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Wetland loss due to land use change in the Lower Paraná River Delta, Argentina

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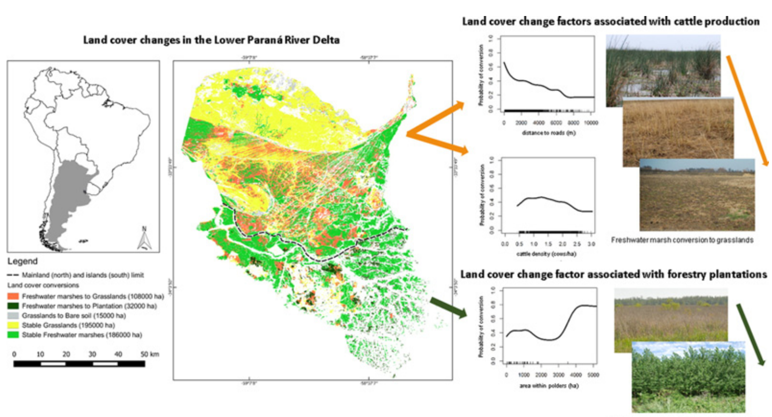
HIGHLIGHTS

- We studied the patterns and drivers of land use change in a major wetland in Argentina.
- One third of the freshwater marshes in the Lower Delta were lost in the last 14 years.
- 70% of the loss was due to conversion to grazing lands.
- Cattle density, water control structures and roads were the main drivers.

GRAPHICAL ABSTRACT



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ABSTRACT

Wetland loss is a global concern because wetlands are highly diverse ecosystems that provide important goods and services, thus threatening both biodiversity and human well-being. The Paraná River Delta is one of the largest and most important wetland ecosystems of South America, undergoing expanding cattle and forestry activities with widespread water control practices. To understand the patterns and drivers of land cover change in the Lower Paraná River Delta, we quantified land cover changes and modeled associated factors. We developed land cover maps using Landsat images from 1999 and 2013 and identified main land cover changes. We quantified the influence of different socioeconomic (distance to roads, population centers and human activity centers), land management (area within polders, cattle density and years since last fire), biophysical variables (landscape unit, elevation, soil productivity, distance to rivers) and variables related to extreme system dynamics (flooding and fires) on freshwater marsh conversion with Boosted Regression Trees. We found that one third of the freshwater marshes of the Lower Delta (163,000 ha) were replaced by pastures (70%) and forestry (18%) in only

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14 years. Ranching practices (represented by cattle density, area within polders and distance to roads) were the most important factors responsible for freshwater marsh conversion to pasture. These rapid and widespread losses of freshwater marshes have potentially large negative consequences for biodiversity and ecosystem services. A strategy for sustainable wetland management will benefit from careful analysis of dominant land uses and related management practices, to develop an urgently needed land use policy for the Lower Delta.

1. Introduction

Human activities have globally modified wetlands (Mitsch and Gosselink, 2007; O'Connell, 2003) and more than half of the world's wetlands have been altered, degraded, or lost in the last 150 years (Gardner et al., 2015). At present, the rate of conversion of wetlands is greater than that of any other aquatic or terrestrial ecosystem (Kandus et al., 2011). Causes of wetland declines are manifold. Some wetlands are over-exploited for fish, fuel and water, whereas others are drained and converted for farming activities and urban development (Baker et al., 2007). Furthermore, wetland loss and degradation is likely to intensify as global demand for land and water increases and climate changes (Junk et al., 2013). Given these trends, it is important to quantify the spatio-temporal patterns of wetland loss and to understand their underlying drivers, in order to identify sustainable wetland use strategies.

Wetland loss can have major consequences for biodiversity and the ecosystem services that wetlands provide (Zedler and Kercher, 2005). Wetlands are among the most productive ecosystems of the world, they offer a great variety of goods and ecosystem services such as storage and purification of water, filtration of agricultural pollutants, flood buffering, fixation of carbon, and the provision of protein via hunting and fishing, among others (Brander et al., 2006; Mitsch and Gosselink, 2007). Wetlands also provide critical habitat for flora and fauna, and often represent highly diverse ecosystems (Dudgeon et al., 2006). Processes of wetland loss and degradation undermine the capacity of wetlands to provide these valuable services to humanity (Zedler and Kercher, 2005). Hence, wetlands are ecosystems of global and local importance, which lends support for their conservation (Keddy, 2010).

Wetland loss can be caused by either human activities or natural causes. The most important human activities include infrastructure development (e.g., roads, polders, levees and ditches), drainage to gain arable or urban land, biological invasions, aquaculture, and peat extraction (Millennium Ecosystem Assesment, 2005; van Asselen et al., 2013; Zedler and Kercher, 2004). These proximate causes are mainly associated with two underlying driving forces of wetland conversion, i.e., population growth and rising consumption levels. Wetland loss due to natural causes are less widespread, but can result from sea level rise, droughts, and storms (Nicholls et al., 1999; White et al., 2002).

Specifically, changes in land use and management frequently result in alterations in wetland hydrology. Management of wetlands for productive purposes generally involves infrastructure constructions to regulate water and prevent the flooding of productive lands (Baigún et al., 2008; Millennium Ecosystem Assesment, 2005). Water management structures such as ditches, polders, levees, and the obstruction of creeks can cause nutrient loss, reduce water and soil quality (Fernández et al., 2010; Simeoni and Corbau, 2009), generate changes in plant species composition and habitat loss (Kingsford and Thomas, 2002; Ouyang et al., 2013; van Asselen et al., 2013). For instance, the draining of wetlands to gain grazing lands in China has drastically decreased groundwater levels and destroyed the wetland integrity (Pang et al., 2010; Xiang et al., 2009).

The Paraná River Delta in Argentina is one of the most important wetland ecosystems in South America due to its location and extent, which is being modified quite rapidly (Baigún et al., 2008). Cattle numbers in the Lower Delta increased by an order of magnitude in a single decade from 160,000 in 1997 to 1,500,000 heads in 2007, and forestry activity has intensified as well, with new types of plantations (Bó et al., 2010; Quintana et al., 2014b). Concomitantly, water management practices (ditches, polders and levees) aimed to protect pastures and plantations from seasonal flooding and expand productive dry lands, have also increased. This resulted in an area of 241,000 ha within polders (almost 14% of the region) and 5181 km of levees in 2012 (Minotti and Kandus, 2013). These structures can turn cyclical flooding ecosystems into lands free of flood similar to grasslands in the Pampas, a process locally called "*pampeanización*", where freshwater marshes are converted to permanently dry grasslands (Galafassi, 2005).

Intensification of management practices can have greater effects during particularly dry and wet periods. The use of fire to enable the growth of more palatable grass species for cattle is a common practice in the grazing lands across the area. In 2008, during a long drought period, many simultaneous fires occurred on over 120,000 ha of the Paraná River Delta (7.2%), mainly in wetland areas dominated by *Schoenoplectus californicus* bulrushes (Salvia, 2010). Many of these burned bulrushes recovered in the next growing season, but some were colonized by grassland species causing a change in plant communities (Salvia et al., 2012). In 2007, on the other hand, during an El Niño Southern Oscillation (ENSO) period, the excess of water in the Paraná River along with great amounts of local precipitation caused a dramatic flooding across the area which left lands under water for several months (Salvia, 2010).

In summary, there is ample evidence suggesting that land use in the Paraná River Delta has intensified, but the patterns and extent of the changes are unclear. Moreover, the relative importance of the different drivers of freshwater marshes' loss is unknown. This information is relevant with regard to identifying potential strategies for sustainable use of this wetland and, more extensively, other wetlands in this region. Our goal was to quantify land use and land cover change across the Lower Paraná River Delta and to identify the factors that cause freshwater marsh conversion. Our first hypothesis was that freshwater marshes are the most affected land cover and are replaced by grasslands. We asked how widespread the "*pampeanización*" process was, and where it was particularly rapid. Our second hypothesis was that land use intensification is the main cause of wetland loss due to expansion of both cattle and forestry activities and the development of related water control structures, while natural factors are less important. We assessed what management practices had the deepest impacts on freshwater marsh conversion and whether their effect differed throughout the entire area.

2. Methods

2.1. Study area

The Paraná River Delta spreads along the final 300 km of the Paraná basin from Diamante (−32°4′S; 60°39′W) to the vicinity of Ciudad Autónoma de Buenos Aires (−34°19′S 58°28′W). As the Paraná River flows from tropical to temperate latitudes, its delta displays unique ecological characteristics (Malvárez, 1999). Its high environmental heterogeneity results in a very high biodiversity (Kandus et al., 2006) and it provides numerous ecosystem services for local communities. According to Köppen and Trewartha climate classification system, the region has a humid subtropical climate with constant precipitation throughout the year and the region (Trewartha and Horn, 1980). The mean annual temperature is 18 °C with a total annual precipitation of 1000 mm (Kandus et al., 2006). The current hydrological regime is dominated by floods from the Paraná River, combined with floods from Gualeguay and Uruguay rivers, tidal and storm surges from the De la Plata River estuary and local rainfall events, each with a distinctive hydrological signature across the area (Baigún et al., 2008, Table S1, Supplementary material).

The study area is the most southern portion of the region called the Lower Delta (−33° 45′S; 58° 51′W). This floodplain covers approximately 4500 km^2 of mainland (southern Entre Rios province) and 3000 km^2 of islands (northern Buenos Aires province; Fig. 1). Five landscape units comprise the Lower Delta differing in their hydrological regime, geomorphic setting, and land cover patterns (Malvárez, 1999; Kandus et al., 2006, Fig. 1, Table S1, Supplementary material). The mainland part of the study area comprises four of these landscape units. Units I and III are characterized by native grasslands (*Panicum miloides* and *Panicum racemosum*) with patches of *espinillo* (*Acacia caven*) and black carob (*Prosopis nigra*) forest; and the fluvial influence is small. Units II (subunits a and b) and V are dominated by freshwater bulrushes (*Schoenoplectus californicus*) in lowlands together with floating or deeply rooted aquatic vegetation. Higher lands have grasses (*Cynodon dactylon*) and the highest sites are belts of *Acacia caven* and *Prosopis nigra* forest. These units have a hydrological regime affected by both local rains and the Paraná and Uruguay rivers. Landscape units I, II, III and V were historically used as seasonal cattle grazing lands, but have shifted towards more intensive and permanent grazing systems accompanied with the use of polders and other water control infrastructure.

The islands of the study area comprise landscape unit IV. These islands have their inner portions permanently flooded and covered with freshwater sedges of *Scirpus giganteus*, and their edges are natural levees. Most of these levees have been transformed since the 1960s into *Salix* spp. and *Poplar* spp. plantations. Since the year 2000, the increasing use of polders has allowed for the establishment of plantations in lower previously flooded island interiors as well.

2.2. Land use and land cover change analysis

2.2.1. Datasets

We acquired 17 Landsat TM and OLI/TIRS cloud-free images from ca. 1999 and 2013, from the United States Geological Survey Earth Resources Observation and Science Center (USGS, 2015) and reprojected them to UTM 21 South. The reduced size of the study area allowed us to use this projection system without generating a problematic distortion in area calculations. Two Landsat footprints covered the entire study area (225/83 for the mainland and 225/84 for the islands).

For 1999, we combined six multispectral bands (excluding the thermal band) of four Landsat 5 TM images (April 1999, August 1999, September 1999 and January 2000) for the mainland part of the Lower Delta. As ground truth, we used data on land cover classes in 1999 described by Kandus et al. (2006), complemented with Quickbird images available in Google Earth. For the islands, we used a land cover map developed by Kandus et al. (2006) based on three Landsat 5 TM images (August 1993, October 1993 and January 1994). This map included 17 land cover classes for the Lower Delta islands for 1994 with an overall accuracy of 85%. We decided to use this map developed by Kandus et al. (2006) for two reasons: (i) it is a precise classification of the islands of the Lower Delta, and (ii) we assume land covers in the Lower Delta islands did not change substantially between 1994 (date of land cover

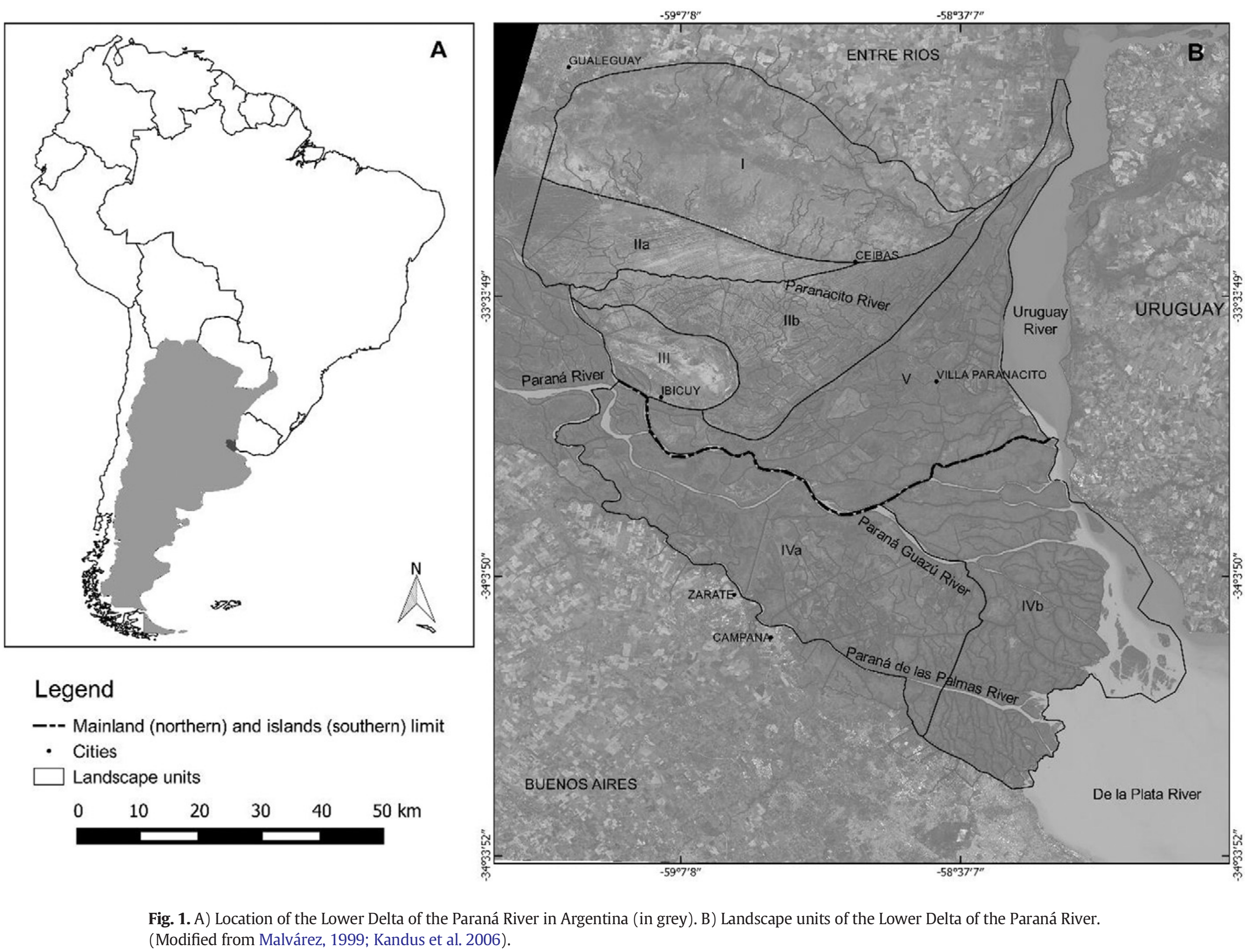

Fig. 1. A) Location of the Lower Delta of the Paraná River in Argentina (in grey). B) Landscape units of the Lower Delta of the Paraná River. (Modified from Malvárez, 1999; Kandus et al. 2006).

map for the islands) and 1999 (date of land cover map for the mainland part) because the potential factors involved in the land cover changes studied started after 1999.

For 2013, we combined six multispectral bands (excluding the thermal band) of six Landsat 8 OLI/TIRS images (April, May, June, July, October, November 2013) for the mainland part of the Lower Delta. For the islands, we used seven Landsat 8 OLI/TIRS images (March, April, May, June, July, September and November 2013). We collected all ground truth data in the field in 2012 and 2013, and complemented it with visual interpretation of Quickbird images available in Google Earth. We digitalized polygons from the ground truth data acquired and split these ground truth polygons into 70% training and 30% validation data.

2.2.2. Classification schemes and change detection analysis

We randomly selected 30–40% of the pixels in the digitalized training polygons as our training sample to parameterize a Support Vector Machines (SVM) classifier. SVM are well-suited to handle complex spectral classes as they fit a separating linear hyperplane between classes in the multidimensional feature space (Foody and Mathur, 2004; Huang et al., 2002). This hyperplane is constructed by maximizing the margin between training samples of opposite classes using only those training samples that describe class boundaries (Foody and Mathur, 2004). To separate classes with non-linear boundaries, kernel functions are used to transform the training data into a higher-dimensional space where linear class separation is possible (Huang et al., 2002). We used Gaussian kernel functions that required estimating the kernel width γ. SVM also requires setting a regularization parameter C that penalizes misclassified pixels, so we tested a wide range of γ and C combinations and selected the optimal combination based on cross-validation errors (Kuemmerle et al., 2008).

We mapped eight land use and land cover classes: (1) willow plantations (*Salix* spp.), (2) poplar plantations (*Poplar* spp.), (3) grasslands, that included *P. miloides* native grass, *Luziola peruviana*, *C. dactylon* and *Leersia hexandra* grasses and *P. racemosum* (typical of sandy soils), (4) native forests dominated by *A. caven* and *P. nigra*, (5) freshwater marshes, including sedges dominated by *S. giganteus*, bulrushes of *S. californicus* and prairies of aquatic macrophytes, (6) bare soil, which included sandy dunes, bald spots, urban areas and roads, (7) open water, and (8) native forests of *Erythrina crista-galli* mixed with *S. giganteus*. We also reclassified the land cover map developed by Kandus et al. (2006) for 1994 to be consistent with our class catalog. To eliminate minor misclassifications, we assigned patches <4 pixels to the dominating surrounding class in both maps.

To determine land cover changes in the Lower Delta, we conducted a post classification comparison. Post classification comparisons avoid the difficulties associated with the analysis of images acquired at different times of the year or by different sensors and focuses on the amount and location of change (Alphan, 2003; Coppin et al., 2004). We compared the classified maps on a pixel-by-pixel basis and summarized the changes in two transition matrices, one for the mainland part of the Lower Delta and another for the islands, and a land cover change map. We generated the land cover change map with all conversion patches >2.5 ha.

2.2.3. Accuracy assessment

We assessed the accuracy of 1999 and 2013 land cover maps and the land cover change map. For 1999 and 2013 land cover maps, we calculated the error matrices, overall accuracies, user's and producer's accuracies and Kappa statistics (Congalton, 1991; Foody, 2002) using the validation data. To assess the accuracy of the land cover change map, we digitalized polygons that represented stable land covers and land cover conversions from the ground truth data acquired in the field and visually interpreted Quickbird images available in Google Earth. We randomly selected 30% of the pixels in the digitalized polygons of the conversion classes: freshwater marshes to grasslands, freshwater marshes to forestry plantations and grasslands to bare soil, stable freshwater marshes and stable grasslands. We calculated the error matrix, overall accuracy, user's and producer's accuracies and the Kappa statistic (Congalton, 1991; Foody, 2002).

2.3. Factors related to land cover change

In order to understand the influence of different factors on land cover change in the Lower Delta, we focused on two main land cover conversions based on the hypothesis proposed: freshwater marsh conversion to grassland and freshwater marsh conversion to forestry plantation. We also examined grassland conversion to bare soil.

2.3.1. Explanatory variables

We identified 12 potential explanatory variables of land cover conversion in the Lower Delta (Table 1) and grouped these into four categories: (1) socioeconomic, (2) land management, (3) biophysical and (4) extreme system dynamics. Increases in population density can have large impacts on land use change (Lambin et al., 2003) but no spatially disaggregated population data was available for our study area. Instead, we included two variables that represent population density: (1) distance to human activity centers, which accounts for the distance to sites of active movement of people such as schools, police and gendarmerie stations, recreation centers and factories, among others; (2) distance to population centers, accounting for distance to marginal settlements, towns, and cities. Moreover, wetlands located close to roads are easily accessible and, hence, more vulnerable to conversion (van Asselen et al., 2013), so we included a variable as a proxy for accessibility: (3) distance to roads, including the distance to roads, railways and levees.

Our second group of explanatory variables involved land management practices. We included a variable related to water management: (1) area within polders, that represents drained areas rounded by artificial levees that are protected from flooding. We also generated the variable: (2) cattle density. We used the kriging function of the Spatial Analyst extension of ArcGIS version 10.1 (ESRI) to create a continuous surface of cattle density based on data from cattle ranches for December of 2013, obtained from Sistema Integrado de Gestión de Sanidad Animal (SIGSA, 2015). Finally, we included the variable: (3) years since last fire.

Our third group of variables captured biophysical factors. We included temperature and precipitation initially, but they had limited explanatory power, which is why we removed them from the final models. The likely reason for their low explanatory power was that the area is fairly homogeneous in terms of climate (Malvárez, 1999). As proxy to the environmental heterogeneity, we included: (1) landscape unit. Freshwater marsh conversion is related to topography as it is involved in water flow, so we included: (2) elevation. Soil quality is another possible predictor of freshwater marsh conversion so we included (3) a soil productivity index, developed from soil characteristics under optimal management conditions in the Soil Map of Argentina (GeoINTA, 2015; Riquier et al., 1970). Finally, we generated a variable as proxy to probability of flooding (in absence of a hydrological model for the region): (4) distance to rivers.

Our last group of variables was related to extreme events, and we included two variables: (1) burned area during the 2008 extreme fire and (2) flooded area during the 2007 extreme flood.

2.3.2. Sampling strategy

Using the land cover change map, we imposed a systematic grid of points (each point was the grid cell center) spaced 500 m apart to account for potential spatial autocorrelation. We generated three sets of data by selecting observations that were: (i) freshwater marsh conversion to grassland and stable freshwater marsh, (ii) grassland conversion to bare soil and stable grassland and (iii) freshwater marsh conversion to forestry plantation and stable freshwater marsh. The sampled points in each data set were intersected with all the explanatory variables resulting in point shapes that included all the data in the respective attribute table. We

Table 1
Explanatory variables used in the analysis and their hypothesized effect.

Explanatory variable	Acronym	Hypothesis	Source
Socioeconomic variables			
Distance to roads and levees (m)	DR	Freshwater marsh conversion is less probable in remote areas	GIS analysis of data from Instituto Geográfico Nacional (IGN, 2015)
Distance to population centers (m)	DPC	Freshwater marsh conversion is more likely in areas adjacent to rural and urban centers	GIS analysis of data from Instituto Geográfico Nacional (IGN, 2015)
Distance to human activity centers (m)	DHA	Freshwater marsh conversion is more likely in places of active human use	GIS analysis of data from Instituto Geográfico Nacional (IGN, 2015)
Land management variables			
Area within polder (ha)	AWP	Freshwater marsh conversion in areas within polders is more probable because flooding is no longer periodic, hence the vegetation is no longer exposed to frequent flooding	GIS analysis of data from Minotti and Kandus (2013)
Interpolated cattle density (number of animals/ha)	ICD	Higher cattle density promotes freshwater marsh conversion to pastures	Krigging performed on data from SIGSA (2015).
Years past since last fire	YLF	Recent burned areas facilitates the colonization of freshwater marshes by grasses	MODIS Burned Area Product, MCD45A1 (LPDAAC, 2015)
Biophysical variables			
Landscape unit	LU	Freshwater marsh conversion is different in each landscape unit due to their different environmental characteristics and different restrictions imposed on human activities	Kandus et al. (2006)
Elevation (m)	E	Freshwater marsh conversion is more likely in lower areas	ASTER Global Digital Elevation Model (LPDAAC, 2015)
Soil productivity index	SPI	Areas of higher soil productivity are more likely to be converted	Soil Map of Argentina (GeoINTA, 2015)
Distance to permanent rivers (m)	DPR	Areas further away from rivers are less prone to freshwater marsh conversion	GIS analysis of data from Instituto Geográfico Nacional (IGN, 2015)
Extreme system dynamics variables			
Flooded area during last extraordinary flooding (2007)	FA	Freshwater marsh conversion is more likely in areas that flooded during the extreme flood	Salvia (2010)
Burned area during last extraordinary fire (2008)	BA	Freshwater marsh conversion is more likely in areas that burned during the extreme fire event	Salvia (2010)

randomly sampled 50% of the points resulting in different sampling sizes according to the land cover conversion analyzed (Table S8, Supplementary material). We analyzed each land cover conversion separately for the mainland and for the islands of the Lower Delta.

2.3.3. Land cover conversion models

We used Boosted Regression Trees (BRTs) to quantify the influence of the hypothesized explanatory variables on land cover conversion in the Lower Delta. BRTs are non-parametric machine learning algorithms that make no a-priori assumptions regarding the distribution of the response or the explanatory variables (Elith et al., 2008). BRTs use two algorithms: regression trees, to generate the model relating the response to its explanatory variables, and boosting, to improve the model accuracy (Friedman, 2001; Schapire, 2003). BRTs are robust in regards to collinearity of variables, non-linear relationships, interaction effects, and spatial autocorrelation of variables or residuals. Nevertheless, we assessed collinearity among explanatory variables calculating a Pearson's correlation coefficient matrix for all continuous variables and generalized linear models among categorical and continuous variables. When the correlation between two variables was ≥0.6, we removed the explanatory variable that correlated with the larger number of variables, or had a less clear relationship with the response variable.

We used the dismo package (Hijmans and Elith, 2014) in R 3.3.1 (R Development Team, 2008) to perform all analyses. BRTs require specifying four main parameters: (i) number of trees (nt), (ii) tree complexity (tc), (iii) learning rate (lr), and (iv) bag fraction. The number of trees that produce the lowest prediction error was selected automatically using ten-fold cross-validation, using the gbm.step routine in the dismo package (Elith et al., 2008). We conducted a systematic sensitivity analysis to test all combinations of tree complexities from 1 to 10 and learning rates from 0.1 to 0.0001 to identify optimal parameter settings by using cross-validation (Levers et al., 2014). For each model iteration, we randomly withheld 60% of the full data set to fit the model (bag fraction = 0.6).

We calculated two performance measures for each model: the explained deviance (i.e., expressed as a percentage of the total deviance) and the predictive performance (measured as the area under the Receiver Operator characteristic Curve, ROC). A ten-fold cross-validation was used to assess the predictive performance. In BRTs, the relative influence of explanatory variables is estimated based on both how often the variable is selected and the improvement to the model when the variable is included. Relative influence of variables sums up to 100%. Only variables with a relative contribution above that expected by chance (100%/number of variables) were interpreted (Müller et al., 2013). We used partial dependency plots to understand the relationship between each explanatory and response variable (freshwater marsh conversion to grassland, freshwater marsh conversion to forestry plantation or grassland conversion to bare soil). These plots show the effect of each variable on land cover conversion after accounting for the average effects of all other variables in the model (Elith et al., 2008; Friedman, 2001). For improved interpretation, the plots were smoothed using a smoothing spline (Müller et al., 2013). The responses were log transformed and shown as a probability of conversion.

We modeled land cover conversions separately on the mainland and on the islands of the Lower Delta. First, to understand freshwater marsh conversion to grassland on the mainland we ran three BRT models. The first model captured the entire mainland area whereas the two additional models focused on landscape units where conversion rates were higher. We also modeled grassland conversion to bare soil on the mainland to have a better understanding of land cover changes. Secondly, to understand freshwater marsh conversion on the islands we ran two BRT models one for freshwater marsh conversion to grassland, and one for freshwater marsh conversion to forestry plantation.

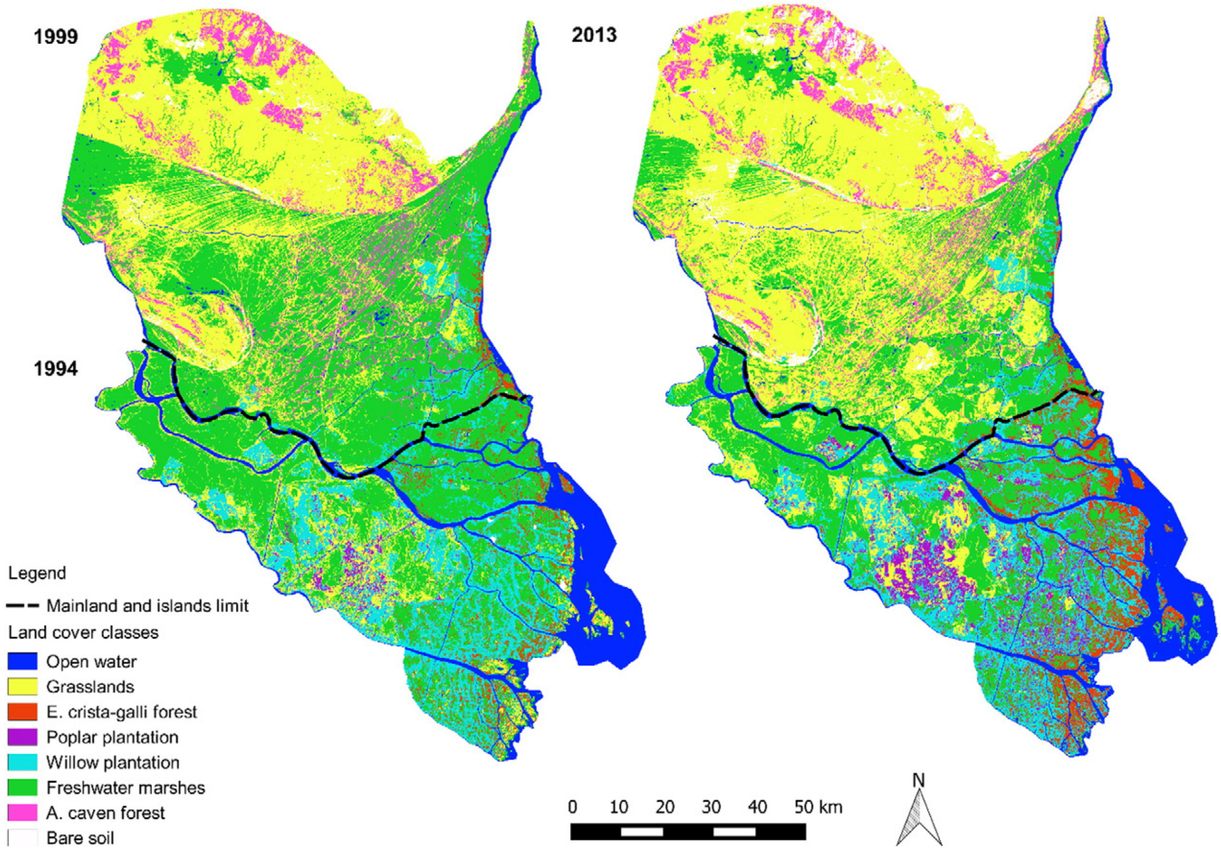

Fig. 2. Land use and land cover maps for the Lower Paraná River Delta in 1999 (mainland), 1994 (islands) and 2013 (entire area). 30 × 30 m pixel resolution.

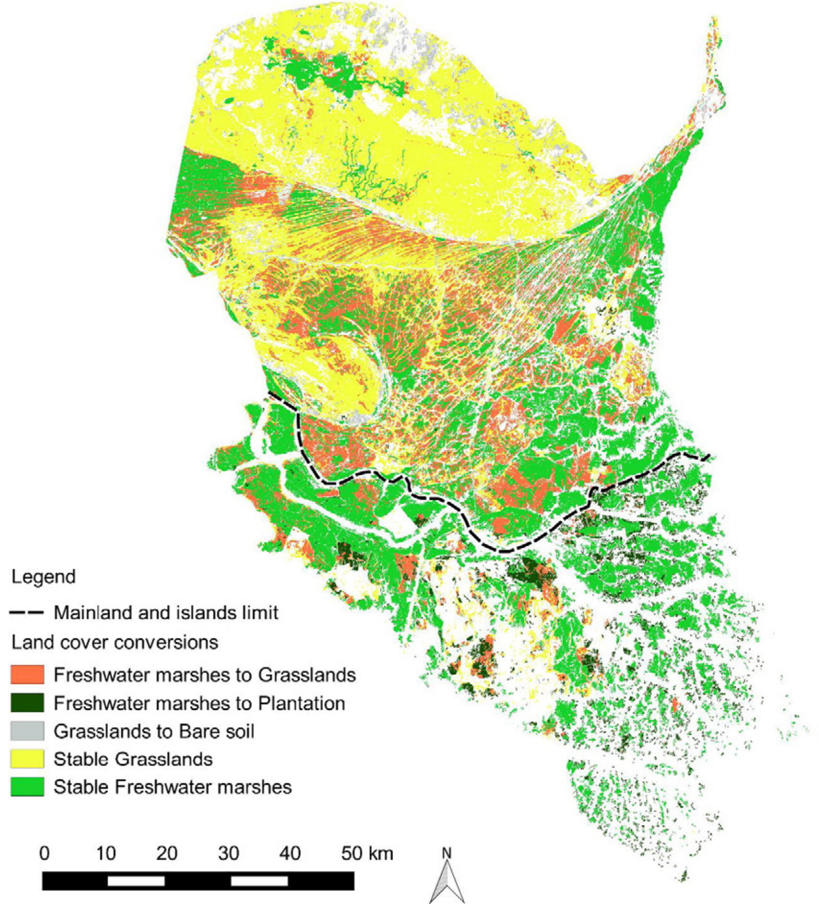

Fig. 3. Land use and land cover change map for the Lower Paraná River Delta. 30 × 30 m pixel resolution.

3. Results

3.1. Land cover changes from 1994/1999 to 2013

Land cover change in the Lower Paraná River Delta from 1994/99 to 2013 has been substantial (Fig. 2). On the mainland, grasslands and freshwater marshes were the dominant land covers in 1999 covering 43.0% and 41.3% of the total area respectively. However, by 2013, grasslands expanded to 58.3% (78,300 ha net gain) and freshwater marshes decreased to 24.2% (88,500 ha net loss). In proportion, grasslands increased by 35.3%, while freshwater marshes decreased by 41.5%. We also found a considerable increase in bare soil (17,500 ha net gain representing a relative change of 187%) and a decrease in *Acacia caven* forests (5800 ha net loss representing a relative change of 13.5%). On the islands, freshwater marshes were the main land cover in 1994 followed by willow plantations, covering 42.0% and 23.7% of the area respectively. By 2013, freshwater marshes shrank to 30% (41,000 ha net loss) while willow plantations expanded only to 26.7% (10,000 ha net gain). Relatively, freshwater marshes decreased by 28.5%, while willow plantations increased only by 12.1%. Poplar plantations and *Erythrina crista-galli* forests also increased by 250% and 146%, respectively, representing 16,000 ha gained in poplar plantations and 23,000 ha gained in *Erythrina crista-galli* native forests.

Table 2
Relative importance of explanatory variables and predictive performance of models.

	Freshwater marshes to grasslands (mainland)	Freshwater marshes to grasslands (unit II)	Freshwater marshes to grasslands (unit V)	Grassland to bare soil (mainland)	Freshwater marshes to grasslands (islands)	Freshwater marshes to forestry (islands)
Explanatory Variables						
DR	14.55	15.35	16.85	14.01	15.03	7.41
DPC	13.66	18.45	18.41	13.26	7.41	11.74
DHA	10.46	13.53	11.28	16.68	11.04	15.42
AWP	10.79	3.46	21.82	0.61	44.22	28.26
ICD	14.48	19.06	11.51	17.82	13.06	13.06
YLF	1.29	0.54	1.38	2.39	0.72	1.56
LU	7.55			3.84	0.4	5.56
E	2.71	3.67	3.03	7.07	1.75	5.61
DPR	11.96	16.25	10.85	14.27	4.4	10.67
SPI	8.56	3.96	2.62	6.63	0.21	1.16
FA	1.50	0.4	1.74	3.40	0.47	1.13
BA	2.45	0.79	0.5		1.28	1.05
CV ROC	0.79	0.87	0.8	0.78	0.92	0.88

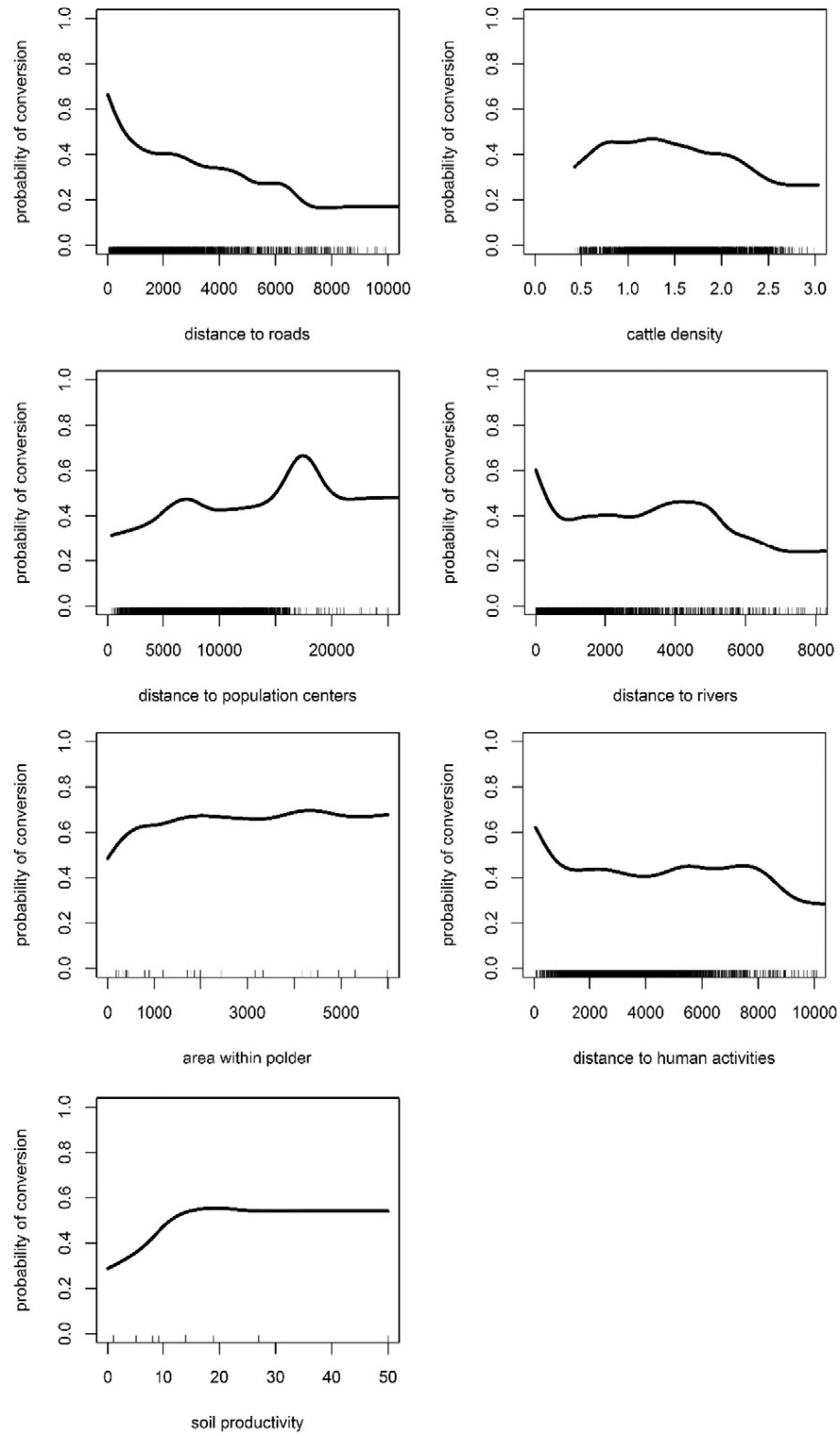

Fig. 4. Partial dependency plots for the seven most influential variables that describe the probability of freshwater marsh conversion to grassland on the mainland. The vertical axis shows probability of conversion along the explanatory variable's data range displayed on the horizontal axis. The horizontal axis includes rug plots that show the distribution of the data in percentiles.

The most widespread land cover conversion on the mainland, was freshwater marsh conversion to grassland (94,000 ha) followed by grassland conversion to bare soil (15,000 ha, Fig. 3). *Acacia caven* forest conversion to grassland was also important (15,000 ha). The Kappa indices showed that all land cover classes have changed substantially in 14 years, but open water and bare soil changed the least (Table S2, Supplementary material). On the islands, freshwater marsh conversion to willow plantation was the main land cover conversion (24,000 ha, Fig. 3) followed by freshwater marsh conversion to *Erythrina crista-galli* forest (18,000 ha). Again, the only land cover class that remained stable was open water (Table S3, Supplementary material).

3.2. Accuracy of the land cover maps

The SVM classification resulted in accurate land cover maps for the Lower Delta in both periods of time and both parts of the study area. For the mainland, the overall classification accuracy for 1999 was 95.02%, with a Kappa of 0.93 (Table S4, Supplementary material) and for 2013, the overall classification accuracy was 93% with a Kappa of 0.91 (Table S5, Supplementary material). For the islands, the overall classification accuracy for 2013 was 93% with a Kappa of 0.92 (Table S6, Supplementary material). The land cover change map had an overall classification accuracy of 85% and a Kappa of 0.75 (Table S7, Supplementary material).

3.3. Factors affecting freshwater marsh conversion on the mainland part of the Lower Delta

The BRT models of conversion of freshwater marshes to grasslands explained 43.0% of the total variation. Conversion was more likely in lands close to roads (<2 km), with middle cattle densities between 0.7 and 1.5 cows/ha, further away from population centers, close to rivers (<1 km), in areas within polders, close to human activity centers (<1 km), and in soils with a productivity index higher than 10 (Table 2, Fig. 4). We found an interaction among variables where the effect of cattle density was higher closer to rivers (Fig. S1, Supplementary material).

In landscape unit II, freshwater marsh conversion to grassland was mainly explained by cattle density, distance to population centers, rivers, roads and human activities centers (Table 2, Fig. S2, Supplementary material). On the contrary, in landscape unit V, area within polder, distance to population centers, roads and human activity centers, and cattle density explained freshwater marsh conversion to grassland (Table 2, Fig. S3, Supplementary material).

3.4. Factors affecting grassland conversion on the mainland part of the Lower Delta

The BRT model for grassland conversion to bare soil explained 53.0% of the variation, and cattle density, distance to human activity centers, rivers, roads and population centers explained together more than half of the variance captured by the model (Table 2). However, the partial responses of grassland conversion to bare soil for the five most influential variables indicated that none of these variables by themselves had a major effect on grassland conversion (Fig. S4, Supplementary material).

3.5. Factors affecting freshwater marsh conversion on the islands of the Lower Delta

The BRT model explaining the conversion of freshwater marshes to grasslands on the islands explained 65% of the variance, and the area

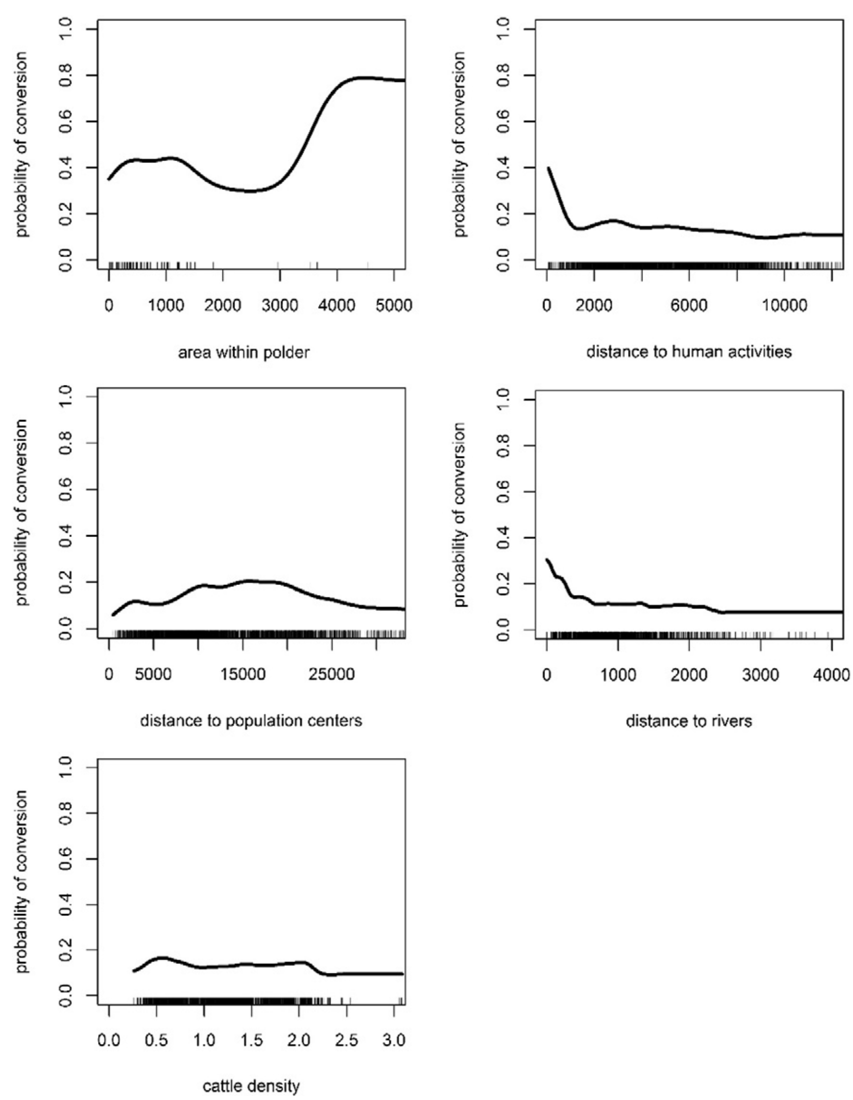

Fig. 5. Partial dependency plots for the five most influential variables that describe the probability of freshwater marsh conversion to forestry plantation on the islands of the Lower Delta. The vertical axis shows probability of conversion along the explanatory variable's data range displayed on the horizontal axis. The horizontal axis includes rug plots that show the distribution of the data in percentiles.

within polders alone contributed to almost half the model's explained variance (Table 2). The partial responses of the four most influential variables showed that freshwater marsh conversion to grassland was more likely in areas within polders, closer to roads (<1 km) and with cattle densities between 0.3 and 0.7 cows/ha (Fig. S5, Supplementary material).

The BRT model explaining the conversion of freshwater marshes to forestry plantations explained 55.0% of the variation. The area within polders and distance to human activity centers contributed together to almost half of the model's explained variance (Table 2). The partial responses of the most influential variables indicated that conversion was more likely in areas within polders, closer to human activity centers (<1 km), 10 to 20 km away from population centers and close to rivers (<500 m) (Fig. 5).

4. Discussion

We found rapid and widespread losses of freshwater marshes in the Lower Paraná River Delta in Argentina, where almost a third of all freshwater marshes were lost in only 14 years. Of those freshwater marshes losses, two thirds were due to the conversion to pastures and only one sixth due to the conversion to forestry plantations. The latter occurred mainly on the islands where forestry has historically been the main economic activity, but land use is now shifting to silvopastoral practices (Bó and Quintana, 2013). Factors related to land management and accessibility (i.e., cattle density, area within polders, distance to roads and population centers) were the main factors explaining the loss of freshwater marshes in the Lower Delta. Our results support our hypothesis that freshwater marsh conversion in the Lower Delta is mainly driven by human activities, particularly intensifying cattle farming, which are turning freshwater marshes into pastures. This "*pampeanización*" process is widespread, and large areas that were flooded frequently in prior years, are not reached by the periodic floods (within polders) and have been converted to dryer pastures.

Native wetlands in temperate regions have been frequently used as pastures (Brinson and Malvárez, 2002), and this is increasingly the case for the mainland part of the Lower Delta. Here, a combination of socio-economic and land management variables were the major factors affecting wetland loss. Cattle densities were included in almost all models, and the increase of cattle densities in the last decades is also the underlying cause for the increase in water control structures (Quintana et al., 2014b). For example, in landscape unit V, active water management is necessary due to frequent floods of Paraná and Uruguay rivers, and polders were the most influential factors explaining freshwater marsh conversion. Once freshwater marshes are within polders and no longer flooded, they can be drained and converted into productive lands, generally pastures. In contrast, in landscape unit II, where the use of polders was less common, higher cattle density became the main driver of freshwater marsh conversion. In some areas (e.g. unit IIa), drainage with ditches is a common practice. Despite we could not quantify the area under this type of practice for water management; we have observed their strong effects draining the wetlands in the study area. A similar trend has occurred in south east Cordoba (center of Argentina) where 42% of the lowlands and flooded areas have been lost due to the construction of drainage ditches that mitigate floods and favors agriculture expansion (Brandolin et al., 2013).

Similarly, increasing cattle numbers have degraded grasslands in the region, but we had only limited data to capture this. We could only detect an increase in bare soil related to bald spots on the mainland area. Due to its geomorphologic origins the entire region has marine salt deposits next to the soil surface which tend to arise causing bald spots bare of any vegetation (Kandus et al., 2006). These bald spots are frequent in unit I, but they are becoming more frequent and extensive across the area. Cattle grazing and trampling can promote the creation of bare patches in meadows (Reeves and Champion, 2004), as was observed in native grasslands of the Lower Delta when the number of cattle increased. Furthermore, grasslands closer to roads and other places of relatively high human activity (e.g., recreational areas) are more likely to be converted to bare soil.

Throughout the world, wetland conversion is largely due to the expansion of croplands and settlements (Gerakis and Kalburtji, 1998; Rebelo et al., 2009; Song et al., 2012). However, in the Lower Delta, urban areas remained underdeveloped even at the end of our time series (2013). In the present study, the cause of increased bare soil is not only related to urban development but to overgrazing. Only in the Lower Delta islands (particularly landscape unit IVb), urban development is expanding through the development of private nautical neighborhoods (Fabricante et al., 2012). These neighborhoods are replacing former wetlands, but their impact and extent is reduced. Furthermore, row crops remain uncommon in the area, unlike most tropical and subtropical wetlands (Gerakis and Kalburtji, 1998; Rebelo et al., 2009; Song et al., 2014). Nevertheless, some soybean fields and forage crops have been introduced in recent years (especially within polders), a process that could grow in the future (personal obs).

The natural heterogeneity of the region resulted in different land cover change patterns. There are major differences in land uses between mainland and the islands of the Lower Delta. Mainland areas witnessed the highest increases in cattle density and exhibited the highest rates of freshwater marsh conversion to grassland as well as the increasing of bare soil. On the islands, freshwater marshes' loss was also high but mainly due to the expansion of forestry plantations. *Salix* spp. remains the most important plantation type in the Lower Delta, but the development of *Populus deltoides cv.* clones adapted for the Paraná River Delta region has fostered the use of this species in plantations (Borodowski and Suárez, 2004). In summary, cattle ranching and forestry were the main forces causing land cover changes in the Lower Delta, and their relative importance varied among landscape units.

Acacia caven and *Prosopis nigra* dominated native forest area decreased on the mainland part of Lower Delta, as in many other areas worldwide in that period of time (Hansen et al., 2013). Wood extraction, fires and the impact of cattle grazing and trampling may have caused a decrease in tree density converting this habitat into more open shrub lands, that were likely mapped as grasslands in our classifications (as was suggested for other ecosystems by Hosonuma et al. (2012)). On the other hand, *Erythrina crista-galli* forests have increased in the islands of the Lower Delta. This increase might have been the result of the primary succession that took place in the new islands formed in the Lower Delta front on the estuary of De la Plata River (Biondini and Kandus, 2006) and the lowest anthropic impact that these islands experienced.

Extreme events of fires and floods were of minor importance in our models of freshwater marsh conversion in the Lower Delta. Burned area was not an important variable in any of our models. The rapid recovery of wetland vegetation such as bulrushes after fires could account for this (Salvia et al., 2012), highlighting that wetlands are very resilient environments as long as the water dynamics are not disturbed (Quintana et al., 2014c). As for biophysical factors, freshwater marsh conversion was different across landscape units showing the importance of environmental heterogeneity in wetland conversion at landscape scale. However, our results indicates that biophysical factors and the Lower Delta dynamics do not have great influence in freshwater marsh conversion when compared to human related factors. When the hydrological regime is altered by water management practices freshwater marshes in the Lower Delta cannot recover, at least during the time studied.

In the future, we expect that freshwater marsh conversion will continue in the Paraná River Delta, with potentially unpredictable negative consequences for the people and the environment. The low price of lands in the Lower Delta compared to lands in nearby regions (Pampa's and Espinal regions) could promote the freshwater marsh conversion to different land uses, not only pastures (Gerardo Mujica - INTA Delta office - personal communication). For instance, urban expansion could be a future conversion factor, especially on the islands of the Lower

Delta where private neighborhoods are becoming popular urbanization types (Fabricante et al., 2012). In addition, pressure from people from Buenos Aires looking forward to live closer to natural amenities is increasing. Crop cultivation could also expand, particularly in lands within polders. These land use changes can generate deeper impacts to the environment, and also social conflicts (e.g., the sending off local communities from the area as agribusiness companies set in the Delta; Quintana et al., 2014a).

The modification of the Delta's hydrological regime due to water management infrastructure has already undermined important wetland ecosystem services. For instance, carbon storage, hydric soils characteristics and flood buffering capacity have been altered due to freshwater marsh conversion to willow plantation (Ceballos, 2011; Oddi and Kandus, 2011). If conversion continues, local communities and nearby cities could be affected by a reduced flood buffering capacity. The "*pampeanización*" process could also have negative effects for wetland species and, on the contrary, alien species may be favored by this process such as mammals and plants typical of the adjacent Pampean areas which have been observed within levees in recent years (Bó et al., 2010; Fracassi et al., 2010).

5. Conclusions

The Lower Paraná River Delta is a prime example of a wetland landscapes being rapidly modified by human activities. Unlike most wetland conversion examples, cattle grazing expansion and intensification with extensive use of water management infrastructure was the main force behind wetland loss. The rate of conversion is very high and loss of wetland areas will continue if environmental regulation and spatial planning are not implemented. A management plan for a sustainable use of wetlands in the Delta of Paraná River (Plan Integral Estratégico para la Conservación y Aprovechamiento Sostenible en el Delta del Paraná), elaborated in 2008, represents a first step towards planning of human activities in this region (Gaviño Novillo, 2011). However, our results show little effectiveness of these management policies due to the lack of national laws or regulations protecting wetlands in Argentina. These regulations should both determine the land management practices recommended for this wetland, and control wetland conversion to productive systems. Thus, effective land use planning will not only benefit forestry and livestock producers, but also to the local community by ensuring the provision of key ecosystem services.

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Appendix A. Supplementary material

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