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Ecosystem loss assessment following hydroelectric dam flooding: The case of Yacyretá, Argentina

Valeria Bauni [a,*], Facundo Schivo [b], Virginia Capmourteres [a], Marina Homberg [a]

[a] Fundación de Historia Natural Félix de Azara, Universidad Maimónides, Hidalgo 775, Piso 7, C1405BCK Ciudad Autónoma de Buenos Aires, Argentina

[b] Instituto de Investigación e Ingeniería Ambiental, Universidad Nacional de San Martín, Campus Miguelete, 25 de Mayo y Francia (1650) San Martín, Provincia de Buenos Aires, Argentina

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ABSTRACT

The Yacyretá dam is one of the most important hydroelectric projects in La Plata Basin. As a consequence of the filling of the reservoir to its final height of 83 m, approximately 1,076 km^2 of terrestrial and riparian ecosystems were flooded in Argentina and Paraguay. In order to evaluate the ecosystem loss due to this impounding, we generated two maps of land use/land cover from Landsat satellite images: 1987 (prior to the dam) and 2011 (after the final height was reached). We applied a post classification method and tested the gain, loss, and net change of natural and anthropic ecosystems in the study area with a cross tabulation matrix. Water bodies were the land cover type that showed the greatest degree of change, increasing 14.8% between periods. This was in detriment of, primarily, wetlands by 7.5%, grasslands by 4.0%, and native forests by 2.8%. However, sandbanks presented the highest probability of transition to another land class and, thus, correspond to the most vulnerable land cover in the study area. Also, we detected a differential ecosystem loss, both in type and magnitude, up and downstream of the dam. Our work is the first one to address ecosystem loss in the Yacyretá area and our results should help to improve management policies, such as the design of the current network of compensatory reserves.

1. Introduction

1.1. Impacts of land use and land cover changes

Natural land covers, the biophysical surface features of the land, have been converted to anthropic ones, mainly by the removal and replacement of native vegetation. Also, natural land covers have been exploited under several land uses that reflect the socio-economic and political functions of the land (Nagendra et al., 2004; Haines-Young, 2009). Land use and land cover (LULC) changes are fomented by increasing human population and rates of resource consumption and currently are one of the main causes of global ecological change (Vitousek, 1994; Sala et al., 2000; Guida Johnson and Zuleta, 2013). Impacts of land use include changes in atmospheric composition, nutrient cycles, and energy and water balances (see Foley et al. (2005) and references therein). In addition, anthropic activities such as deforestation have led to the fragmentation of ecosystems, which has been recognized as one of the major causes of biodiversity loss and the so-called "biodiversity crisis" in the last decades (Harris, 1984; Noss, 1993; Wu et al., 2003). Moreover, impacts on natural habitats not only threaten biological diversity, but also the

* Corresponding author. Tel: +54 11 4905 1230.
E-mail addresses: valebauni@gmail.com (V. Bauni), fschivo@unsam.edu.ar (F. Schivo), vcapmour@uoguelph.ca (V. Capmourteres), hombergm@yahoo.com.ar (M. Homberg).

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provision of ecosystem services for human well-being, changing the paradigm of a "crisis of extinction" to a broader "crisis of biomes" (Hoekstra et al., 2005).

Globally, croplands have increased at the expense of forests, grasslands and wetlands, and Argentina is not an exception to this global trend. In this country, regional ecological change is evidenced through the conversion of natural land to cultivation systems and the gradual intensification of agriculture on lands that are already cultivated (Viglizzo et al., 1997). To complicate matters, in the north-eastern sector of Argentina, relatively large extents of native grassland are being converted to afforestation of eucalyptus and pine trees, often enhanced by governmental policies such as the National Law of Investment for Cultivated Forests No 25.080/98 (Nosetto et al., 2005).

Another LULC change that usually goes unnoticed, despite having significant impact on natural ecosystems, is the construction of river dams and the creation of water reservoirs. River damming is a human enterprise that has major social, economic, and environmental implications, and has historically responded to several purposes such as irrigation, flood control, and fresh water supply. Later on, large impoundings aimed to produce energy and provide water for the industry (Baxter, 1977; Blanco et al., 2003; Maza-Álvarez, 2004; Baigún and Oldani, 2005). Although the social benefits gained from dams are huge, a wide range of risk always exists and includes partial changes in land cover (Keken et al., 2015).

From an environmental point of view, large dams have fragmented and transformed water flows (WCD, 2000; Blanco et al., 2003; Baigún and Oldani, 2005), which are the major forces shaping freshwater ecosystems (Agostinho et al., 2004). Modifications to water flows result in chemical, geomorphological and hydrological changes (Agostinho et al., 2008). In the case of vegetation, the loss of terrestrial and riparian plant communities is highly significant. For faunal species, those that depend on unique habitats are the most affected by dams (WCD, 2000). Hence, local extinctions of threatened, endangered, rare or habitat-specialist species can occur (Brandão and Araújo, 2008).

Besides the loss of native biodiversity, the transformation of lotic to lentic environments can ease the spread of invasive species, the release of greenhouse gases, and the deterioration of the fishing activity (Junk and Mello, 1990; WCD, 2000; Maza-Álvarez, 2004; Johnson et al., 2008).

1.2. Yacyretá hydroelectric dam

La Plata Basin (LPB) is the second largest one in South America after the Amazon Basin, and comprises almost 3 million km^2. LPB extends through part of Brazil, Bolivia, Paraguay, Uruguay, and Argentina, and is divided in three subwatersheds belonging to major rivers: Paraná, Uruguay, and Paraguay. LPB is of major socio-economic importance in the region since nearly 70% of the Gross Domestic Product of these countries is produced in the area (Palomino Cuya et al., 2013). The important hydroelectric potential of LPB has enabled the construction of more than 150 power units, out of which 75 are in operation (WWAP, 2005). Countries that are part of the LPB are highly dependent on water resources for energy production and currently 76% of the power produced in the region comes from hydropower (Palomino Cuya et al., 2013). Itaipú, Salto Grande and Yacyretá are the largest reservoirs in the basin for energy generation (Fig. 1a). Given this scenario, LPB has been identified as one of the most vulnerable basins at a global scale due to ongoing ecosystem fragmentation (Schelle et al., 2004).

In LPB, the Paraná River flows from the centre-south region of Brazil, across Paraguay and Argentina, and discharges its waters in the Atlantic Ocean through the La Plata River (Schelle et al., 2004). After the Amazon River, this water flow is the most important one is South America due to its length, mean flow, and total catchment area (Araya et al., 2005; Wong et al., 2007; Baigún et al., 2008). Moreover, the Paraná River is a major commercial artery in the region and navigation has been made possible through the dredging of several sectors of the channel (Schelle et al., 2004).

The Yacyretá dam, a governmental enterprise between Argentina and Paraguay, was built in the Paraná River for hydroelectric exploitation. It is located 90 km downstream of the cities of Encarnación (Paraguay) and Posadas (Argentina) (Blanco et al., 2003) and anchored on the Yacyretá Island (Canziani et al., 2006). Its construction was initiated in December 1983 and concluded in February 2001, and began activities in September 1994 under the management of the Yacyretá Binational Entity (*Entidad Binacional Yacyretá*- EBY). In February 2011, the final height of 83 m above the sea level (m.a.s.l.) was reached (López, 2013).

In Paraguay, Yacyretá has improved the irrigation and drainage of 1,400 km^2 of agricultural lands; in Argentina, 67 km^2 of surplus area are now suitable for crops, especially rice (Secretaría de Energía, 2003). Approximately 95.7% of the generated energy is supplied to the Argentine Interconnection System (SADI) and 4.3% to the Paraguayan National Interconnected System (SINP) (EBY, 2014a).

Despite Yacyretá's contribution to the economic and social development of the area, the final height resulted in the definite loss of terrestrial and riparian ecosystems. Unique island habitats of the Paraná River were impacted, such as the case of the Yacyretá Island that lost 75% of its extent (Bertonatti and Banchs, 1993;Carrillo-Reyes and Steinmann, 2011). Similarly, alluvial floodplains of streams in the Upper Paraná River were flooded and consequently, the biological connectivity of the region significantly decreased. Flora and fauna species have been affected, including species of particular conservation concern such as endemic snails (*Aylacostoma* spp.) of the Yacyretá-Apipé corridor (Blanco et al., 2003). Differences pre- and post-dam construction related to conductivity, pH, orthophosphate, and phytoplankton were also reported for the area (Zalocar de Domitrovic et al., 2007). Beyond the Yacyretá area of influence, it is believed that the dam could have an impact in the water levels of the Iberá Wetlands, if alleged groundwater connections between them are proved true (Cózar et al., 2005a).

Despite that the abovementioned studies focused on the impacts of the Yacyretá dam, no research has estimated the type and extent of habitats lost due to its construction and operation. Hence, in this work we assessed the land cover change of the area by comparing pre (1987) and post (2011) satellite images.

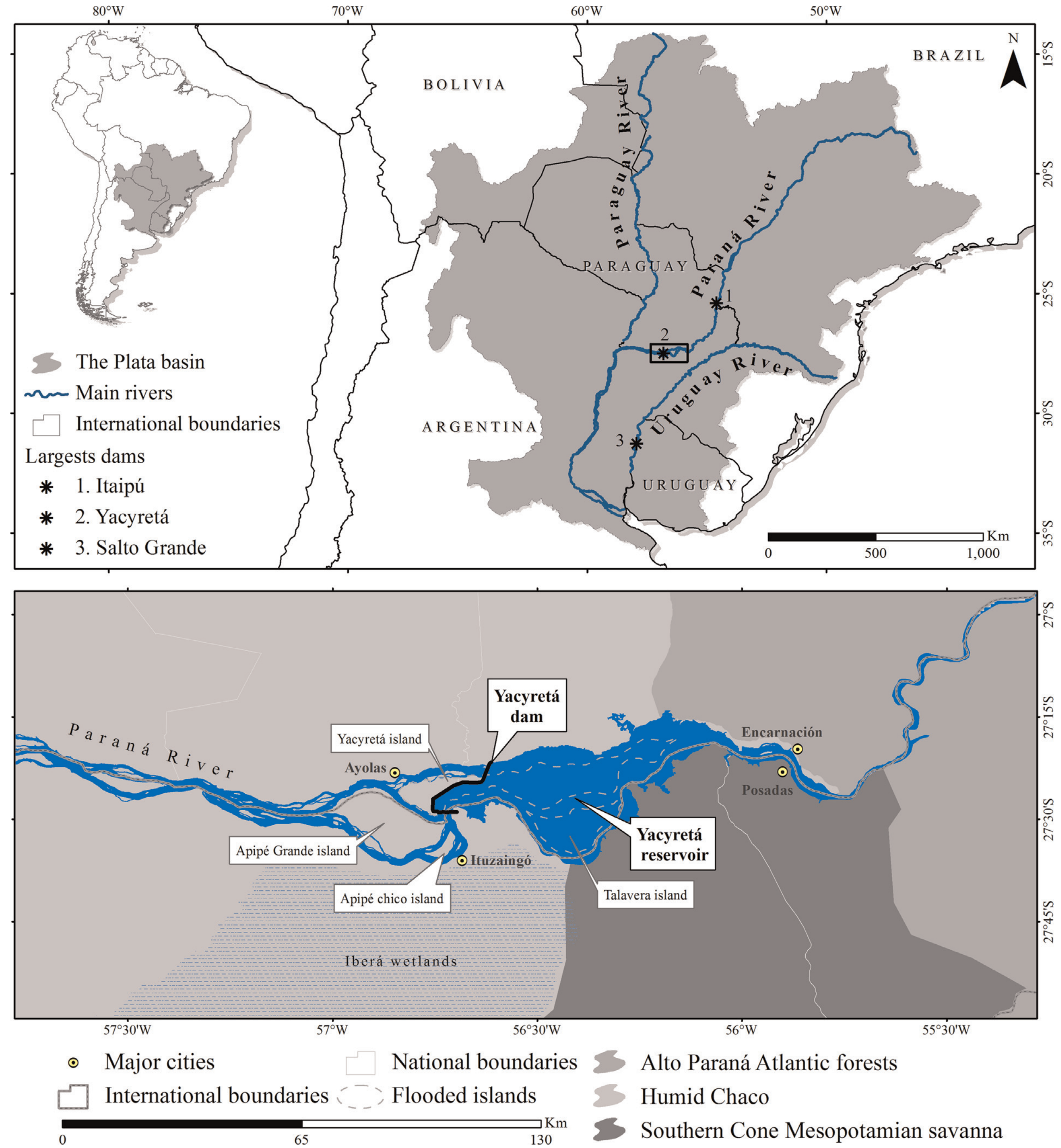

Fig. 1. (A) Location of La Plata Basin, its major rivers and largest dams. (B) Location of the Yacyretá dam and main cities in the context of terrestrial ecoregions of the world.

2. Methodology

2.1. Study area

The Yacyretá dam is located in the Middle Paraná River, where the islands of Yacyretá, Talavera (Paraguay), and Apipé Grande (Argentina) are found. Neighbouring cities are Ituzaingó (Argentina) and Ayolas (Paraguay) (Secretaría de Energía, 2003; López, 2013) (Fig. 1b).

In the area, three ecoregions converge: the Southern Cone Mesopotamian savannas (SCMS), the Humid Chaco and the Alto Paraná Atlantic forest (Olson et al., 2001) (Fig. 1b).

Extensive grasslands, with a gently undulating topography, principally dominate the north sector of the Southern Cone Mesopotamian savannas. The vegetation comprises grasslands and meadows (*pajonales*) with several herbaceous communities (Burkart et al., 1999). Trees appear in isolated patches or as riparian forests, whereas palm trees can form open woodlands or grow mixed among the grasses (Krapovickas and Di Giacomo, 1998). In this region, forestry plantations and crops like yerba mate, tea, and rice prevail (Viglizzo et al., 2005). The Humid Chaco is a great floodplain characterized by riparian forests, flooded grasslands, savannas, and deciduous woodlands in non-flooded zones. The complex hydrological regime, combined with the geomorphological, climatic, and edaphic features of the area, resulted in diverse and various wetlands (Ginzburg and Adámoli, 2006). As for the Alto Paraná Atlantic forest, the predominant vegetation type is a subtropical semi-deciduous forest. Since most forests have been exploited for wood extraction, some sectors are still recovering and thus this ecorregion presents both primary and secondary forests (Di Bitetti et al., 2003).

In the Paraná River, islands and other deposits of sediments exist due to sedimentation processes. These islands exhibit riparian forests in their perimeter, usually densely populated by bamboo-like canes (*Guaduatrinii* sp.). They can also present high sandy dunes or sandy savannas with dense palm tree communities of yatay poñi (*Butia paraguayensis*) (Álvarez et al., 1995).

2.2. Processing satellite images to detect changes in land use/land cover (LULC)

The conventional method to assess land change consists of comparing bi-temporal maps based on satellite imagery and to produce land use/cover change matrices. These methods focus primarily on the type of land that has changed, its extent, and location (Romero-Ruiz et al., 2012). In this work, we refer to land uses and land cover types as "ecosystems", embracing both natural and anthropic systems.

To analyze changes in LULC types, we obtained Landsat 5 TM images (Path/Row 224/79 and 225/79) with 30 m resolution from the National Institute of Space Research of Brazil. Each year is composed of two satellite images. Images corresponded to September and October 1987 (before flooding) and 2011 (after flooding) to include seasonal and phonological differences for each year since their acquisition dates were similar (Guida Johnson and Zuleta, 2013). Change detection for ecosystem monitoring generally assumes overall phenological conditions to be comparable (Coppin et al., 2004). Both images were radiometrically (radiance and reflectance) and geometrically corrected, minimizing distortion due to solar illumination and satellite observation angles, to improve the quality of the data and, consequently, the precision of classifications (Chander and Markham, 2003; Chander et al., 2009).

The study area was demarcated considering the limits of the Paraná River in 2011 and adding a 5 km buffer, covering a total of 6,493.4 km^2 (Fig. 2). This buffer represents the area of influence of the project and ensures the entire reservoir is included in the study area. The up and downstream limits of the study area were defined where the river presented no changes between periods.

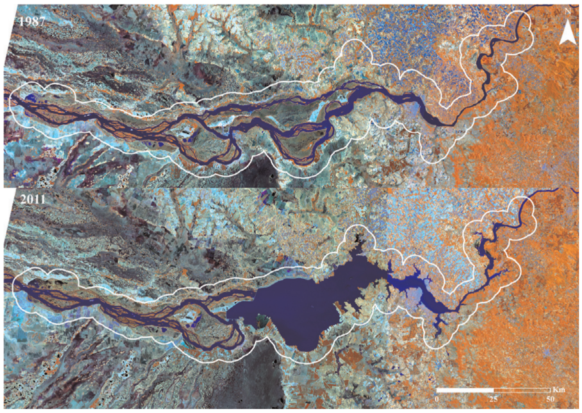

Fig. 2. Mosaic Landast 5 TM images of 1987 and 2011. The images are shown in false-colour-composition (RGB 453). The study area is delimitated in white.

To obtain LULC maps for both years, we performed an unsupervised classification using the non-hierarchical grouping method Interactive Self Organizing Data Analysis (ISODATA) (Tou and Gonzalez, 1974). We established a minimum of 50 individual classes, 1,000 iterations, and 95% convergence threshold on an ENVI platform. With the aim of improving classification results, we added an additional layer of texture to consider differences between adjacent pixels. We digitized the boundaries of urban areas from each year because their classification tends to present difficulties due to the heterogeneity and small spatial size of the surficial materials, leading to significant subpixel mixing (Stefanov et al., 2001). Finally, a statistical filter of majority (3×3 pixels) was applied to minimize the 'salt and pepper' effect – a common type of image noise consisting of pixels transformed either to the lowest or highest intensity values – (Chuvieco, 2002; Jubair et al., 2011).

To assign the final classes, we analyzed the reflectivity behaviour of the different classes (spectral signatures) and performed photointerpretation from high resolution imagery available from Google Earth (Google Earth v.7, 2015) and literature of the region (Fontana, 2009, 2010). All procedures were conducted using ArcGis 10 (ESRI, 2011) with a WGS84 UTM 21S projection.

Eight classes of LULC types were identified for 1987 and 2011: water bodies, grasslands, wetlands, sandbanks, native forests, afforestation, crops and bare soil, and urbanization (Table 1). The first five LULC corresponded to natural land covers, whereas the other three represented non-natural or anthropic covers.

The accuracy assessment for 2011 maps was calculated with 275 random points obtained from high-resolution images from the same period (Google Earth v.7, 2015). Using reference points and the classification data, we built an error or confusion matrix (Congalton, 1991). Also, we estimated the Kappa coefficient (κ), which measures the degree of concordance due to classification, eliminating that one caused by random factors (Hudson and Ramm, 1987). A κ of 1 indicates perfect agreement, whereas a κ of 0 indicates agreement equivalent to chance. We assumed that the accuracy of the 1987 map was similar to that of 2011, since the same classification methods were used for both images (Demaría et al., 2003; Izquierdo et al., 2008; Guida Johnson and Zuleta, 2013).

2.3. Land use/cover change (LUCC) analysis

To detect the LUCC that occurred after the creation of the reservoir, we used the change detection post-classification methodology (Serra et al., 2003; Coppin et al., 2004). The overlapping of the maps from both years generated a cross tabulation matrix, where the rows show the categories from an initial time, the columns show the categories from a subsequent time, and the entries show the size of the area that transitioned from the initial category to the subsequent category during the time interval. Entries on the diagonal indicate land persistence and entries off the diagonal show land change. Furthermore, the matrix for each time interval presents a column of gross losses at the far right and a row of gross gains at the very bottom (Aldwaik and Pontius, 2012). The matrix was converted from km^2 to percentage land cover. This technique shows not only the presence of change, but also the direction of such change, analyzing LULC pixel by pixel for each year (Apan et al., 2000; Lu et al., 2004).

Table 1
Description of LULC in the study area.

LULC	**Description**
Water bodies	Lotic and lentic environments
Grasslands	Extensive livestock areas
Wetlands	Flooded scrublands (*pajonales*) and reedbeds dominated by bushes of tall grasses
Sandbanks	Coarse alluvial deposits of the Paraná River
Native Forests	Patches and riparian forested habitats
Afforestation	Planted forests, mainly eucalyptus and pine trees
Crops And Bare Soil	Croplands – essentially yerba, tea, and rice – and soil without vegetation
Urbanization	Urban and suburban areas

Landscape changes were summarized in terms of net change, gain, and loss, following Pontius et al. (2004). Net change is the difference in area of a land cover between times t_1 and t_2. Gain and loss refer to an increase and decrease in area of a land cover, respectively. The gain-to persistence ratio was calculated as $g_p=$ gain/persistence, the loss-to-persistence ratio was calculated as $l_p=$ loss/persistence, and the net change-to-persistence was calculated as $n_p=g_p-l_p$ (Pontius et al., 2004; Versace et al., 2008). Also, we specifically calculated LUCC up and downstream of the dam.

3. Results

3.1. Classification accuracy

Overall accuracy of the 2011 LULC map was 80.7% (Table 2). The statistical Kappa (κ) for the error matrix is 0.78, indicating a good degree of agreement due to classification.

3.2. Land use/land cover changes in the study area

The percentage of area covered by each land category at each time point and net loss or gain for each LULC type are shown in Table 3. In 1987, natural and non-natural covers occupied nearly 91% and 9% of the study area, respectively. However, in 2011 the extent of anthropic land had increased up to a 14.5% of the study area (Table 3; Fig. 3).

The LULC class that showed a greater degree of change were water bodies, which increased by 14.8%: in 1987, water bodies covered 1, 208.5 km^2 (18.6% of the area), but currently extend over 2,166.8 km^2 (33.4% of the area) (Fig. 3; Table 3). Also, wetlands decreased by a 10.1%, native forests by a 5.1%, and grasslands by 4.2%; although with less magnitude, sandbanks were lost by a 0.8%. As it can be inferred, the extent of all natural land covers decreased from 1987 to 2011, except for water bodies. Accordingly, increasing tendencies in LULC were observed

Table 2
Confusion matrix for 2011 LULC map.

		Reference data Water bodies	Grass-lands	Wet-lands	Sand-bank	Native forests	Afforestation	Crops and bare soil	Urbanization	Row total	User's accuracy (%)
Classified data	Water bodies	39		9	2					50	78.0
	Grasslands		30	9	1			3		43	69.8
	Wetlands		6	20		1		1		28	71.4
	Sandbank				17					17	100.0
	Native forests	1	1	1		37	6	3		49	75.5
	Afforestation			1		2	33			36	91.7
	Crops and bare soil		3				1	33	2	39	84.6
	Urbanization								13	13	100.0
	Column total	40	40	40	20	40	40	40	15	**275**	
	Producer's accuracy (%)	97.5	75.0	50.0	85.0	92.5	82.5	82.5	86.7		
	Overall accuracy	80.7									
	Kappa coefficient (κ)	0.78									

Table 3
Changes of LULC in Yacyretá area of influence from 1987 to 2011. Gain-to-persistence (g_p= gain/persistence), loss-to-persistence (l_p= loss/persistence), and net change-to-persistence ($n_p = g_p - l_p$) ratios of LCLU classes from 1987 to 2011 in the study area. The values of gain and loss express change in terms of percent of the landscape.

LULC	1987		2011		Gain	Loss	Net change	g_p	l_p	n_p*
	Extent (km^2)	% area	Extent (km^2)	% area						
Water bodies	1,208.5	18.6	2,166.8	33.4	15.8	1.1	+14.8	0.9	0.1	0.8
Grasslands	1,715.3	26.4	1,442.1	22.2	11.8	16.1	−4.2	1.1	1.5	−0.4
Wetlands	1,643.5	25.3	986.0	15.2	8.2	18.3	−10.1	1.2	2.6	−1.4
Sandbank	104.9	1.6	50.3	0.8	0.5	1.3	−0.8	1.7	4.7	−2.9
Native forests	1,241.2	19.1	906.7	14.0	3.9	9.1	−5.1	0.4	0.9	−0.5
Afforestation	98.4	1.5	166.8	2.6	2.2	1.1	+1.1	5.3	2.7	2.6
Crops and bare soil	384.9	5.9	632.5	9.7	7.1	3.3	+3.8	2.7	1.2	1.4
Urbanization	97.2	1.5	142.2	2.2	0.9	0.2	+0.7	0.7	0.2	0.5
Totals	6,493.0		6,493.0		50.4	50.4				

* Gain (+); loss (−).

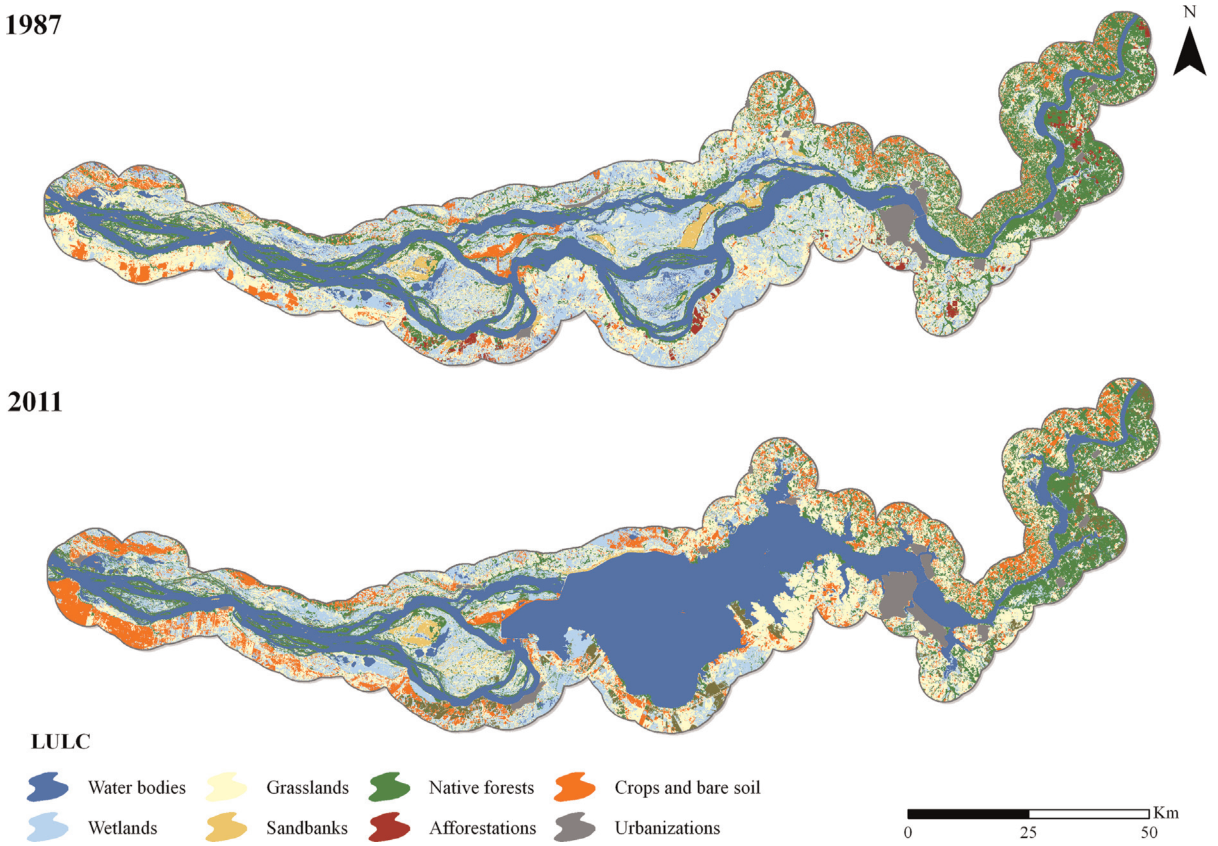

Fig. 3. LULC map of the study area for the years 1987 and 2011, showing pre- and post-flooding scenarios, respectively.

for anthropic classes between periods: crops and bare soil (3.8%), afforestation (1.1%) and urbanization (0.7%).

Concerning gain-to-persistence ratios, afforestation had the highest g_p ratio (5.3), followed by crops and bare soil (2.7) (Table 3). These g_p, that exceed the value of 1, indicate that land covers experienced more gain than persistence between time periods (Braimoh 2006; Versace et al., 2008). Grasslands, wetlands and sandbanks showed this trend as well (Table 3).

With respect to loss-to-persistence ratios, sandbanks had the highest l_p ratio (4.7), which denotes that they were the LULC class with the highest tendency to transition to other land classes rather than to persist. Also, grasslands, wetlands, afforestation and crops and bare soils had a relatively high tendency to be lost than to persist. Instead, water bodies and urbanizations had a l_p ratio close to zero, meaning they did not show a tendency to be lost between time periods. The net change-to-persistence ratios had the

Table 4
Matrix of change showing magnitude and direction of land uses and land cover changes between 1987 and 2011 in the study area. Numbers are expressed as percent of the study area.

		2011								Total 1987	Loss
		WB	GR	WE	SB	NF	AF	CR	UR		
1987	**WB**	***17.6***	0.2	0.5	0.0	0.2	0.0	0.1	0.0	18.6	1.1
	GR	**4.0**	*10.4*	4.8	0.3	1.8	0.7	4.1	0.4	26.4	16.1
	WE	**7.5**	7.0	*7.0*	0.1	1.3	0.6	1.6	0.1	25.3	18.3
	SB	**0.9**	0.1	0.1	*0.3*	0.0	0.0	0.1	0.0	1.6	1.3
	NF	**2.8**	2.7	1.6	0.0	*10.0*	0.6	1.1	0.2	19.1	9.1
	AF	**0.2**	0.2	0.2	0.0	0.3	*0.4*	0.1	0.0	1.5	1.1
	CR	**0.4**	1.5	0.8	0.0	0.3	0.1	*2.7*	0.1	5.9	3.3
	UR	**0.1**	0.0	0.0	0.0	0.0	0.0	0.0	*1.3*	1.5	0.2
Total 2011		33.4	22.2	15.2	0.8	14.0	2.6	9.7	2.2	100.0	
	Gain	15.8	11.8	8.2	0.5	3.9	2.2	7.1	0.9		

WB: water bodies; GR: grasslands; WE: wetlands; SB: sandbanks; NF: native forests; AF: afforestations, CR: crops and bare soil; UR: urbanizations. **Bold letters:** flooded by the dam. *Italics*: persistence of land covers in time.

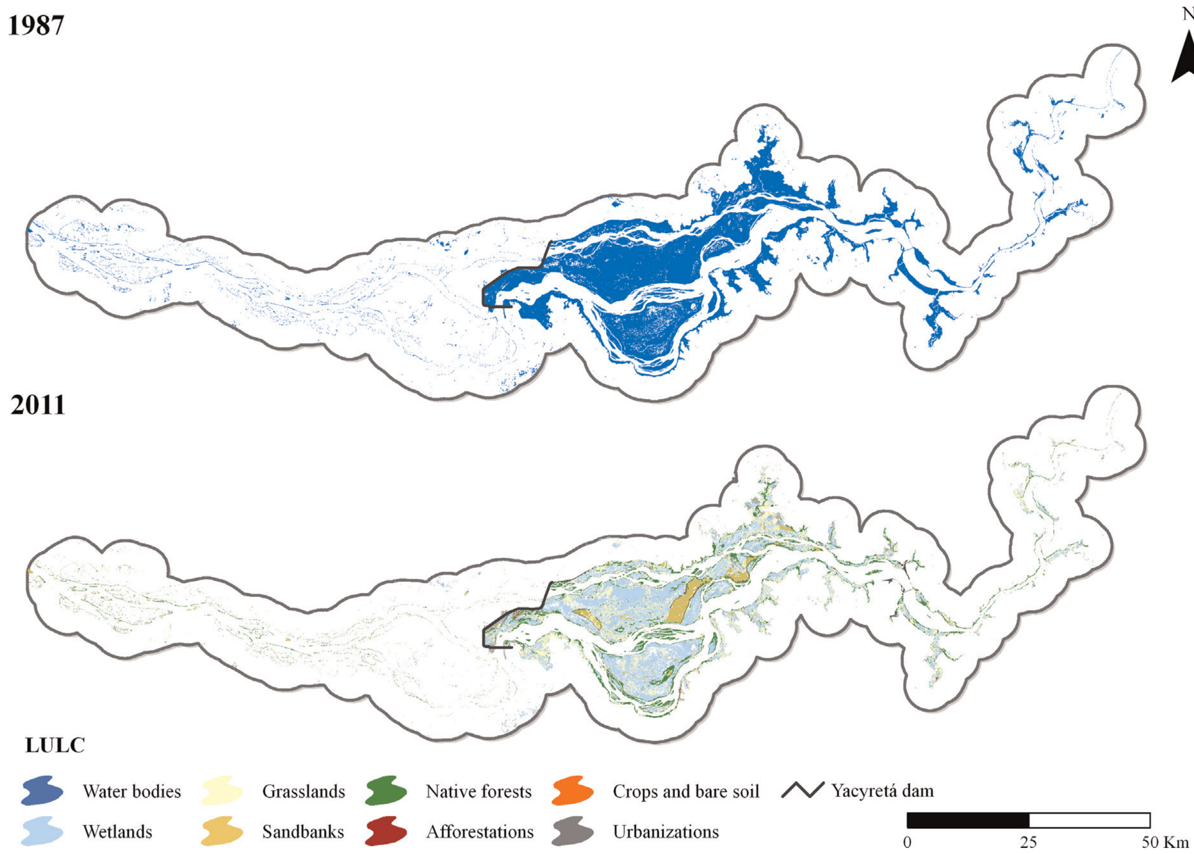

Fig. 4. Flooded surface in 2011 and 1987 LULC types lost by the Yacyretá reservoir.

highest net positive amount of change for afforestation (n_p=2.6), while sandbanks showed the highest negative change (n_p=−2.9) (Table 3).

3.3. Land use/land cover changes due to Yacyretá project

The matrix of LULC change is shown in Table 4. The diagonal indicates the persistence of LULC, that is, the percentage of each LULC that did not change from 1987 to 2011.

Furthermore, the first column shows the change from any LULC to water bodies, which is interpreted as the habitats that were flooded by Yacyretá dam. From Table 4 it can be observed that water bodies persisted by a 17.6% in the study area, meaning that 1,136 km^2 belonged to water bodies in 1987 and remained under the same class in 2011. However, the increase of water by a 15.8% implies an extra

Table 5
LULC types lost by the Yacyretá reservoir up and downstream of the dam.

	Downstream		Upstream	
	Extent (km^2)	% lost	Extent (km^2)	% lost
Grasslands	7.0	16.1	254.3	25.9
Wetlands	8.4	19.5	477.8	48.6
Sandbank	5.2	12.1	53.3	5.4
Native forests	17.70	41.1	161.2	16.4
Afforestation	1.6	3.6	8.4	0.9
Crops and bare soil	3.2	7.5	22.9	2.3
Urbanization	0.0	0.1	5.5	0.6
Total	43.0	4.2	983.4	95.8

1,027 km^2 of water bodies in 2011. This water increase was in detriment of, primarily, wetlands by 7.5% (486 km^2) and grasslands by 4.0% (262 km^2). Secondarily, native forests were converted to water bodies by a 2.8% (179 km^2).

The total persistence of the area, given by the sum of the diagonal in Table 3, was 49.7%. This reveals that approximately 50% of the study area presented LUCC between 1987 and 2011. The location of the original LULC lost by the reservoir are shown in Fig. 4.

When specifically analyzing the loss of LULC due to the reservoir (1,027 km^2), 95.8% of that loss occurred upstream and 4.2% downstream (Table 5). Upstream of the dam, almost 50% of wetlands, 26% of grasslands, and 16% of native forests were covered by water. In contrast, native forests were mainly flooded (41%) downstream of the dam, followed by wetlands (20%), grasslands (16%), and sandbanks (12%).

4. Discussion

Works related to the evaluation of land cover and land use changes analyze the transitions between different land use types due to the advance of agricultural areas and urbanization over natural areas (Viglizzo et al., 1997; Goldewijk 2001; Braimoh, 2006; Guida Johnson and Zuleta, 2013). Regional land change patterns are the combined result of changes, that are driven by complex economic, policy and institutional, demographic and market forces (Munteanu et al., 2014). In this paper, we evaluated a unique land use change: the flooding of lands as a result of the construction of a dam destined to the production of hydroelectric energy.

Although several other land use changes were observed between land classes in the study area, here we focused on the flooding caused by the Yacyretá dam. In the study area, the extent occupied by water bodies increased from 18.6% to 33%, which represented the inundation of 1,027 km^2 of land in the study area.

For the Yacyretá dam, in this work we provide the first ecosystem lost assessment. The flooding resulted mainly in the loss of wetlands, grasslands, and native forests. Although these were the most notorious changes in extent, sandbanks, probably overlooked because riparian habitats tend to be addressed for dam impacts, was the land class that presented the highest probability of transition to another LULC. Since the loss of sandbanks was three times higher, this ecosystem corresponds to the most vulnerable category in the study area. Furthermore, we were able to show that habitat loss occurred differently up and downstream of the dam. Effects of dam flooding were more notorious upstream, where flooded habitats extended over 983.40 km^2.

The loss of these habitats will likely have an impact at the national and regional scale. In the case of wetlands, these are a significant landscape type throughout South America (Junk, 2013) that can be considered of evolutionary and historical importance since they represent the humid periods of the Quaternary. These ecosystems are highly productive and the amphitolerant populations are well adapted to fluctuating water regimes. Furthermore, large wetlands present higher richness and a more complex trophic structure than solely terrestrial and aquatic systems (Iriondo, 2004). Floodplains, in particular, are unique systems because of their complexity and physicochemical seasonal changes, which lead to a wide array of assemblages (Alves Ferreira et al., 2011). Not only they have conservation value due to their species diversity, but they also play a major role in ecosystem processes. For example, the floodplain wetlands of the Paraná River exhibit decomposition processes that are greatly dependent on species composition and the hydrologic regime of rivers (de Neiff et al., 2006). Thus, the loss of wetlands described here could indicate potential changes in ecosystem processes in the area. Lastly, given the proximity to the Iberá wetlands, one of the largest and pristine inland wetland ecosystems in Argentina (Cózar et al., 2005b), the loss of floodplains in our study area is likely to be affecting the connectivity among wetlands in the region.

Lost grasslands are part of the Río de la Plata Grasslands (Soriano, 1991), which are threatened by cattle grazing, agricultural expansion, afforestation, and uncontrolled fire management (Baldi et al., 2006). To complicate matters, less than 0.5% of these ecosystems are protected in Argentina (Murdoch et al., 2010) and the Southern Cone Mesopotamian Savannas ecoregion is under-represented in protected areas: only 0.11% of its extent is protected (Bilenca and Miñarro, 2004; Burkart et al., 2007). In this scenario, the flooding caused by the Yacyretá dam further contributes to grassland loss and degradation in the area.

As for native forests, these are relatively scarce in the ecorregion, and only exist as riparian forest and isolated patches in a matrix of grassland. However, the riparian forests are considered to be a continuation of the Atlantic Forest from Brazil, which is one of the most threatened and diverse ecorregion in the world (Zurita et al., 2006) and might allow the dispersal of Atlantic Forest species farther south (Nores et al., 2005). More over, riparian forests are important corridors in non-forested regions such as the Mesopotamian Savannas and they can provide refugia to tropical and subtropical species in temperate regions (Martínez-Crovetto, 1963).

Sandbanks of the Paraná River, which were the LULC type that presented the highest tendency to conversion, are known to be complex with variations in height, wavelength, depth, and curvature. Some of them were formed in the Quaternary period (Iriondo and García, 1993) and up to date, they play major geomorphological and ecological roles. For example, they control the turbulent flow of the river and thus regulate transport and deposition of sediment (Parsons et al., 2005). From an ecological standpoint, dunes in the Paraná River are unique habitats for macroinvertebrates since they act as 'hydraulic biotopes' at a mesohabitat scale. Benthic densities vary principally according to the dune location in the main channel, but also within-dune scales (Amsler et al., 2009).

Our results serve as a guideline to identify species that could be at higher risk of extinction. For example, typical threatened species from the Mesopotamian Savannas ecorregion that use grasslands and wetlands are the Maned wolf (*Chrysocyon brachyurus*), Pampas (*Ozotoceros bezoarticus*) and Marsh deer (*Blastocerus dichotomus*), and the extirpated Giant anteater (*Myrmecophaga tridactyla*) (Chebez and Cirignoli, 2008; Bauni et al., 2013).

As for vegetation, several species were under threat and classified as rare in the area, and thus had to be relocated before reaching the final height of the reservoir. This was the case of the Ararí (*Calophyllum brasiliense*), small-flowered Xylopia (*Xylopia brasiliensis*), Tacuaruzú (*Chusquea chacoensis*), some orquids (e.g. *Vanilla chamissonis*) and the Dwarf tree fern (*Blechnum brasiliense*) (Bertolini pers. comm.). For our study area, LULC lost by the dam construction could be posing these species' population at a higher risk of extinction. Thus, we recommend a more exhaustive analysis of remnant habitat quality to address conservation management. The loss of these ecosystems also generated social and economic impacts. Productive areas were flooded by the creation of the reservoir and activities such as fishing, developed by local communities, were affected as well as access to the river for recreational use.

Our results showed that almost half of the study area exhibited land use changes between 1987 and 2011. We found a general trend that natural covers decreased in time, whereas anthropic land uses increased; the only exception to this changes were water bodies that increased as well, but because of the creation of the reservoir. These trends shown in our results are neither exclusive from our study area nor surprising. Extensive LUCC have been described for LPB and include deforestation due to the intensification of agriculture (with a decrease of 70% of forests in the Upper Paraná Basin in Brazil) and transitions between crops (e.g. coffee to soybeans and sugarcane) (Coutinho et al., 2006; Lee and Berbery, 2012).

Lastly, the EBY has begun a program of compensatory reserves with the aim of protecting equivalent lands to the ones lost in Argentina and Paraguay (EBY, 2010). Compensation involves undertaking measures to replace lost or adversely impacted environmental values that should have similar functions equaling existing environmental values. If the lost values are irreplaceable, compensation concerns the creation of values which are as similar as possible (Rajvanshi, 2008). So far, 14 reserves have entered the program, adding up to a total of 1,300 km^2 of protected lands (EBY, 2010, 2014b). As stated by Ledec and Quintero (2003), the new areas under protection ought to be of comparable or larger size than the ones lost. This is somewhat accomplished by the EBY, since flooding covered 1,200 km^2 of land in 2011. However, some of those areas coincide with provincial parks, which would mean that they are not actually contributing to a greater protected area surface. Furthermore, reserves lack connectivity both among themselves and with their surroundings. This decreases the probability of occurrence of species inside the reserves (Cabeza, 2003) and implies higher extinction risk than in a reserve of larger area (Diamond, 1975). More importantly, there are doubts about the representation of different lost habitats within the compensation reserves. In this context, our results can be used to determine which type of lands should be acquired to compensate for habitat loss in the area and to provide the local community with natural resources that were once lost.

5. Conclusions

The construction of dams significantly impacts aquatic, terrestrial ecosystems, and riparian communities, mainly through river fragmentation and flooding of habitats. Dams can also drastically modify economic and cultural aspects of societies living in their area of influence. For the Yacyretá dam, however, there was no quantification of the types and extent of habitats affected by its reservoir. In this paper, we classified and compared the LUCC between 1987 and 2011, based on two maps of LULC from Landsat satellite images. Furthermore, with the application of a cross tabulation matrix, we estimated the gain, loss, and net change of LULC in the study area.

Our results revealed that dam flooding affected mainly wetlands, grasslands, forests and sandbanks. Also, we found that 95.8% of the habitat loss occurred upstream of the dam, affecting mainly wetlands and grasslands. Downstream of the dam, however, native forests were predominantly flooded.

Our results could be used to improve the design of the current network of compensatory reserves in the area, since we specified which habitats should be mainly compensated for and in what extent. Further analysis on this topic should be conducted to ensure an adequate representation of all habitats in the network and the connectivity between reserves. Moreover, the information we provided here can be used as a baseline to better assess the extinction risk of species in the area.

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