Limnologica 43 (2013) 18–26

Contents lists available at SciVerse ScienceDirect

Limnologica

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

Effects of land use on environmental conditions and macrophytes in prairie lotic ecosystems

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ARTICLE INFO

Article history:
Received 24 June 2011
Received in revised form 5 June 2012
Accepted 6 June 2012
Available online 12 July 2012

Keywords:
Streams
Nitrates
Cattle
Agriculture
Argentina
Riparian zone

ABSTRACT

Fluvial hydrosystems are environments with large landscape to water surface ratio and therefore particularly vulnerable to changes in land use. We analysed the connection of environmental conditions in 31 prairie streams of the Pampa Plain (Argentina) with regional phytogeography and surrounding land use. Furthermore, the relationships between riparian conditions, macrophytes and water physico-chemistry on the reach scale were explored by considering nutrient levels, pH, water conductivity, riparian conditions and the presence of in-stream vegetation cover. Streams draining croplands were characterized by better conservation of the riparian zone, lower pH and higher nitrate than those exposed to cattle intrusion. Unlike surrounding land use, our results revealed that regional phytogeography showed only marginal significant effects on streams. Our results also revealed that a particular combination of environmental variables (poor riparian conditions, high total phosphorous, high pH and low nitrate) was detrimental for the presence of macrophytes. However, the abundance of submersed and emergent macrophytes was not dependent on surrounding land use nor on regional phytogeography.

Introduction

Changes in land use strongly affect rivers and streams (Brookes 1994), by altering the load of suspended sediments (Kuhnle et al. 2000), phosphorus (Sharpley et al. 1992; Cooke and Prepas 1998), nitrogen (Hill 1978) and organic matter (Strayer et al. 2003). In addition, land-use intensity in the catchment directly controls riparian habitat structure (Steiger et al. 2005). Agricultural practices, including the application of fertilizers and manure to cultivated fields, have been linked to high nitrate concentration in streams (Royer et al. 2006; Tarkalson et al. 2006). The overall rate of nitrate leaching from agricultural areas is largely determined by the irrigation and N management practices (Thompson et al. 2007). Unrestricted cattle access to lotic ecosystems negatively affect bank stability (Vidon et al. 2008). These changes are associated with poorer water quality in comparison to streams where cattle access is restricted (Nagels et al. 2002; Line 2003; Muenz et al. 2006). In particular, bank deterioration following cattle access is responsible for high loadings of phosphorus and sediment to surface waters (Sekely et al. 2002). In addition, grazing management significantly affects nutrient distributions as animals tend to deposit more excreta in lounging areas near shade and water (Sauer et al. 1999). Therefore, stream fencing and riparian zone conservation may lead to a 90% reduction in sediment and nutrient exports (McKergrow et al. 2003).

Water quality in lotic ecosystems is responsible for community composition of macrophytes (Hering et al. 2006) and the relative abundance of different growth forms (Feijoó and Lombardo 2007). Negative effects can range from a shift towards predominantly floating and emergent species (Egertson et al. 2004) to a complete collapse of the macrophyte community (Philips et al. 1978; Rasmussen and Anderson 2005). Particularly, sediment and nutrients in runoff from land use causes eutrophication resulting in concomitant declines in submersed aquatic plants (Crosbie and Chow-Fraser 1999; Gleason et al. 2003).

In the Pampa Plain, the land use for agriculture has been heavily intensified during the last decades, as in many parts of the world. The impacts of such practices on Pampean wetlands increase the nutrient loads entering the already naturally eutrophic shallow lakes (Quirós et al. 2006). A large scale survey of environmental conditions of streams in the Pampas is missing. Only recently a regional approach to determine baseline water quality conditions of relatively undisturbed streams was elaborated (Feijoó and Lombardo 2007). Here, we evaluated the riparian conditions, water quality and presence and type of macrophyte growth in 31 streams of two different phytogeographic regions of the Pampa Plain, Argentina, exposed to intensive land use by means of cropland and livestock breeding in the surrounding landscape. Our main goal was to evaluate which regional and local features affect environmental conditions and macrophytes in prairie streams. The main

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http://dx.doi.org/10.1016/j.limno.2012.06.001

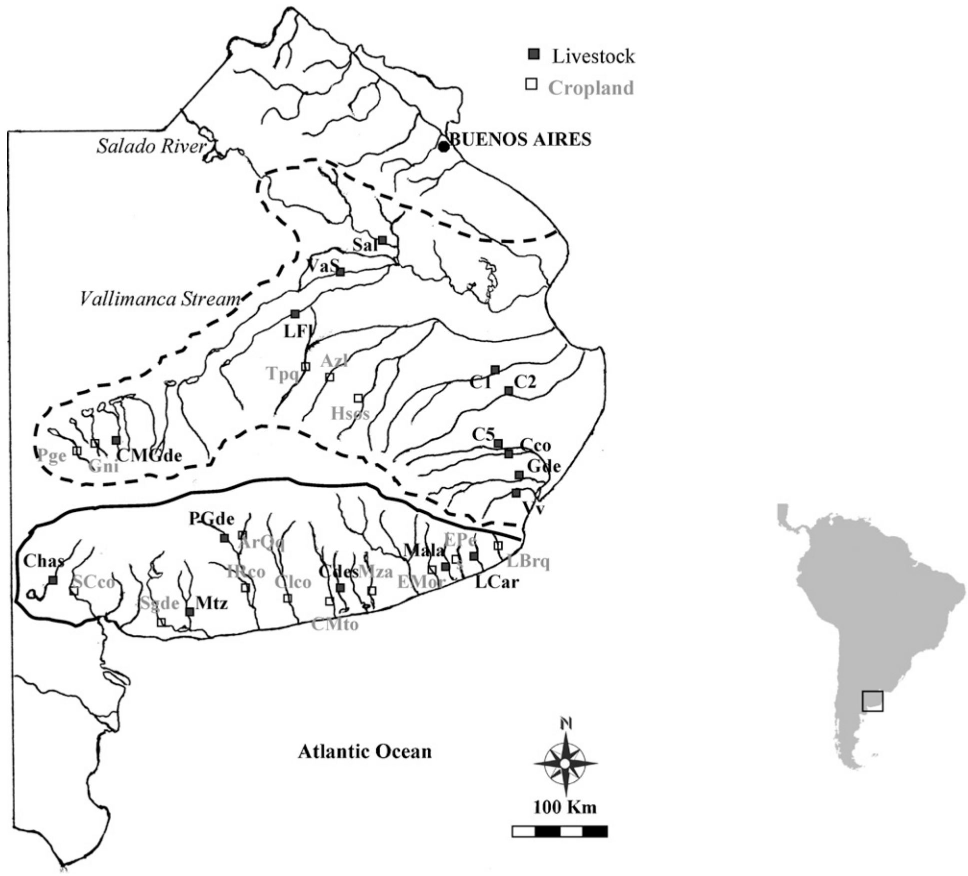

Fig. 1. Map of the study region showing locations of sampled fluvial hydrosystems. Site codes as in Table 1 and coloured by land use. Dashed and solid lines encircle the Flooding and Southern Pampa ecosystems respectively.

hypothesis is that lotic ecosystems exposed to contrasting land use in the surrounding landscape show differences in water quality and riparian conditions, which in turn may affect the development of in-stream macrophytes. Due to patterns of regional phytogeography we further hypothesise that observed responses will vary between regions.

Materials and methods

Study area

The Río de la Plata Grasslands cover more than 700,000 km^2 in the large plains of center-east Argentina, Uruguay and Southern Brazil, located between the 28° and 38° South (Soriano 1991). The Buenos Aires province accounts for most of this biome in Argentina, where the landscape is characterized by gentle slopes (mean 0.25 m/km) only occasionally interrupted by coastal sand dunes and two mountain elevations (Tricart 1973). Based on geomorphology, soils, drainage, physiography and vegetation characteristics four phytogeographic districts can be distinguished within the Buenos Aires province: the Rolling Pampa, the Southern Pampa, the Flooding Pampa and the Inland Pampa (León 1991). 43–55% of the Rolling, Southern, and Inland Pampa regions is covered by cropland. In these regions grasslands and associated livestock barely cover 50% whereas almost 80% of the Flooding Pampa is used for livestock breeding on grasslands (Baldi et al. 2006). The climate of this region is warm temperate with warm (22 °C) summers and gentle (10 °C) winters. Mean annual precipitation averages 950 mm/y 70% of which concentrated in spring-summer months (Sierra et al. 1994). Hydrography is dominated by a large number of shallow lakes and low order rivers and streams. Pampean lakes have been described as polimictic, eutrophic to hypereutrophic environments (Quirós 1988). Pampean streams are low stepped environments with low current velocities and are further characterized by the absence of dry periods or extreme temperatures (Feijoó and Lombardo 2007). In these ecosystems, habitat heterogeneity is not primarily the result of the type and size of substrata (sand-mud dominated) but of submerged vegetation (Giorgi et al. 2005).

Sampling design and environmental variables

Sampling sites were selected on the basis of the following criteria: (1) absence of natural or semi-natural conditions in their immediate landscapes to exclusively evaluate modified landscapes; (2) absence of nearby urban, industrial and municipal discharges to avoid masking effects from these point source stressors; (3) exclusive use of the surrounding land for annual crops (cropland) or livestock (i.e. lateral, upstream and downstream areas; at least 2-km surrounding land).

Thirty-one different streams covering more than 120,000 km^2 of the Flooding and Southern Pampa matched these criteria (Fig. 1). Sampling was carried out in spring 2009 during base flow conditions. According to the adjacent land use, each site was classified as exposed to cropland (Crp) or livestock (Lvs) activities. Livestock sites were characterized by grasslands with unrestricted (unfenced) access of cattle. Physico-chemistry, riparian conditions, and macrophytes were measured and mapped. Triplicate water samples were taken at mid-depth and midstream (Burt et al. 1993) and were analysed for total phosphorous (TP) and nitrate (NO_3)

following APHA (1995). Water conductivity and pH were measured in the field.

Riparian conditions and macrophytes were assessed by wading or walking 200 m along the stream bank. Riparian conditions were evaluated by mean width of the riparian zone, the percentage of stable banks and the percentage of woody cover. The width of the riparian zone at each sampling site was calculated by averaging five different transects. The percentage metrics were calculated as the relative length of bank stability and aerial woody cover to the total length of observation (200 m). The extension of stable banks was calculated as observed bank length fully covered by macrophytes and/or woody plant roots.

The percentage of spatial coverage by submersed and emergent macrophytes was recorded. This metric was used because it is reasonably rapid, relatively non-destructive, and allows a quantification of abundance (Wright et al. 1981; Madsen and Adams 1989). Following Fletcher et al. (2000), macrophyte data were collected from five transects perpendicularly to flow direction at 0, 25, 50, 75, and 100% the length of the surveyed stretch. The linear distances across each transect that were covered by each of the two types of macrophytes were measured and the proportion of the stream width accounted for each type was calculated. A site mean was calculated by averaging the coverage in the five transects.

Data analysis

A riparian index (Ri) was developed using the metrics riparian zone width, bank stability, and woody cover. First, riparian zone width was standardized setting the largest value to 100%. Second, percentages of the three metrics were summed and divided by 100. The resulting riparian index ranges from 0 (bad riparian condition) to 3 (all three metrics having a value of 100%, i.e. good riparian condition).

Several univariate and multivariate approaches were applied. The simple linear relationships among variables were explored using a Pearson product–moment correlation analysis. Differences between land use categories and phytogeographic regions were tested with a Multiple Analysis of Variance (MANOVA) using land use and region categories as fixed factors and Ri, NO_3, TP, pH, water conductivity and percentage cover by emergent and submersed plants as response variables. The effects of cattle intrusion and cropland activities on the response variables were tested whereas the phytogeographic regions accounted for the combined effects of geomorphology, soils, drainage, physiography and vegetation characteristics. This analysis also tested for the interaction between land use and phytogeographic region. Once the MANOVA found a term being significant, we used the univariate ANOVA to determine which of the variables and factors were "causing" the significance. A two sample *t*-test explored the differences between sites with and without macrophytes. Environmental differences among streams with contrasting relative abundances of macrophyte growth forms were also tested using a one-way ANOVA with a Bonferroni Multiple Comparison Test to identify differences between streams. A Principal Component Analysis (PCA) was conducted to detect gradients along environmental conditions. Components with eigenvalues larger than 1 were retained and interpreted using the matrix of factor loadings. Loadings over 0.5 were considered significant (Hair et al. 1987) but only the highest absolute loading for each variable were included in the component interpretation (simple structure solution). The resulting ordinations were evaluated with external categorical data (ter Braak 1995) by labelling sites regarding land use and phytogeographic region. Entities were additionally labelled regarding the presence of macrophytes and the relative abundance of both growth forms. Finally, we performed a Canonical Correlation Analysis (CANCOR) to account for the proportion of the total variance in the abundance of submersed and emergent macrophytes explained by the environmental and riparian metrics. To assess the importance of canonical analysis we report the redundancy coefficient. Redundancy provides a summary measure of the ability of one set of variables (taken as a set) to explain the variation in the other variables (taken one at time). As such, the redundancy measure is perfectly analogous to the R^2 statistic in Multiple Regression Analysis, and its value as a statistic is similar (McGarigal et al. 2000). In our case, only the redundancy in the macrophyte set was calculated as it is considered to be the dependent (response) variable set.

Variables were transformed (logarithmic or square root) as appropriate to reduce their skewness and kurtosis before analyses. All statistical analyses were performed using the NCCS statistical software (Hintze 1998).

Results

Environmental conditions

The streams were characterized by a wide range of physical, chemical and riparian conditions (Table 1). The relative abundance of submersed and emergent macrophytes also varied greatly. Values of pH were high (always above 8) whereas water conductivity, TP and NO_3 spanned several orders of magnitude. Particularly, NO_3 concentrations ranged from 0.17 to 16.43 mg/L. Water conductivity (483–7180 $\mu S\,cm^{-1}$) and TP (0.12–6.66 mg/L) spanned across two orders of magnitude. The riparian conditions ranged from completely disturbed situations lacking any riparian cover and bank stability (Ri = 0) to well developed riparian zones and protected banks (Ri = 2.56). The riparian conditions and pH were significant related ($r = -0.47$; $p < 0.01$), with pH being lower at sites with high Ri values, i.e. better riparian conditions.

Nine sites were completely depleted of macrophytes. In the remainder 22 sites, the proportion of different growth forms varied markedly. Ten sites were dominated (over 70% cover) by emergent macrophytes (E) whereas submersed plants dominated in nine streams (S). Three sites displayed proportional amounts of both growth forms (E/S). Ordination extracted more than 50% of the total variance in the original data (Table 2). On axis 1, a gradient in pH, NO_3, riparian conditions and coverage by emergent plants was identified. Along this axis, sites loading high on the positive end were characterized by high NO_3 concentrations, larger areas covered by emergent plants and better riparian conditions (Table 2). At the negative extreme of this factor the opposite conditions prevailed together with higher pH. The second axis displayed a much simple structure, mainly reflecting gradients in TP and coverage by submersed plants (Table 2).

The role of surrounding land use and phytogeography

The MANOVA showed that land use in the surrounding landscape has a significant effect on riparian conditions and water chemistry (Wilks' Lambda test on land use factor: *F*-ratio = 7.76 and $p < 0.001$). Particularly, lotic ecosystems draining croplands were characterized by better conservation of the riparian zone (ANOVA; *F*-ratio = 38.43 and $p < 0.001$) higher NO_3 (ANOVA; *F*-ratio = 4.21 and $p = 0.049$) and lower pH (ANOVA; *F*-ratio = 7.32 and $p = 0.011$) than those exposed to livestock. Unlike land use, MANOVA showed that regional phytogeography was not as important (Wilks' Lambda test on phytogeographic factor: *F*-ratio = 2.51 and $p = 0.051$). However, there was a clear difference in the abundance of emergent macrophytes between phytogeographic regions (Fig. 2), being higher in the Southern Pampa (ANOVA; *F*-ratio = 4.16 and $p = 0.051$). A similar trend but of much smaller magnitude was observed for submersed macrophytes. The interactive effect

Table 1
Environmental conditions of sampled ecosystems by means of macrophyte, riparian and physico-chemistry variables. Macrophytes: Type: 0 (no plants), E (over 70% area covered by emergent plants), S (over 70% area covered by submersed plants) and E/S (proportional coverage by both growth forms); Subm (%): relative abundance (%) of submersed macrophytes; Emerg (%): relative abundance (%) of emergent macrophytes. Riparian condition and Index: Width%: values of riparian width expressed as percentages of the largest value; Ri: riparian index. Physico-chemistry: Conduc (water conductivity in $\mu S\,cm^{-1}$); TP (total phosphorous) pH and NO_3 (nitrate). Land use: Crp (cropland), Lvs (livestock). Region: Phytogeographic region.

Site	Code	Region	Land_use	Physico-chemistry				Riparian condition and index					Macrophytes		
				Conduc	pH	TP (mg/L)	NO_3 (mg/L)	Bank stability (%)	Wood cover (%)	Width (m)	Width (%)	Ri	Type	Subm (%)	Emerg (%)
de los Huesos	Hsos	Flooding	Crp	690	8.67	1.6	10.79	70	10	0	0	0.8	0	0	0
Azul	Azl	Flooding	Crp	927	8.46	6.6	9.97	100	0	10	33.33	1.33	E/S	50	50
Tapalqué	Tpq	Flooding	Crp	908	10.33	6.6	2.51	100	15	7	23.33	1.38	0	0	0
Las Flores	LFl	Flooding	Lvs	952	9.51	4.4	3.75	50	2	10	33.33	0.85	0	0	0
Vallim-Saladillo	VaS	Flooding	Lvs	7180	9.81	2.1	3.16	0	0	0	0	0	0	0	0
Salado 1	Sal	Flooding	Lvs	4000	9.47	3.7	0.55	20	0	0	0	0.2	0	0	0
Vivoratá	Vv	Flooding	Lvs	1096	8.91	0.8	1.27	0	0	0	0	0	E	20	80
Grande	Gde	Flooding	Lvs	1004	9.23	2.08	12.44	30	10	5	16.67	0.56	E/S	50	50
Chico	Cco	Flooding	Lvs	720	9.38	0.64	6.12	20	0	3	10	0.3	E/S	50	50
CANAL 5	C5	Flooding	Lvs	771	9.26	0.16	0.17	80	0	0	0	0.8	S	100	0
CANAL 2	C2	Flooding	Lvs	851	9.78	3.36	0.93	70	0	0	0	0.7	S	70	30
CANAL 1	C1	Flooding	Lvs	1270	10.56	5.76	0.96	30	0	0	0	0.3	0	0	0
El Pescado	EPes	Southern	Crp	885	8.71	0.16	10.17	75	0	5	16.67	0.91	E	10	90
Malacara	Mala	Southern	Lvs	1129	8.94	1.28	10.76	0	0	0	0	0	E	20	80
El Moro	EMor	Southern	Crp	1091	9.1	1.12	4.43	100	0	10	33.33	1.33	E	0	100
Mendoza	Mza	Southern	Crp	1496	9.02	1.68	11.07	100	25	30	100	2.25	E	0	100
Cortaderas	Cdes	Southern	Lvs	2365	9.36	2.64	7.42	0	0	0	0	0	0	0	0
Cristiano Muerto	CMto	Southern	Crp	1303	9.11	1.44	10.03	100	0	17	56.67	1.56	E	0	100
Claromecó	Clco	Southern	Crp	1919	9.02	3.12	1.24	100	5	15	50	1.56	S	100	0
Indio Rico	IRco	Southern	Crp	1669	9.22	2.64	3.68	0	0	0	0	0	S	100	0
de las Mostazas	Mtzs	Southern	Lvs	2190	8.96	5.28	3.71	30	15	2	16.67	0.61	E	0	100
Sauce Chico	SCco	Southern	Crp	969	8.97	2.64	0.76	90	5	12	40	1.35	E	30	70
Chasicó	Chas	Southern	Lvs	3270	9.11	0.12	0.17	10	2	15	50	0.62	S	100	0
Piguë	Pge	Flooding	Crp	733	8.58	2.52	8.49	100	90	20	66.67	2.56	S	80	20
Guaminí	Gni	Flooding	Crp	749	8.62	0.96	5.53	100	15	20	66.67	1.81	0	0	0
Cura Malal Gde	CMGde	Flooding	Lvs	483	8.83	0.12	2.78	0	0	0	0	0	0	0	0
Pillahuincó Gde	PGde	Southern	Lvs	625	10.3	1.56	0.31	20	0	0	0	0.2	S	90	10
Arr. Quequén	ArQq	Southern	Crp	486	8.84	0.12	1.65	80	1	15	50	1.31	S	100	0
La Carolina	LCar	Southern	Lvs	1245	9.41	0.12	2.37	20	0	1,5	5	0.25	E	10	90
Las Brusquitas	LBrq	Southern	Crp	1192	8.84	0.6	16.43	100	20	10	33.33	1.53	E	0	10
Sauce Grande	Sgde	Southern	Crp	1550	8.01	0.9	0.51	90	90	10	33.33	2.13	S	70	30

Table 2
PCA results showing eigenvalues, variance explained and factor structure summary for the retained factors. Bold values highlight the variables composing factor structure.

Axis	Eigenvalue	Individual percent	Cumulative percent
1	2.039	29.14	29.14
2	1.696	24.23	53.37

Variables	Factor1	Factor2
Ri	**0.655**	0.094
sqrt_sum	−0.065	**0.798**
sqrt_emer	**0.645**	−0.202
log_pH	**−0.758**	−0.277
log_TP	−0.161	**−0.652**
log_NO_3	**0.633**	−0.584
log_Cond	−0.432	−0.407

between land use and phytogeography was not significant (Wilks' Lambda test on interaction between factors: F-ratio = 0.39 and p = 0.895).

The external evaluation of the PCA with land use patterns, evidenced a gradient in environmental conditions between lotic ecosystems exposed to cropland activities (Crp) and those exposed to livestock breeding (Lvs) (Fig. 3c). Particularly, Crp sites grouped towards the top of the ordination loading high on the positive end of the first factor. This position is associated with high NO_3, better riparian conditions and low water conductivity and pH. Conversely, Lvs sites grouped at the other extreme of the first factor where the opposite conditions prevailed. It was evident that neither Lvs nor Crp sites were related to the gradients in TP and submersed macrophytes coverage extracted by the second PCA axis. The ordination of the phytogeographic regions was not as straightforward as for land use.

Macrophytes and environmental conditions

The PCA regarding the presence–absence of macrophytes suggested the existence of a critical "zone" for macrophytes (Fig. 3b). Sites lacking macrophytes mostly grouped tightly at the lower-left quadrant. This position was defined by a combination of high levels of pH and TP, low NO_3 concentrations and the poorest riparian conditions. Indeed, lotic ecosystems lacking macrophytes showed poorer (T-value = −1.38; $p < 0.10$) conditions of the riparian zone, higher pH (T-value = 1.91; $p < 0.05$) and higher TP (T-value = 1.45; $p < 0.10$) than those systems with macrophytes. On the other hand, the one-way ANOVA showed that sites dominated by submersed (S) plants had lower (F-ratio = 5.61; $p < 0.01$) NO_3 concentrations than sites where emergent (E) plants dominated and those where both types prevailed proportionally (E/S). Consequently, as the coverage by the submersed plants increased, the NO_3 concentrations decreased (r = −0.44; $p < 0.05$). Moreover, the first environmental canonical variate, mostly represented by the NO_3 concentrations (Table 3), was able to explain more than 20% of the abundance in submersed macrophytes (Table 4).

In the PCA, the relative abundance of submersed (S) and emergent (E) macrophytes mostly followed a gradient extracted by the combination of the first two factors. Sites dominated by emergent plants (E) grouped tightly towards the upper-left corner with a maximum in riparian conditions, TP and NO_3 and low pH. Conversely, sites where submersed (S) plants prevailed dispersed along a wide range of levels of the first factor but were mostly restricted to the positive end of the second factor, characterized by low TP.

Table 3
Canonical structure coefficients for the first two pairs of canonical variates.

Variables	Variates	
	Macroph1	Macroph2
sqrt_sum	0.912	0.408
sqrt_emer	−0.501	0.865
Variables	Variates	
	Environ1	Environ2
Ri	−0.039	0.581
log_pH	−0.017	−0.908
log_TP	−0.277	−0.408
log_NO3	−0.895	0.371
log_Cond	−0.213	−0.506

Discussion

The role of surrounding land use and phytogeography

The landscape influences its water bodies through multiple pathways and mechanisms, operating at different spatial scales (Allan et al. 1997). The importance of local habitat conditions is best revealed by comparisons at the within-subcatchment scale (Lammert and Allan 1999). Moreover, the comparison between catchment and local proximity land-use have shown that the strongest influence on stream water quality and biotic communities occurred within a 200-m buffer (Sponseller et al. 2001; Tran et al. 2010). In accordance with these results, our findings showed that water quality and riparian conditions were intimately aligned with the prevailing land use in the surrounding landscape. The external evaluation of the PCA performed with land use criteria showed a noteworthy separation between cropland and livestock exposed sites. In addition, the univariate and MANOVA analyses were also able to significantly discriminate between these groups. Particularly, all these analyses demonstrated that lotic ecosystems exposed to cropland displayed better riparian conditions. Land use has an important influence on stream vegetation (Riis et al. 2000; Strayer et al. 2003). In our survey it was evident that cattle accessing stream margins impaired the development of the riparian zone. The presence of cattle eroding the riparian zone, triggers the "stream channel incision syndrome" (Shields et al. 2010) and its effects on water quality. This situation commonly enhances the export of sediments due to both the lack of bank stabilization by plant roots and the degradation of soil margins by cattle intrusion (Sekely et al. 2002; Vidon et al. 2008). The presence of riparian vegetation on riverbanks significantly reduces the likelihood of erosion by mass failure (Hubble et al. 2010). It was also observed that the mobilization of sediment from the channel and banks had led to water quality reduction (Brooks et al. 2006). Both, the deterioration of the physical stream environment (Riis and Sand-Jensen 2001) as well as changes in riparian vegetation type (Kuhar et al. 2007) have resulted in changes in macrophyte distribution. Therefore, it is possible to speculate that observed unrestricted cattle access to streams, impairing the riparian zone, probably have affected the development of macrophytes. It has been shown that coppicing and riparian fencing successfully excludes grazing on banks while increasing in-stream vegetation cover (Clews et al. 2010).

Our results also revealed that cropland exposed streams showed lower pH and higher NO_3 concentrations than those where cattle was present in the landscape. Natural riparian vegetation along streams reduces nitrogen loss through run-off and retains nutrients (Mugni et al. 2005). However, our results showed that streams draining croplands with a well preserved riparian zone had higher concentrations of NO_3 than livestock sites with poorer riparian conditions. The main processes identified as sinks for nitrate within

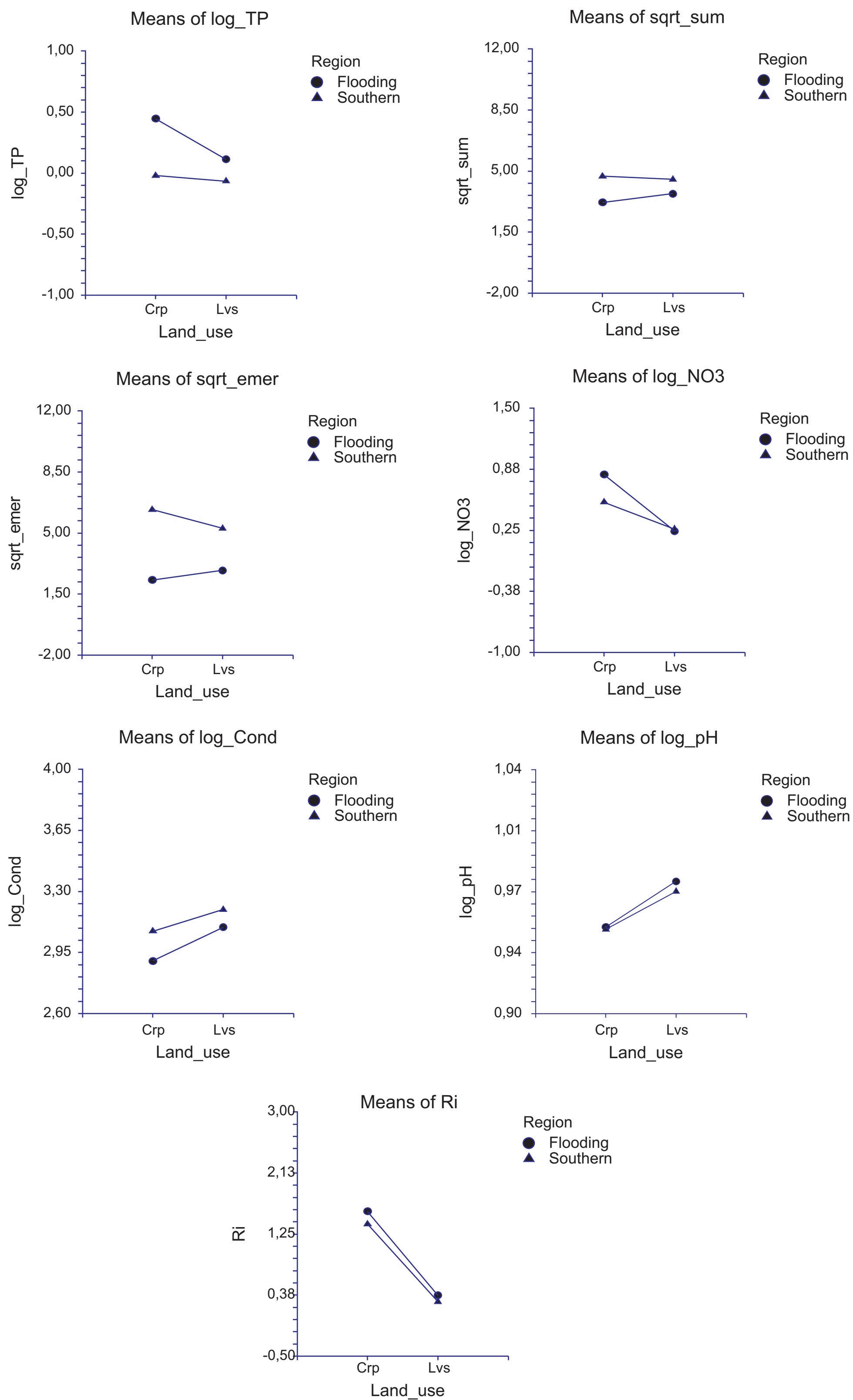

Fig. 2. Means of Ri, abundance of emergent and submersed plants, NO_3, TP, pH and water conductivity when the different land uses were explored against two different phytogeographic regions.

riparian zones are biological uptake (Hill 1996; Gold et al. 2001; Hefting et al. 2005) sedimentation (Busse and Gunkel 2002) and denitrification (Hill et al. 2000; Molenat et al. 2008). The high NO_3 observed in cropland streams with well preserved riparian conditions may obey to either a reduced capacity of species composing the riparian vegetation to uptake NO_3 or an inappropriate chemical environment in water table to allow efficient denitrification processes. Alternatively, a rate of fertilization with nitrogen exceeding both the biological uptake and denitrification rates is possible and values of NO_3 could be even higher without current

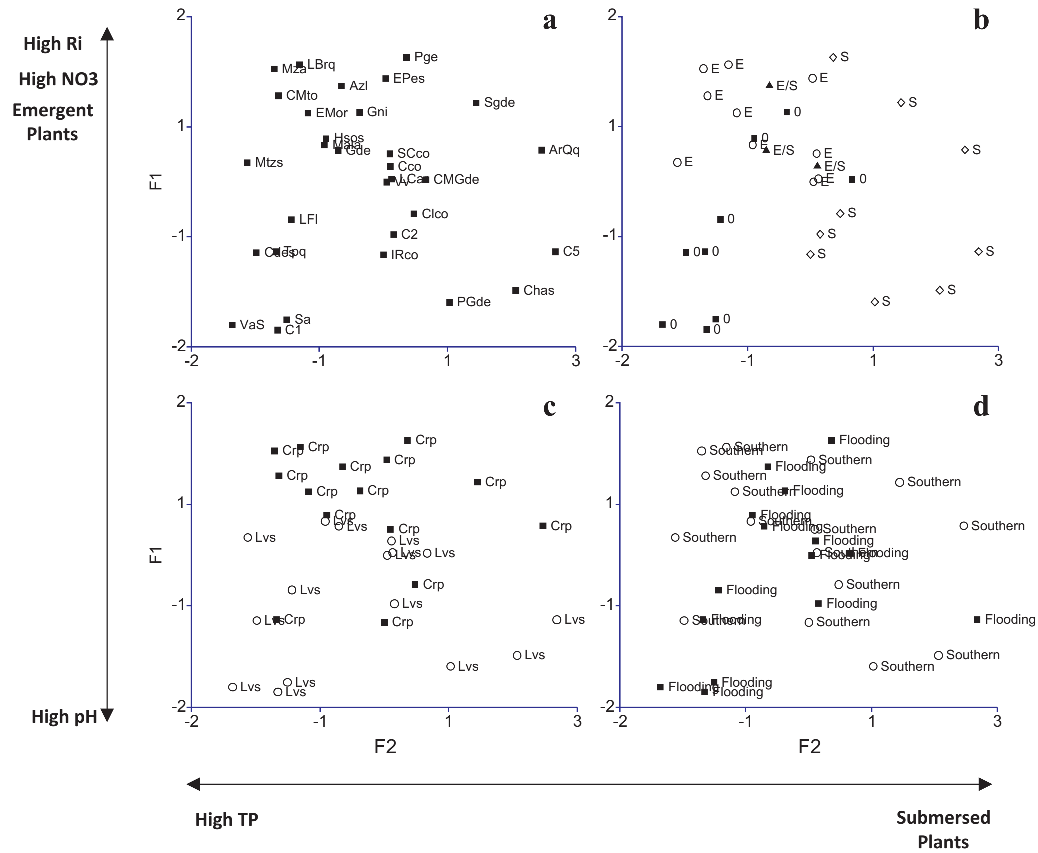

Fig. 3. PCA ordinations by means of environmental conditions of sampled lotic ecosystems labelled by study sites (a), macrophyte growth forms (b), land use (c) and phytogeographic region (d). Codes as in Table 1. Crp: cropland sites; Lvs: livestock sites; 0: absence of macrophytes; S: dominance of submersed macrophytes; E: dominance of emergent macrophytes; E/S: proportional abundances of submersed and emergent macrophytes. Principal component structures are displayed.

Table 4
Canonical correlation significance test and variation explained section (Redundancy Analysis). R_c^2 is the squared canonical correlation coefficient.

Variate	Can. Correlation	R_c^2	*F*-Value	Prob. level
1	0.617	0.381	1.81	0.084
2	0.382	0.146	1.07	0.391

Variate	Variation	Explained by	Individual % expl.	Cumulative % expl.	R_c^2
1	Macrophytes	Macrophytes	54.2	54.2	0.381
2	Macrophytes	Macrophytes	45.8	100	0.146
1	Macrophytes	Environment	20.7	20.7	
2	Macrophytes	Environment	6.7	27.4	

riparian cover. Base flow conditions may also be responsible for this NO_3 enrichment. Indeed, the riparian system may vary from a nutrient sink to a nutrient source at different times of a year depending on high or low water levels (Busse and Gunkel 2001). Irrespective of the processes behind the empirical association between NO_3, riparian conditions and land use, the exports of nitrogen from soils to streams in the Pampa Plain are still modest compared to those reported for intensively cultivated basins of Europe and North America (Mugni et al. 2005).

We also found empirical evidence which inversely linked the riparian conditions and the pH of the water. Accordingly, Crp sites with significantly better riparian conditions (mean Ri, Crp: 1.45; Lvs: 0.33), displayed significantly lower pH (mean pH, Crp: 8.9; Lvs: 9.42). One of the major natural processes that affect the pH in aquatic environments is photosynthesis by driving the pH up as a result of the release of hydroxyl (OH^-) ions (Lampert and Sommer 2007). Much of the control of observed primary productivity within running waters has been attributed to the availability of solar insolation reaching the water (Minshall 1978). Light availability within small order river channels is largely regulated by canopy cover of riparian vegetation (Wetzel 2001). Therefore, the availability of PAR radiation and the pH of the water would be reduced in streams with well "vegetated" riparian zones.

Unlike the surrounding landscape, regional phytogeography only showed marginally significant effects on response variables, perhaps, because regional attributes more often affect hydrological and geomorphological aspects of river ecosystems (Richards et al. 1996; Allan and Johnson 1997), variables that were not evaluated here. Nevertheless, the abundance of emergent and in lesser extent submersed macrophytes was higher in the Southern Pampa (Fig. 2). Some differences in streamwater chemistry between regions could explain this pattern. The higher levels of TP in Flooding Pampa lotic ecosystems (Fig. 2), albeit not significant, could be detrimental for macrophytes. Previous authors already pointed out that Southern Pampa lotic ecosystems (the region 4 in Feijoó and Lombardo 2007) are significantly less enriched with phosphorous. When exposed to high levels of TP, macrophytes are commonly out-competed by excessive epiphytic growth (Hilton et al. 2006). High levels of phosphorous might be related to the phosphorus rich volcanic material deposited in the plains during the Quaternary (Morrás 1999). However, regional distribution of phosphorous in soil samples from the early 20th century (1910–1920) showed an opposite pattern (Morrás 1999) when compared with current TP in surface waters (this study). This means that original content of phosphorous in soils encompassed by the Flooding Pampa was lower than in Southern Pampa and development of land use in the last century probably reversed this pattern for lotic ecosystems. In this respect, Mugni et al. (2005) suggested mineralization of organic matter in soils and land use associated to cattle breeding as important phosphorous sources. Feijoó and Lombardo (2007) further suggested that regional phosphorus distribution would be not related to soil type but to land use. Indeed, almost 80% of the Flooding Pampa is used for livestock breeding on grasslands whereas grassland barely covers >50% in the Rolling, Southern, and Inland Pampa regions (Baldi et al. 2006). Our results suggest that the surrounding land use of streams did not affect TP. Therefore, it could be expected that regional aspects of land use, more closely regulate the phosphorous loading to streams and partially drive the growth of in-stream macrophytes.

Macrophytes and environmental conditions

Macrophytes were able to grow under a wide range of environmental conditions. However, at the lower left quadrant of the PCA ordination, where particular environmental conditions are combined, sites lacked macrophytes. Particularly, the interactive effects of high pH and TP together with low NO_3 and poorer riparian conditions were detrimental for macrophytes. The univariate analysis further suggested that pH, TP and riparian conditions could be probably the most limiting factors impairing the growth of macrophytes.

Macrophyte metrics usually show a consistent response to environmental gradients, but different metrics best reflect these gradients in different stream types (Hering et al. 2006). In the Pampa Plain, the specific composition of macrophytes assemblages is not useful to discriminate among large hydrological regions (Feijoó and Lombardo 2007). Instead, these authors found that macrophyte species grouped according to their growth form (submersed and emergent) following chemical properties of water as conductivity and nitrate. Similarly, our correlation and ANOVA results indicated that sites where vegetation was dominated by submersed species had significantly lower NO_3 concentration than sites where emergent forms prevailed. Decrease in water nitrate concentration is known to result from assimilation by in-stream submersed macrophytes (Burt et al. 1993). Moreover, CANCOR showed that more than 20% of the abundance in submersed macrophytes was explained by a variate mostly represented by the NO_3 concentrations.

The dispersion of sites dominated by submersed macrophytes along the PCA, showed a threshold towards the negative end of the second factor (indicative of high TP). Beyond this point, streams lacked macrophytes or were dominated by emergent forms. Stands of emergent forms under such high TP concentrations seemed to depend upon particular conditions of pH, NO_3 concentrations and riparian conditions, as suggested by the PCA. Particularly, the high pH of the Pampa Plain streams (always above 8) could be detrimental for macrophytes. At pH 8 there are almost exclusively bicarbonate ions present. If the pH shifts further to the alkaline side, the equilibrium moves toward the carbonates. This pH relationship is very important because most aquatic plants can only utilize carbon dioxide and bicarbonate for photosynthesis (Lampert and Sommer 2007).

Conclusions

In every respect, the valley rules the stream (Hynes 1975). Therefore, effective water management in lotic ecosystems requires an understanding of how the surrounding terrestrial landscape, including the riparian zone, influences the structure and functioning of streams and rivers. This study showed that lotic ecosystems exposed to contrasting land use in the surrounding landscape displayed significantly different environmental conditions regarding riparian conservation, pH and eutrophication by nitrate. Additionally, we provide evidence suggesting that a combination of a complex set of environmental variables (riparian conditions, TP, pH and nitrate concentration) may be relevant for the presence of macrophytes. There was not enough evidence to directly link the presence and growth type of macrophytes with surrounding land use nor regional phytogeography. However, regional levels of phosphorous in streams are suspected to reflect regional patterns in land use and postulated to be related with the regional patterns in the abundance of macrophytes.

Acknowledgements

Juan José Rosso and Alicia Fernández Cirelli acknowledge support from the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) and the Universidad de Buenos Aires (UBA). We thank Juan José Troncoso, Nahuel Schenone and Alejo Perez-Carrera for their support and help in the laboratory. The original version of this manuscript was largely improved by the acute and judicious revisions of one anonymous reviewer.

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