L}^{-1}$ , and again within 168 h at 40 m ranging from  $8.5 \mu\text{g S-metolachlor L}^{-1}$  to  $15.8 \mu\text{g atrazine L}^{-1}$ , indicating loading in the first 10 m of the wetland (Figure 3). Sediment herbicide concentrations during this treatment peaked within 24–288 h at 10 m ranging from  $37 \mu\text{g S-metolachlor kg}^{-1}$  to  $38 \mu\text{g atrazine kg}^{-1}$  and within 24 h at 40 m with concentrations of  $9 \mu\text{g kg}^{-1}$  for both herbicides (Figure 4). Nutrients + pesticides

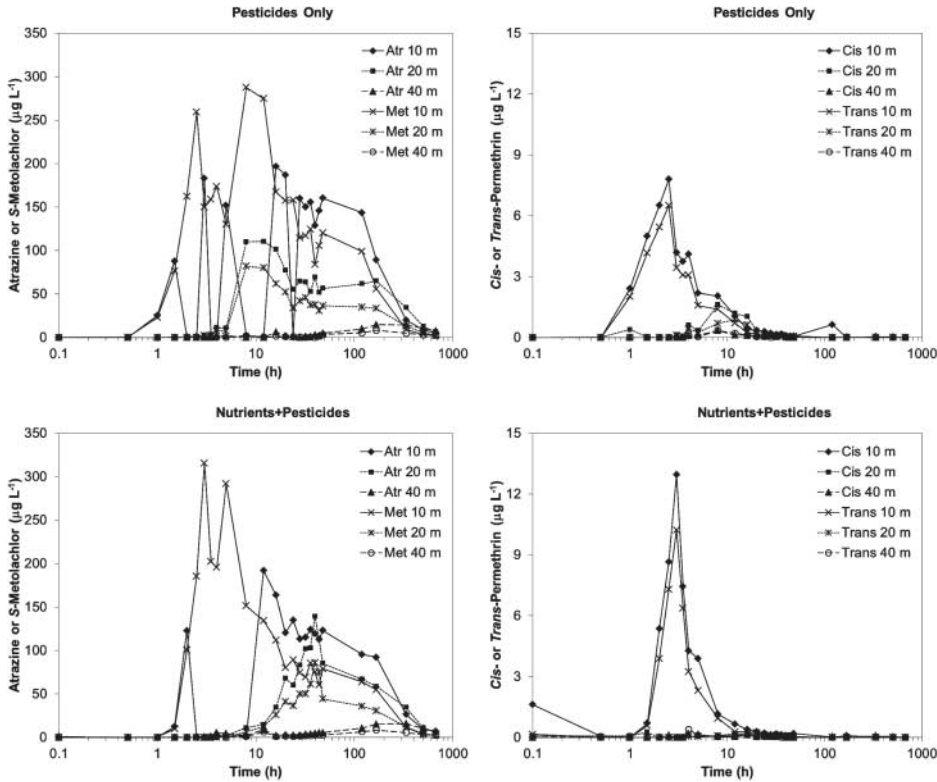


Figure 3. Herbicides atrazine and *S*-metolachlor and insecticide isomers *cis*-permethrin and *trans*-permethrin aqueous concentrations under pesticides only and nutrients + pesticides conditions in a free water surface constructed wetland mesocosm.

treatment forward stepwise regressions showed atrazine was influenced by distance and time variables, whereas *S*-metolachlor was influenced by distance, plant density and time (Table 4). Dissipation half-lives of herbicide during nutrients + pesticides treatment were 150 and 16–276 h for atrazine and *S*-metolachlor, respectively (Table 6). Herbicide water column dissipation in the current study was comparable with other studies in similar wetland systems.[45–49] In previous studies, water column atrazine dissipation in free water surface constructed wetlands has been reported to range from as low as 34–37% after 35 days [45] to as high as 70–89% after 20 days,[49] whereas the current study observed a range of atrazine dissipation of 50–97%. Dissipation of metolachlor from wetland water column has been reported to range from 48 to 83% [46] and is similar to the results of this study of 67–99%. Observed herbicide concentrations within selected sediment samples indicate a significant fraction of both herbicides sorbed to wetland bed sediments at concentrations comparable with those reported by Belden et al. [50] in southern playa wetland sediments receiving agricultural run-off. Wide ranges in reported half-lives of metolachlor (408–1464 h) were concentration dependent, with lower concentrations having shorter half-lives.[45] This explains the wide range of observed half-lives of *S*-metolachlor in the present study (16–276 h). In this study, dissipation did not appear to be affected by the absence or presence of nutrients with herbicides.

Insecticide permethrin concentrations in wetland water during pesticides only treatment had peak concentrations occurring within 2.5–12 h at all sites, with concentrations of 6.5–7.8 µg L<sup>-1</sup> at 10 m, 0.9–1.6 µg L<sup>-1</sup> at 20 m and 0.3 µg L<sup>-1</sup> at 40 m for *cis*- and *trans*-isomers (Figure 3). Permethrin dissipation during pesticides only treatment was rapid, with 98–100% dissipation

Table 6. Aqueous exponential dissipation model coefficients and calculated aqueous dissipation half-lives for pesticides in east and west sections of a constructed wetland mesocosm.

Distance	Atrazine	S-Metolachlor	<i>cis</i> -Permethrin	<i>trans</i> -Permethrin
Pesticides only (east section)				
10 m				
Coefficient ( <i>b</i> )	0.0045*	0.0109*	0.3567*	0.4943*
Half-life (h) $T_{1/2}$	154	62	2	1.4
20 m				
Coefficient ( <i>b</i> )	0.0033*	0.0073*	0.1007*	0.0847*
Half-life (h) $T_{1/2}$	209	94	6.9	8.1
40 m				
Coefficient ( <i>b</i> )	0.0012	0.0026*	0.0878*	0.1056*
Half-life (h) $T_{1/2}$	NC <sup>a</sup>	265	7.9	6.5
Nutrients + Pesticides (West Section)				
10 m				
Coefficient ( <i>b</i> )	0.0046*	0.0432*	0.8458*	0.9337*
Half-life (h) $T_{1/2}$	150	16	0.8	0.7
20 m				
Coefficient ( <i>b</i> )	0.0046*	0.0058*	0.0575*	0.0917*
Half-life (h) $T_{1/2}$	150	120	12	7.5
40 m				
Coefficient ( <i>b</i> )	0.0014	0.0025*	0.0455*	1.3114*
Half-life (h) $T_{1/2}$	NC	276	15	0.5

\*Statistically significant model coefficient of determination ( $R^2$ )  $p < 0.05$ .

<sup>a</sup>NC, not calculated due to insignificant model coefficient of determination ( $R^2$ ).

within 48 h. Variables influencing permethrin during this treatment were plant density and time (Table 4). Permethrin dissipation half-lives during this treatment ranged from 1.4 to 7.9 h (Table 6). In comparison, permethrin concentrations during nutrients + pesticides treatment peaked at 3 h at 10 m, but at 16–20 h at 20–40 m. Measured permethrin concentrations during this treatment were comparable with pesticides only treatment with 10.2–13.0  $\mu\text{g L}^{-1}$  at 10 m, 0.1–0.2  $\mu\text{g L}^{-1}$  at 20 m and 0.1  $\mu\text{g L}^{-1}$  at 40 m for *cis*- and *trans*-isomers (Figure 3). Surface sediment samples analysed for permethrin showed that nearly all samples were below detection for this pesticide. Only a single sample within the nutrients + pesticides treatment at 10 m at 288 h measured 1  $\mu\text{g permethrin kg}^{-1}$ , indicating that minimal amounts of this pesticide reached wetland surface sediments (Figure 4). Forward stepwise regression analysis showed that permethrin during nutrients + pesticides treatment was influenced by distance, plant density and time (Table 4). Permethrin dissipation half-lives during this treatment ranged widely from 0.8 to 15 h for the *cis* isomer and from 0.7 to 7.5 h for the *trans*-isomer (Table 6). Comparisons of water column permethrin dissipation in this study with other previously reported studies within similar vegetated wetland systems [13,48,51] showed similarity in abatement efficiency. Budd et al. [13] observed 90–94% dissipation of permethrin after 5 h in a free surface water wetland vegetated primarily with *Paspalum distichum*, *Polygonum lapathifolium* and *Echinochloa crus-galli*, and receiving agricultural run-off after rainfall events from May to August. Moore et al. [51] observed dissipation of permethrin after 12 h in free surface water wetland mesocosms vegetated with emergent aquatic macrophytes *Typha latifolia* (67–78%) and *Leersia oryzoides* (71–81%). The lack of observed permethrin in wetland surface sediment in the current study is in contrast to other wetland studies showing significant sorption of permethrin to sediment [51,52] and indicated that permethrin within the study wetland likely sorbed to numerous other plant surfaces, algae, dissolved organic carbon and other particulates suspended in the water column prior to reaching bed sediments. Although the present study reports a 48 h permethrin dissipation of 98–100%, the short half-life reported (0.8–15 h) would make our results comparable with both reported studies. As

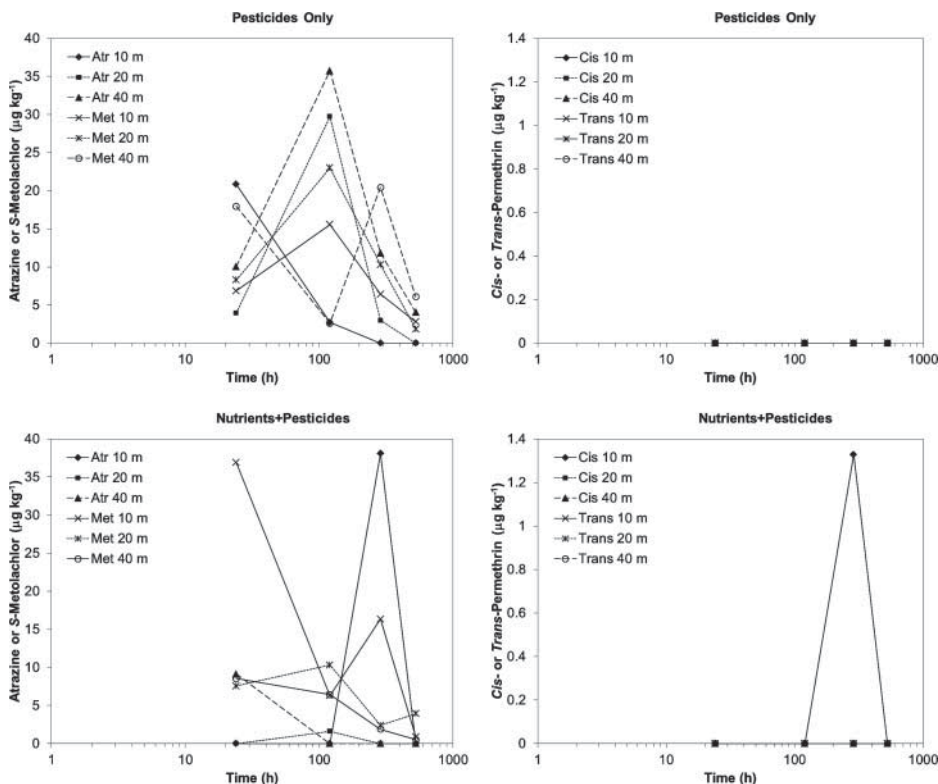


Figure 4. Herbicides atrazine and *S*-metolachlor and insecticide isomers *cis*-permethrin and *trans*-permethrin surface sediment (top 5 cm) concentrations under pesticides only and nutrients + pesticides conditions in a free water surface constructed wetland mesocosm.

with herbicides, permethrin dissipation did not appear to be affected by the absence or presence of nutrients.

#### 4. Conclusions

Non-point source agricultural run-off is, by nature, a mixture of various pollutants that includes nutrients and pesticides.[13,14] Because of this, the current study is increasingly important in understanding the abatement efficiency and increased use of free surface water constructed wetlands as an agricultural best management practice in mitigating water quality impacts in rivers, lakes and streams. Emergent aquatic vegetation density plays an important role in the abatement of both nutrients and pesticides. However, nutrient abatement could be inhibited in the presence of herbicides. Further study is needed to better understand the interactions of agricultural pollutants on the efficacy of vegetated free water surface constructed wetlands in abating agricultural run-off.

#### Acknowledgements

We thank the numerous technicians and support personnel who provided assistance with logistics, sample collection, and analysis, especially John Massey, Lisa Brooks and Renée Russell. We also thank the several anonymous reviewers who provided helpful comments and improved the manuscript. Mention of equipment, computer programs, or a chemical does not constitute an endorsement for use by the US Department of Agriculture nor does it imply pesticide registration under FIFRA as amended. The US Department of Agriculture is an equal opportunity employer.



## References

- [1] Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci USA*. 2011;108:20260–20264.
- [2] Khan S, Hanjra MA. Footprints of water and energy inputs in food production—Global perspectives. *Food Policy*. 2009;34:130–140.
- [3] Reichenberger S, Bach M, Skitschak A, Hans-Georg F. Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; a review. *Sci Total Environ*. 2007;384:1–35.
- [4] Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff S, Swackhamer D. Forecasting agriculturally driven global environmental change. *Science*. 2001;292:281–284.
- [5] Liu D, Ge Y, Chang J, Peng C, Gu B, Chan GYS, Wu X. Constructed wetlands in China: recent developments and future challenges. *Front Ecol Environ*. 2009;7:261–268.
- [6] Lu S, Zhang P, Jin X, Xiang C, Gui M, Zhang J, Li F. Nitrogen removal from agricultural runoff by full-scale constructed wetland in China. *Hydrobiologia*. 2009;621:115–126.
- [7] Zhang D, Gersberg RM, Keat TS. Constructed wetlands in China. *Ecol Eng*. 2009;35:1367–1378.
- [8] Schulz R, Peall SK. Effectiveness of a constructed wetland for retention of nonpoint-source pesticide pollution in the Lourens River Catchment, South Africa. *Environ Sci Technol*. 2001;35:422–426.
- [9] Schulz R, Hahn C, Bennett ER, Dabrowski JM, Thiere G, Peall SK. Fate and effects of azinphos-methyl in a flow-through wetland in South Africa. *Environ Sci Technol*. 2003;37:2139–2144.
- [10] Maillard E, Payraudeau S, Faivre E, Grégoire C, Gangloff S, Imfeld G. Removal of pesticide mixtures in a stormwater wetland collecting runoff from a vineyard catchment. *Sci Total Environ*. 2011;409:2317–2324.
- [11] Braskerud BC. Factors affecting phosphorus retention in small constructed wetlands treating agricultural non-point source pollution. *Ecol Eng*. 2002;19:41–61.
- [12] García-Lledó A, Ruiz-Rueda O, Vilar-Sanz A, Sala L, Bañeras L. Nitrogen removal efficiencies in a free water surface constructed wetland in relation to plant coverage. *Ecol Eng*. 2011;37:678–684.
- [13] Budd R, O'Geen A, Goh KS, Bondarenko S, Gan J. Efficacy of constructed wetlands in pesticide removal from tailwaters in the Central Valley, California. *Environ Sci Technol*. 2009;43:2925–2930.
- [14] Díaz FJ, O'Geen AT, Dahlgren RA. Agricultural pollutant removal by constructed wetlands: implications for water management and design. *Agr Water Manage*. 2012;104:171–183.
- [15] Kadlec RH. Free surface water wetlands for phosphorus removal: the position of the everglades nutrient removal project. *Ecol Eng*. 2006;27:361–379.
- [16] Moore MT, Cooper CM, Smith S Jr, Cullum RF, Knight SS, Locke MA, Bennett ER. Mitigation of two pyrethroid insecticides in a Mississippi Delta constructed wetland. *Environ Pollut*. 2009;157:250–256.
- [17] O'Geen AT, Maynard JJ, Dahlgren RA. Efficacy of constructed wetlands to mitigate non-point source pollution from irrigation tailwaters in the San Joaquin Valley, California, USA. *Water Sci Technol*. 2007;55:55–61.
- [18] Vymazal J. Removal of nutrients in various types of constructed wetlands. *Sci Total Environ*. 2007;380:48–65.
- [19] Vymazal J. Constructed wetlands for wastewater treatment: five decades of experience. *Environ Sci Technol*. 2011;45:61–69.
- [20] Millhollon EP, Rodrigue PB, Rabb JL, Martin DF, Anderson RA, Dans DR. Designing a constructed wetland for the detention of agricultural runoff for water quality improvement. *J Environ Qual*. 2009;38:2458–2467.
- [21] Kadlec RH, Roy SB, Munson RK, Charlton S, Brownlie W. Water quality performance of treatment wetlands in the Imperial Valley, California. *Ecol Eng*. 2010;36:1093–1107.
- [22] Gu B, Dreschel T. Effects of plant community and phosphorus loading rate on constructed wetland performance in Florida, USA. *Wetlands*. 2008;28:81–91.
- [23] Lu SY, Wu FC, Lu YF, Xiang CS, Zhang PY, Jin CX. Phosphorus removal from agricultural runoff by constructed wetland. *Ecol Eng*. 2009b;35:402–409.
- [24] Gregoire C, Elsaesser D, Huguenot D, Lange J, Lebeau T, Merli A, Mose R, Passeur E, Payraudeau S, Schütz T, Schulz R, Tapia-Padilla G, Tournebize J, Trevisan M, Wanko A. Mitigation of agricultural nonpoint-source pesticide pollution in artificial wetland ecosystems. *Environ Chem Lett*. 2009;7:205–231.
- [25] Moorman TB, Hatfield JL, Kanwar RS. Herbicide and nitrate in surface and groundwater: results from the Iowa management systems evaluation area. In: Nett MT, Locke MA, Pennington DA, editors. *Water quality assessments in the Mississippi Delta*. Washington, DC: ACS Symposium Series 877; 2004. p. 235–250.
- [26] Southwick LM, Grigg BC, Fouss JL, Kornecki TS. Atrazine and metolachlor in surface runoff under typical rainfall conditions in southern Louisiana. *J Agric Food Chem*. 2003;51:5355–5361.
- [27] Smith S Jr. Pesticide retention by a programmable automatic water/suspended-sediment sampler. *Bull Environ Contam Toxicol*. 1993;50:1–7.
- [28] Eaton AD, Clesceri LS, Rice EW, Greenberg AE. *Standard methods for the examination of water and wastewater*. 21st ed. Washington, DC: APHA AWWA WEF; 2005.
- [29] Smith S, Cooper CM, Lizotte RE, Locke MA, Knight SS. Pesticides in lake water in the Beasley Lake watershed, 1998–2005. *Int J Ecol Environ Sci*. 2007;33:61–71.
- [30] Bennett ER, Moore MT, Cooper CM, Smith S. Method for the simultaneous extraction and analysis of two current use pesticides, atrazine and lambda-cyhalothrin, in sediment and aquatic plants. *Bull Environ Contam Toxicol*. 2000;64:825–833.
- [31] Berenson ML, Levine DM, Goldstein M. *Intermediate statistical methods and applications: A computer package approach*. New Jersey: Prentice-Hall; 1983.

- [32] Reddy KR, Tucker JC, Debusk F. The role of egeria in removing nitrogen and phosphorus from nutrient enriched waters. *J Aquat Plant Manage.* 1987;25:14–19.
- [33] Systat Software, Inc. (SYSTAT). SigmaPlot v.12.0 user's guide: Part 1. Illinois: Systat Software, Inc.; 2011.
- [34] Glantz SA. Primer of biostatistics. 4th ed. New York: McGraw-Hill; 1997.
- [35] Mitsch WJ, Gosselink JG. Wetlands. 4th ed. New Jersey: John Wiley & Sons, Inc.; 2007.
- [36] Kröger R, Lizotte RE Jr, Shields FD Jr, Osborne E. Inundation influences on bioavailability of phosphorus in managed wetland sediments in agricultural landscapes. *J Environ Qual.* 2012;41:604–614.
- [37] Bouldin JL, Farris JL, Moore MT, Smith S Jr, Cooper CM. Assessment of diazinon toxicity in sediment and water of constructed wetlands using deployed *Corbicula fluminea* and laboratory testing. *Arch Environ Contam Toxicol.* 2007;53:174–182.
- [38] Miranda LE. Depth as an organizer of fish assemblages in floodplain lakes. *Aquat Sci.* 2011;73:211–221.
- [39] Lizotte RE Jr, Shields FD Jr, Knight SS, Bryant CT. Efficiency of a modified backwater wetland in trapping a pesticide mixture. *Ecohydrology.* 2009;2:287–293.
- [40] Lytle JS, Lytle TF. Atrazine effects on estuarine macrophytes *Spartina alterniflora* and *Juncus roemerianus*. *Environ Toxicol Chem.* 1998;17:1972–1978.
- [41] Lytle JS, Lytle TF. Use of plants for toxicity assessment of estuarine ecosystems. *Environ Toxicol Chem.* 2001;20:68–83.
- [42] Reddy KR, DeLaune RD. Biogeochemistry of wetlands: Science and applications. New York: CRC Press; 2008.
- [43] Lytle TF, Lytle JS. Growth inhibition as indicator of stress because of atrazine following multiple toxicant exposure of the freshwater macrophyte, *Juncus effusus* L. *Environ Toxicol Chem.* 2005;24:1198–1203.
- [44] Moore MT, Locke MA. Phytotoxicity of atrazine, S-metolachlor, and permethrin to *Typha latifolia* (Linnaeus) germination and seedling growth. *Bull Environ Contam Toxicol.* 2012;89:292–295.
- [45] Moore MT, Rodgers JH Jr, Cooper CM, Smith S Jr. Constructed wetlands for mitigation of atrazine-associated agricultural runoff. *Environ Pollut.* 2000;110:393–399.
- [46] Moore MT, Rodgers JH Jr, Smith S Jr, Cooper CM. Mitigation of metolachlor-associated agricultural runoff using constructed wetlands in Mississippi, USA. *Agric Ecosyst Environ.* 2001;84:169–176.
- [47] Passeport E, Tournebize J, Chaumont C, Guenne A, Coquet Y. Pesticide contamination interception strategy and removal efficiency in forest buffer and artificial wetland in a tile-drained agricultural watershed. *Chemosphere.* 2013;91:1289–1296.
- [48] Moore MT, Tyler HL, Locke MA. Aqueous pesticide mitigation efficiency of *Typha latifolia* (L.), *Leersia oryzoides* (L.) Sw., and *Sparganium americanum* Nutt. *Chemosphere.* 2013;92:1307–1313.
- [49] Locke MA, Weaver MA, Zablotowicz RM, Steinriede RW, Bryson CT, Cullum RF. Constructed wetlands as a component of the agricultural landscape: mitigation of herbicides in simulated runoff from upland drainage areas. *Chemosphere.* 2011;83:1532–1538.
- [50] Belden JA, Hanson BR, McMurry ST, Smith LM, Haukos DA. Assessment of the effects of farming and conservation programs on pesticide deposition in high plains wetlands. *Environ Sci Technol.* 2012;46:3424–3432.
- [51] Moore MT, Kröger R, Cooper CM, Smith S Jr. Ability of four emergent macrophytes to remediate permethrin in mesocosm experiments. *Arch Environ Contam Toxicol.* 2009;57:282–288.
- [52] Lizotte RE Jr, Shields FD Jr, Testa S III. Effects of a simulated agricultural runoff event on sediment toxicity in a managed backwater wetland. *Water Air Soil Pollut.* 2012;223:5375–5389.