Journal of Environmental Management 222 (2018) 148–154

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Indicators of nutrient removal efficiency for riverine wetlands in agricultural landscapes of Argentine Pampas

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ARTICLE INFO

Keywords:
Riverine wetlands
Nutrient removal
Macrophytes
Ecosystem services
Argentine Pampas
Wetland functional groups

ABSTRACT

Main objectives of this study were (a) to assess wetlands contribution to regulation of surface water quality of riverine wetlands in agricultural landscapes through their nutrient removal efficiency (RE), (b) to understand how RE of wetlands is related to hydrological, morphological, chemical and biological attributes, and (c) to identify RE indicators suitable for remote RE assessment. Macrophytes composition, hydrological, chemical, and morphological properties were estimated for 14 riverine wetlands of the Argentinean Pampas, and related to empirically estimated removal-exportation levels of phosphorus (dissolved and total) and nitrogen (inorganic and total). Nutrient inputs and outputs were assessed in four opportunities, two under baseline and two after storm events. A discriminant function based on remotely assessed wetland attributes was able to discriminate three wetland groups according to their contrasting mean RE for total phosphorus and total nitrogen. Descriptors of wetland size (area, length, perimeter) and vegetation (cover of the tall emergent macrophytes) showed the main weights and hence the main value as indicators for conservation and/or management of wetlands according to their nutrient removal capacities.

1. Introduction

One of the main causes of downstream degradation of freshwater ecosystems within agricultural basins is the transport of nutrients excess in the runoff from non-point sources (Carpenter et al., 1998; de Jonge et al., 2002). Excess of phosphorus (P) and nitrogen (N) that are transported to water courses reduce water quality, produce anoxia and favor algae proliferation, with the consequent biodiversity loss and the impairment of water sinks to satisfy different social demands (irrigation, commercial fishing, drinking water, recreation).

Wetlands can play an important role in water quality maintenance within the basins through the removal of nutrients (Fisher and Acreman, 2004; Jordan et al., 2011; Mitsch and Gosselink, 2000; Verhoeven et al., 2006) thus contributing to reduction of eutrophication in adjacent water bodies. Wetlands contribution to water quality in agricultural landscapes was recently estimated by Hansen et al. (2018) in the Minnesota River basin, who conclude that at moderate–high streamflow conditions, wetland conservation or restoration is several times more efficient per unit area at reducing riverine nitrate concentration than land-based nitrogen mitigation strategies (i.e. crops replacement by pastures).

Due to the degradation of wetland ecosystems resulting from changes in the composition of land use of their catchments (Papastergiadou et al., 2008) general models and reliable indicators that prioritize the conservation of wetlands according to their contribution to water quality are urgently needed (Zedler, 2000). Several studies have focused their efforts on identifying wetlands that are critical for maintaining the water quality of basins through the removal of the nutrients that flow through them (e.g. Cohen and Brown, 2007; Moreno-Mateos et al., 2010; Tomer et al., 2003). Most studies addressing wetlands functionality as filters have focused on linking nutrient removal to a limited number of hydrological, chemical and biological attributes, generally for constructed wetlands (Fink and Mitsch, 2004; Kadlec, 2003; Reddy et al., 2013), but adoption of simple indicators of nutrient removal pose serious limitations to the assessment of ecosystem services and proper decision-making in different contexts.

Nutrient removal in the wetlands is influenced by several factors include such as the hydraulic residence time (HRT), flow, depth, soil type, water chemistry, coastline development, pH, and temperature (Ambus and Christensen, 1993; Hansson et al., 2005, 2005; Kadlec, 2003; Kadlec and Knight, 1996; Machefert et al., 2002; Mander et al., 1991; Mitsch and Gosselink, 2000; Richardson, 1985; Uusi-Kämppä

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https://doi.org/10.1016/j.jenvman.2018.05.070
Received 24 December 2017; Received in revised form 18 April 2018; Accepted 21 May 2018

Table 1
P-values for different sources of variation of nutrient concentrations and removal efficiencies, according to a series of repeated measures ANOVA independently applied for each nutrient, according to sampling condition (base flow vs. post-rain flow), sampling place (inlet vs. outlet) and sampling time (first vs. second sample). Bold numbers indicate significant p-values ($p \leq 0,05$).

Sources of variation	p-values for Nutrients concentrations				p-values for Removal efficiencies			
	DP[a]	TP	DIN	TN	DP	TP	DIN	TN
Condition (C)	0.089	0.284	**0.001**	0.286	0.609	0.865	0.354	0.307
Place (P)	0.278	0.428	0.403	0.302	–	–	–	–
C * P	0.953	0.682	0.298	0.787	–	–	–	–
Time (T)	**0.001**	**0.001**	**0.001**	**0.001**	0.116	0.306	0.721	0.359
C * T	0.129	**0.003**	**0.001**	**0.001**	–	–	–	–
P * T	0.433	0.663	0.427	0.704	0.881	0.424	0.656	0.396
C * P *T	0.884	0.429	0.404	0.611	–	–	–	–

[a] DP: dissolved phosphorus, TP: total phosphorus, DIN: dissolved inorganic phosphorus, TN: total nitrogen.

et al., 1996; Zurayk et al., 1997).

Vegetation can also indirectly influence N removal through nitrification and denitrification processes by affecting oxygen concentration, particularly in the rhizosphere (Greenway, 2007; Tanner, 2001) and increasing the supply of potentially limiting organic carbon and nitrate to denitrifying bacteria (Brix, 1997; Reddy et al., 1989). Vegetation presence within wetlands may also promote nutrient removal by decreasing flow speed and increasing HRT (Greenway, 2007) and reducing sediments resuspension (Braskerud, 2001).

In order to contribute to the development of reliable indicators for nutrients removal efficiency (RE) by wetlands, main objectives of this article were (a) to assess wetlands contribution to regulation of surface water quality of riverine wetlands in agricultural landscapes through their nutrient removal efficiency (RE), (b) to understand how RE of wetlands is related to hydrological, morphological, chemical and biological attributes, and (c) to identify RE indicators suitable for remote RE assessment. Field work was performed in the Argentinean southeastern Pampa, where economic pressures and low regulations are leading to the replacement of perennial pastures by annual crops and strong increments of fertilizers consume (10 times from 1990 to 2010, CIAFA, 2017), at the same time that wetlands are being impaired by eutrophication and channelization (Booman et al., 2012; Brandolin et al., 2013; Quirós et al., 2006).

2. Materials and methods

2.1. Study area

Mar Chiquita watershed was selected as representative of the main land uses in the Pampas region (León, 1991), covering a surface of 1,000,000 ha within the Buenos Aires province of Argentina (34°55′17″S, 57°57′17″W). This watershed is characterized by the presence of lowland streams, floodplains, permanent and intermittent shallow lakes and the Mar Chiquita coastal lagoon that is a sink of many streams. The watershed gives place to multiple land uses, including extensive annual crops (soybean, maize, sunflower, wheat, and potato), cattle livestock and mixed agriculture-livestock systems. The climate is temperate and humid, and the average annual rainfall of about 900 mm is distributed throughout per the year.

With the aid of Google Earth images and terrain observations, we searched for wetlands that meet satisfying three conditions: a) they were located within or nearby the study area, b) they have identifiable single water entries and exits which feed and drain the main water body, and c) both, water entries and water exits were relatively accessible after severe storms. A total of 14 riparian wetlands were chosen for this study, 12 wetlands located within Vivoratá (VI, V2, V3), Tajamar (T1, T2, T3), Junco (J1, J2, J3) and Dulce (D1, D2, D3) streams that correspond to Mar Chiquita basin and the other two wetlands are within Malacara (M1, M2) stream, close to the basin. In riverine wetlands that have superficial and unidirectional flow, it is possible to quantify the nutrient removal by considering the balance concentrations between tributaries and effluents, without affecting the natural flow. The selection of sampling wetlands was made in order to cover the widest variability of sizes (from 0.1 ha to 70.3 ha), macrophytes cover and adjacent land uses (agriculture, livestock or mixed).

2.2. Water sampling

Water samples were carried out four times in each selected wetland, two sampling dates under base flow conditions, and two sampling dates during peak flows. In November 2008 and 2009, under base flow conditions (at least 1 week without rain events) water samples were taken manually using 1 L opaque plastic bottles which were placed at the entry and exit of selected wetlands. Additionally, in December 2009 and June 2010, water samples were obtained during peak flows due to rain events (post-rain samples). Both the 2008–2009 drought and human activities (due to drainage and channeling works) ruined several samples for different wetlands and sampling dates, so 44 input/output from 56 potential samples were obtained and processed.

In December 2009 and June 2010, water samples were obtained during peak flows due to rain events (post-rain flow samples). Water samples were collected in the field within 24 h of a storm event of 63 mm on 19 December 2009 and 39 mm on 14 June 2010. Post-rain-sampling method was based on 120 mL siphon samplers described by (Graczyk et al., 2000), which consisted of two tubes with different lengths inserted into the bottle cap. Samplers were placed at the entrance and exit of wetlands tied to iron rods firmly stacked into the sediment. Height of the siphon was regulated so that the sample was taken at the time when the peak flow occurred. The peak flow of each point was previously calculated, using the rational method (Cronshey, 1986), for an event of 20 mm that produces expected elevations of the water table between 10 and 18 cm depending on properties of the drainage area to each point. The simulation was made with 20 mm-rain events, and despite they cause runoff in the area, are within the minimum rain events that can result in rise peaks detectable by the siphons.

The siphons remained in the field for approximately a month in 2009 and a week in 2010 (until the rain occurred) and were periodically inspected for checking their functionality. All water samples taken after rainfalls were placed in a cooler in the field, and transported to the laboratory for analysis.

Parallel to each sampling the following variables were surveyed: turbidity, total dissolved solids (TDS), salinity, conductivity, pH and temperature of the wetland water, water depth, wetland perimeter (P), maximum width (MW), cross-sectional area, maximum total length (MTL) and area, as well as land use type (annual crops or perennial pastures at each wetland margin) in adjacent fields.

Wetlands contour was mapped only once in October 2009 using a GPS and walking along the limits, considering as such the transition from dry to saturated soil and/or the presence of hydrophytic

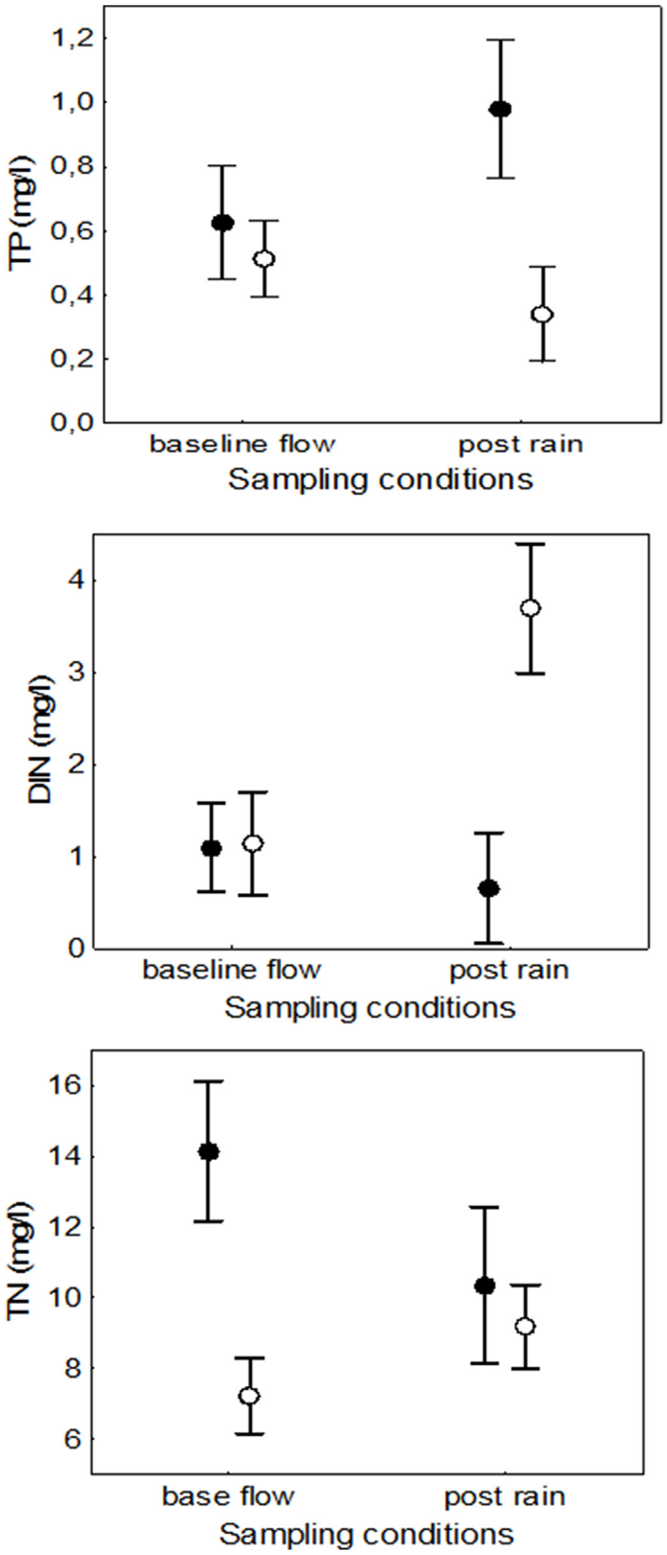

Fig. 1. Mean nutrient concentrations for different sampling conditions (base line and post rain flows) and sampling dates (●: date = 1; ○: date = 2). TP: total phosphorous, DIN: dissolved inorganic nitrogen, TN: total nitrogen. Vertical bars indicate 0.95 confidence intervals.

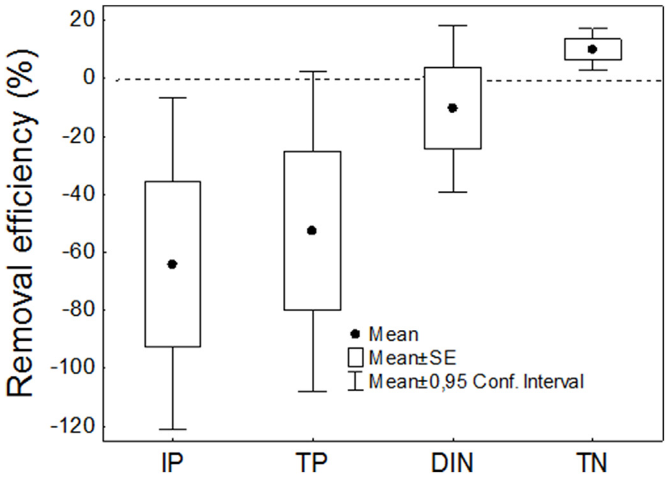

Fig. 2. Boxplots showing the overall removal efficiencies of dissolved phosphorus (DP), total phosphorus (TP), dissolved inorganic nitrogen (DIN) and total nitrogen (TN) by wetlands. Middle point in each box indicates the mean of observed distribution, box length represent two SE, and whiskers represent the 95% confidence interval.

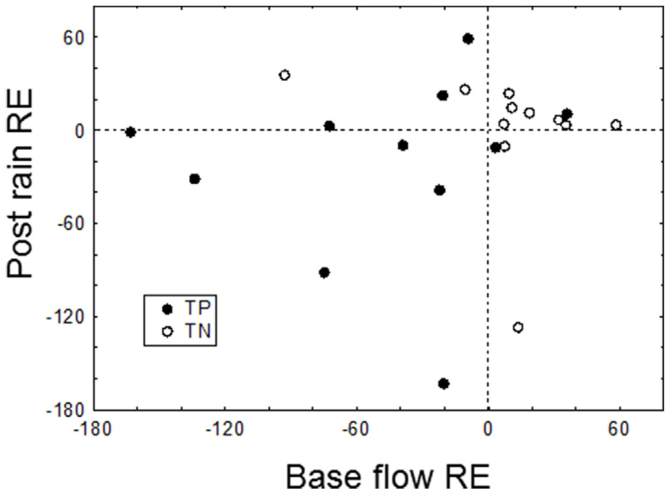

Fig. 3. Variation of removal efficiency (RE) of total phosphorus (TP) and total nitrogen (TN) by wetlands in post rain flow conditions along with their RE in base flow conditions.

vegetation. Wetland maps were used to calculate wetland area, ellipticity (E) (length: width ratio) and shoreline development (D) (perimeter:area).

Water turbidity was measured by using a portable turbidimeter (Aquafluor handheld fluorometer, *Turner designs*). The values of pH, temperature, conductivity, salinity and TDS were obtained by using a portable multiparameter sensor (LaMotte®).

2.3. *Determination of flows and nutrient removal in the wetlands*

The HRT was estimated in the base flow conditions using the following equation:

$$HRT = V/Q \tag{1}$$

where V is the volume of the wetland measured during base flow conditions, obtained by multiplying the area and the average depth, and Q is the average also measured in base flow conditions.

Average water speed was determined at the input, middle and output of the wetlands, using repeated addition (n = 5) of a dye settled in the middle of the channel stream, in a preset starting point, and recording the time for the colored spot to transit a known distance (1 m) on a white table attached to the bottom of the channel stream. We designed this method due to the difficulties found when trying to use floaters (due to the obstruction caused by the vegetation) and flow-

Table 2
Results of multiple linear (ML) and non-parametric multiple regressions (DistLM) of removal efficiency (RE) of dissolved phosphorus (DP), total phosphorus (TP), dissolved inorganic nitrogen (DIN), and total nitrogen (TN) variation in relation to different wetland attributes (independent variables). Multiple linear regression analysis includes the slope of the adjusted regression (Beta). Corrected information criteria of Akaike (AICc) was used to select the most significant group of variables when non-parametric multiple regressions had to be performed. Only independent variables with $p \leq 0.05$ are shown.

Dependent variable	Sampling conditions and date	Analysis method	Independent variables	Beta	AICc	R^2 (acumul.)	p
RE of DP	Base line 11-11-2008	ML	I. Wetland area	−0.85	–	0.60	< 0.01
			II. % floating macrophytes	−0.43	–	0.78	
	Base line 26-11-2009	DistLM	I. % total macrophytes cover	–	−57.86	0.35	0.11
	Post-rain 21-12-2009	No significant variables					
	Post-rain 16-06-2010	ML	I. Mean depth	−0.89	–	0.77	< 0.01
RE of TP	Base line 11-11-2008	DistLM	I. Adjacent use	–	141.4	0.24	0.09
	Base line 26-11-2009	No significant variables					
	Post-rain 21-12-2009	ML.	I. E	0.70	–	0.43	0.03
	Post-rain 16-06-2010	DistLM	I. pH	–	86.54	0.50	0.024
RE of DIN	Base line 11-11-2008	DistLM	I. % floating macrophytes	–	194.23	0.8	0.08
	Base line 26-11-2009	No significant variables					
	Post-rain 21-12-2009	ML	I. Turbidity	−0.91	–	0.78	–
	Post-rain 16-06-2010	ML.	I. Adjacent use	−0.90	–	0.46	< 0.01
			II. Mean flow	−0.55	–	0.69	
			III. % floating macrophytes	−0.38	–	0.82	
			IV. % trees	−0.39	–	0.90	
RE of TN	Base line 11-11-2008	ML.	I. % floating macrophytes	−0.9	–	0.79	< 0.01
	Base line 26-11-2009	ML	I. Adjacent use	1	–	0.48	< 0.01
			II. Turbidity	0.75	–	0.82	
			III. HRT	0.34	–	0.93	
	Post-rain 21-12-2009	No significant variables					
	Post-rain 16-06-2010	DistLM	I. HRT	–	58.68	0.51	< 0.01
			II. E	–	50.46	0.86	
			II. % trees	–	83.40	0.76	

E:ellipticity, HRT: hydraulic residence time.

Table 3
Removal efficiency (RE) of total phosphorus (TP) and total nitrogen (TN) of wetland groups based on cluster analysis. ANOVA tests and post hoc multiple comparisons are showed.

Wetland group	RE of TP mean ± SD	RE of TN mean ± SD
1	$8.82^{b} \pm 9.30$	$5.45^{a} \pm 3.77$
2	$25.69^{b} \pm 9.30$	$20.12^{b} \pm 3.77$
3	$-48.97^{a} \pm 8.32$	$9.16^{ab} \pm 3.37$
ANOVA	F (2, 10) = 20.32 P = 0.0003	F (2, 10) = 4.13 P = 0.049

Different letters within each column indicate significant differences ($p \leq 0.05$) in RE of TP and TN among wetland groups.

Table 4
First canonical discriminant functions (CDF1) of wetland groups defined by removal efficiency of nutrients and Spearman correlation coefficients between CDF1 and wetland attributes.

Attributes	First canonical discriminant function	First canonical discriminant function (standardized)	Spearman correlation coefficient
Constant	154.54	–	–
Area	0.01	2863.98	0.21
Length	3.62	700.28	0.15
Wide	1.00	121.11	0.27
Ellipticity	84.50	20.59	−0.18
Perimeter	−1.57	−3277.36	0.22
Tree cover	−0.41	−9.91	−0.01
Juncus cover	−5.97	−144.38	−0,28
Phragmites cover	4.57	18.95	0.31
Floating macrophytes cover	−4.59	−49.65	−0.16
Other macrophytes cover	−4.28	−152.10	0.26

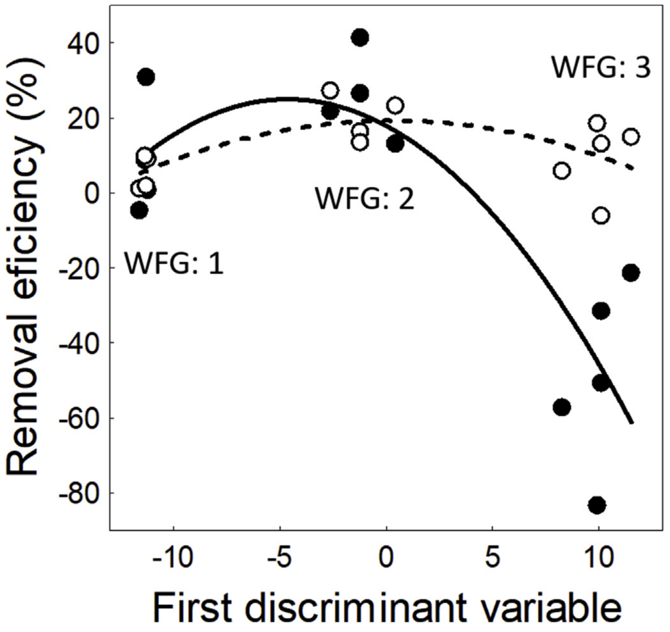

Fig. 4. Fit of removal efficiency of total phosphorus (●) and total nitrogen (○) by wetlands to quadratic functions of the first discriminant function based on both wetland morphological attributes and wetland macrophytes cover ($y = 19.35 + 0.05x - 0.10x^2$, and $y = 17.90 - 3.06x - 0.33x^2$, respectively, where significance level of both quadratic terms is $p < 0,05$). WFG (wetland functional group): 1, 2 and 3.

meters (due to general low water flows in the wetland). When tests were carried out, the used method proved to be highly accurate (standard error < 0.1 s).

Speed measurements were performed at baseline conditions for both types of sampling, because there were no automatic flow-meters available to record the values at post-rain peak flows. The average flow rates at baseline conditions were estimated, at different points of the wetlands (input, middle and exit), from the data of the cross-sectional area and the average water speed.

Wetlands nutrient RE was calculated as the percentage of change in concentrations between the outlet (C_{out}) and inlet (C_{in}) of the wetland (e.g.: Hansson et al. 2005) by using the following calculation:

$$RE = 100(C_{in} - C_{out})/C_{in} \qquad (2)$$

2.4. Multispectral image analysis to determine vegetation cover

Vegetation cover within wetlands was assessed using multispectral aerial images of 0.3–0.5 m resolution obtained by an ultra-light aircraft SKY ARROW 650 TCNS (Institute of Climate and Water of INTA Castelar), in November 2008. The plane camera records radiance in three bands: green (512–599 nm centered at 555 nm), red (618–707 nm centered at 662 nm) and infrared (763–850 nm centered at 806 nm). A supervised classification was performed for each image, using ENVI 3.6 on a false color composite (RGB) configuration. Subsequently, a mask with the corresponding wetland area was applied to each image. Then, by direct visual interpretation in ArcGIS 9.3 the percentage of coverage of trees and the various macrophytes functional groups was determined: rooted short, floating and tall (*Schoenoplectus californicus*, *Typha latifolia* and/or *Phragmites australis*), as well as the percentage of free water.

2.5. Water analysis

Water turbidity was measured in situ for the base flow samples, and in the laboratory for the post-rain samples (previously shaking the samples) using a portable turbidimeter (Aquafluor handheld fluorometer, Turner designs®). The values of pH, temperature, electrical conductivity, salinity and TDS of water were obtained using a portable multiparameter sensor (LaMotte®).

All water samples were analyzed for dissolved P (DP), total P (TP), dissolved inorganic N (DIN) and total N (TN). A 30 mL aliquot of water was digested with potassium persulphate according to Ameel et al. (1993) method for subsequent determination of TN and TP content. A second water aliquot of 5 mL was stored in a refrigerator in 5 mL-glass containers and analyzed for DP content within 72 h of obtaining the sample. The rest of water was kept at −5 °C in brown plastic bottles for nitrate (NO_3^--N) and ammonium (NH_4^+-N) analyses.

The DP and TP contents were determined as orthophosphate by colorimetry, directly in the case of DP or after persulphate digestion for TP. Determinations of P were carried out following the Presley (1971) protocol and using a UV-1700-spectrophotometer (PharmaSpec®).

Both, NO_3^--N and NH_4^+-N concentrations, were analyzed by steam distillation (Bremner and Keeney, 1966). The DIN content was calculated from the sum of NH_4^+-N plus NO_3^--N concentration dissolved in the water samples. The TN content, as NO_3^--N, was calculated after samples were digested with persulphate.

2.6. Data analysis

To investigate general patterns of nutrient flows, descriptive statistics and repeated measures ANOVA were applied using sampling places (inlet and outlet of wetland) and conditions (base flows and post-rain flows) as between-subjects factor while sampling dates as within-subjects factor for each nutrient. General patterns of nutrient removal were also analyzed using repeated measures ANOVA with sampling conditions (base flows and post-rain flows) as ¨between-subjects¨ factor and sampling dates as within-subjects factor for each nutrient. Levenne test for homogeneity of variance was performed before all these analyzes but if that assumption was not meet data were transformed.

Influences of wetlands attributes on RE were analyzed by using multiple regression and multivariate analysis. In multiple regression analysis, stepwise method was conducted separately by sampling dates and conditions. The assumptions for multiple regression analysis were verified by applying test of Durbin-Watson (independent variables), Q-Q plots (normality and homoscedasticity of residues), histograms (normality), eigenvalues, variance inflation factors and condition indices (collinearity). When any assumption was violated, a multivariate non-parametric test was performed using Euclidean distances of similarity matrices, DistLM, (Legendre and Anderson, 1999; Anderson, 2001), with variable selection in successive steps. The selection criteria of variables was based on the corrected Akaike information criterion (AICC), recommended for small number of samples (Burnham and Anderson, 2003).

The multivariate analysis of RE and wetland attributes was performed in two steps. First, a cluster analysis of the 14 studied wetlands was applied on the overall means (sampling conditions and sampling dates) of RE for TP and TN, by using Euclidean distances and Ward agglomeration method. The RE values of the identified wetland groups were compared using one-way ANOVA. Second, a subsequent discriminant analysis of the identified wetland RE groups was separately applied using different sets of variables: a) wetland morphological attributes (area, length, wide, ellipticity and perimeter), b) macrophyte composition attributes (tree species, *Juncus* sp., *Phragmites* sp., floating macrophytes and other macrophytes cover), and c) wetland morphological plus macrophyte composition attributes.

Linear discriminant analysis was performed after testing for homogeneity of covariance matrices, a confusion table was applied for quantification of classification errors, and coefficients of standardized discriminant functions were used as estimators of discriminant relevance of wetland attributes. The significance level used for all tests was $p = 0.05$.

3. Results

3.1. Patterns of nutrient concentrations and removal efficiencies

Nutrient concentrations were only significantly affected by sampling dates, except for DIN concentration that was also affected by sampling conditions ($\bar{x} = 1{,}11$ and $\bar{x} = 2{,}17$ for base and post-rain flow conditions, respectively). A double interaction condition*date was detected in TP, DIN and TN indicating that the effect of sampling dates depends on the level of conditions or vice versa (Table 1, Fig. 1).

Related to removal efficiencies of different nutrients, they were neither affected by sampling conditions nor by sampling dates (Table 1). Except for the positive mean RE of total nitrogen, overall RE by wetlands of the rest of nutrients was highly variable and mostly negative (Fig. 2). Moreover, individual wetlands REs were found not to be linked to sampling data or to sampling conditions so, for example, while RE for TP and TN remained negative or positive for both sampling conditions, other wetlands showed negative RE for TP and TN during base line flow conditions and positive RE values during post rain conditions (Fig. 3).

3.2. Multiple regression models

Explanatory capacity of wetland attributes on RE of different nutrients markedly varied among sampling conditions and sampling dates, so no general influences of wetland attributes can be posed (Table 2.). By being included in 5 out of 16 models, macrophytes cover (floating types or total) was the most important wetland attribute explaining the variation of different nutrients RE. Therefore, RE of DP, DIN and TN decreased with the cover of floating macrophytes in different sampling conditions and dates. While the proxy of adjacent soil stability based on land use showed a negative relationship with the RE of DIN (RE declined with soil stability associated to perennial pastures) for one model the opposite was observed for TN.

Percentage of tree cover in wetland edges explained part of RE of DIN and TN, for both in winter conditions during post-rain peak flows and, in one case, an inverse relationship between the variables was verified (less removal with greater tree cover). On the other hand, HRT was related with TN removal at baseline and post-rain condition, confirming a positive effect in one of the cases, that is, greater removal at higher HRT.

3.3. Multivariate analysis

Three wetland functional groups (WFG) were identified by cluster analysis according to the overall RE of TP and TN removal. First group (WFG = 1) was characterized by high levels of both RE of TP and RE of TN, the second group (WFG = 2) included the negative RE of TP and low RE of TN, and the third group (WFG = 3) showed low but positive values of both RE of TP and TN (Table 3).

The three WFG were not efficiently discriminated neither by a discriminant function based on the five morphometric wetland variables (total classification error = 38,46%) alone nor by the five vegetation composition variables (Total classification error = 46,15%) alone, but they were very well discriminated by the discriminant function based on both variables sets altogether (total classification error = 0%).

The first canonical discriminant function based on both wetland morphometric and vegetation composition variables accounted for 98,95% of total variation, and according to the standardized elements most important variables discriminating WFG were area and perimeter of wetland (Table 4). Therefore, the first canonical discriminant function mainly increased with wetland area and decreased with wetland perimeter, and in minor extent, it also increased with wetland length and decreased with cover of *Juncus* sp. and other macrophyte species. Notwithstanding, no significant correlation coefficients were obtained between canonical scores of the first canonical discriminant function and the estimated wetland attributes (Table 4).

Influences of wetland attributes on RE cannot be interpreted in simple terms from their signs and weights within discriminant functions, because that functions showed non-linear relationships with RE, with a maximum (optimal) value for intermediate values of the first canonical axis (Fig. 4). Below the optimal value, both RE of TP and RE of TN increased with wetland area and decreased with wetland perimeter and also decreased with cover of *Juncus* sp. and other macrophyte species, however, above the optimal discriminant function value, the opposite was true.

4. Discussion

Far from showing simple nutrient removal patterns associated to general morphological, chemical and/or vegetation indicators, as occur for constructed wetlands (e.g. Han et al., 2017), the studied natural wetlands showed highly variable capacities of nutrient removal with nutrient type, with wetland characteristics, with time, with hydrological conditions, and with their interactions. This complexity prevents the identification of natural wetland indicators that are simple and, at the same time, capable of reflecting their efficiency to remove different nutrients under different flow conditions. Two main general messages can be remarked from our results: a) classification of natural wetlands according to their different nutrient RE patterns may provide a better way to identify useful indicators than the exploration of continuous relationships, and b) in addition to wetland size and shape, vegetation variables are important components of an indicator of wetland functional groups.

Despite of their practical convenience, the obtained wetland indicator is not well suited for a complete functional interpretation. The absence of significant correlations between wetland attributes and the indicator scores, reflect that the independent influence of attributes on efficiency of nutrients retention by natural wetlands is relatively weak, and that it has multiple contributing causes.

The majority of the studied wetlands (63%) exhibited the ability to retain TN at different tested conditions, but regarding TP it was only true for the 10% of them (Fig. 3). Partly coinciding with these results, a review based on 57 wetlands showed that most of them (57%) were able to retain N, but even a higher portion showed a positive retention of P (84%) (Fisher and Acreman, 2004). This was expected, especially with N, since denitrification is thought to be the dominant cause of N removal from the wetlands (Bowden, 1987; Van Oostrom and Russell, 1994). Moreover, denitrification has been observed to be one order of magnitude larger than N sedimentation that is the primary mechanism of N retention (Van Oostrom, 1995).

Despite the ability of wetlands to accumulate P is considered to be high, retaining between 40 and 90% of total phosphorus inputs (Reddy et al., 1999), it was not the case for wetlands in this study. Gehrels and Mulamoottil (1990) noted that the P removal mechanisms are exceeded when wetlands cannot accumulate sediments at a rate high enough to provide bonding sites for P.

Discriminant analysis on three wetland groups according to their contrasting mean RE for total phosphorus and total nitrogen was useful to identify an indicator of nutrient RE, consisting in a lineal combination of wetland attributes which can be easily assessed with remote techniques. According to this simple indicator, best levels of removal efficiencies cannot be found in wetlands with the highest values of area, length, perimeter or certain macrophytes cover, but in wetlands where lineal combinations of those variables result in intermediate values of the indicator (Fig. 4).

Despite of the complex nutrient removal patterns described here for Pampa wetlands, it was possible to identify simple descriptors of wetland size and vegetation with high value as indicators for conservation and/or management of wetlands according to their nutrient removal capacities. However, integral assessment and mapping of wetlands according to ecosystem services supply and habitat conservation also requires taking into account complementary sets of wetland indicators (Ausseil et al., 2007).

Acknowledgements

This study was supported by the Fondo para la Investigación Científica y Tecnológica FONCYT (ANPCYT) PICT 12-0607, and PICT 15_0672; BEST-P Inter-American Institute for Global Change Research CRN3095 which is supported by the US National Science Foundation (Grant GEO- 1128040). We thank two anonymous referees for their valuable comments on a previous version of this paper. The authors would like to express particular thanks to Oscar Iribarne, Eugenia Fanjul, and Mauricio Escapa for their early advice and discussions on project design and implementation, as well as to Sebastián Muñoz and Fernanda Buckley, for his invaluable help during the field and laboratory work.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2018.05.070.

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