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Natural grassland remnants in dynamic agricultural landscapes: identifying drivers of fragmentation

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HIGHLIGHTS

- Multi-temporal cropland mask allows accurate classification of grassland remnants.
- Grasslands of Uruguayan Eastern Plains are in an advanced stage of fragmentation.
- Suitability for rice crop establishment drives the grassland fragmentation.

GRAPHICAL ABSTRACT
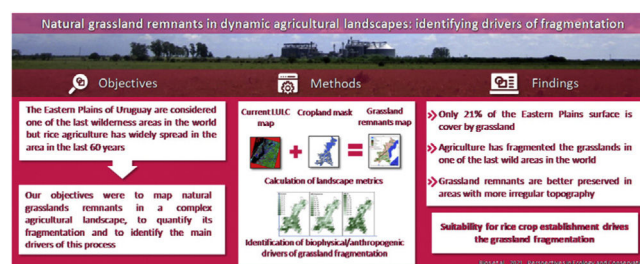
ARTICLE INFO

ABSTRACT

Grasslands have been subject to contraction and fragmentation processes worldwide, mainly due to their transformation into commercial tree plantations and agricultural lands. Identifying the remaining grasslands areas and the drivers of its fragmentation constitute an important step towards their appreciation, conservation and sustainability monitoring. The Eastern Plains of Uruguay constitute a region of recognized national and international conservation importance, but rice cultivation has spread extensively over the last 60 years, resulting in a strong transformation of its natural biomes. Our objectives were to map natural grasslands remnants in this complex landscape characterized by a high presence of different post-agricultural stages of vegetation; to quantify grassland fragmentation and its spatial variability in the landscape; and to identify the main drivers of the fragmentation process. We intersected a current supervised classification of the Eastern Plains of Uruguay (743,600 ha) with a mask of croplands from the previous ten years to discriminate grasslands remnants. We quantified the landscape fragmentation and described the relative contribution of different biophysical and anthropogenic factors in grasslands spatial configuration. Our results showed that natural grassland currently occupies only 21% of the Eastern Plains surface and it is in an advanced stage of fragmentation, comparable to that of the most historically transformed regions of the *Río de la Plata Grasslands*. A few variables that determine the expansion of agriculture (large cadastral parcels size, high road network density and low topographical variation) drive the fragmentation process, relegating grassland to places with unfavorable characteristics for the development of rice cultivation.

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Introduction

Changes in land use/land cover over the last 150–200 years, mainly due to a large increase in cultivated land in natural grassland areas, have led to severe habitat lost and fragmentation of most of the grasslands in the world (Fuhlendorf et al., 2017; Gibson, 2009; Samson et al., 2004). Fragmentation refers to the processes by which the landscape structure is modified from a homogeneous to a more heterogeneous or patchy configuration, and where the original vegetation is preserved in patches surrounded by a matrix with variable degree of transformation (Saunders et al., 1991). While fragmentation per se does not usually have negative effects on biodiversity (Fahrig, 2017), this process often occurs simultaneously with habitat loss and is strongly correlated with it (Villard and Metzger, 2014). When both processes co-occur, they affect biodiversity by changing the quality, size, density, and connectivity of habitat patches and thus altering the balance between immigration and extinction rates (Bennett and Saunders, 2010; Jackson and Sax, 2010; Fahrig, 2003; MacArthur and Wilson, 1967). The vast majority of natural grasslands today are immersed in a diverse matrix of land cover types, often associated with production or economic development (Scholtz et al., 2018). As a result, reduction of proper habitats and decline in metapopulation connections for grassland specialist species affect plant and animal diversity (Deák et al., 2021; Lampinen et al., 2018; Staude et al., 2018; Fahrig, 2003) and promotes biological invasions (Guido et al., 2016). This not only leads to the disappearance of species of conservation interest, but can also negatively affect ecosystem functioning by causing functional homogenisation which considerably decrease the community level resistance and resilience, and thus further aggravate habitat degradation processes (Clavel et al., 2011).

The "*Rio de la Plata Grasslands*" is the largest grassland region in South America (more than 70 million ha) (Soriano, 1991) and it has been transformed into cropland at high rates since the beginning of the 20th century (Hall et al., 1992). Due to technological changes and raised international market demands, agricultural expansion has increased markedly in the last three decades (Baeza and Paruelo, 2018, 2020; Baldi and Paruelo, 2008). Although transformation to agricultural land has allowed the provision of food and fiber, it has had a great impact on the provision of other still undervalued ecosystem services that depend on grasslands, such as carbon storage, soil generation, nutrient cycling, among others (Baeza and Paruelo, 2018; Sala and Paruelo, 1997; Texeira et al., 2019; Viglizzo et al., 2011). Several authors have recognized that the edaphic and climatic variables determine cropland expansion and grassland fragmentation in this region (Baldi et al., 2006; Guerschman et al., 2003; Viglizzo et al., 2001). Therefore, natural grasslands tend to be found in marginal areas, where agriculture or intensive livestock are not economically profitable activities (Baeza and Paruelo, 2018; Baldi et al., 2006; Guerschman et al., 2003; Krapovickas and Di Giacomo, 1998).

Uruguay is completely within the *Rio de la Plata Grasslands*, which also cover the great plain of Central-eastern Argentina and the South of Brazil (Soriano, 1991) (Fig. 1). Particularly the Easter Plains (also known as "Merin Lagoon pit") (Panario, 1988) is a biogeographic subunit of Uruguay, where conservation and productive interests converge (Brazeiro et al., 2015; DIEA and MGAP, 2003). It constitutes an important fresh water reservoir that supplies all the surrounding ecosystems, provides a large number of habitats and numerous supporting services (Clara and Maneyro, 1999). The Eastern Plains wetlands are included in the Ramsar international conservation list (https://rsis.ramsar.org/es/ris/290), due to be considered one of the largest, richest and most varied wetland systems in South America. Notably, Mittermeier et al. (2003) has ranked it as one of the last wilderness areas in the world. At national level, Brazeiro et al. (2015) recognized it as one of the ecoregion in Uruguay with the highest priority for conservation, accounting for 724 species of amphibians, reptiles, birds, mammals and woody plants (grasses and herbaceous plants were not evaluated). However, there has been a strong transformation in the last 60 years as rice cultivation has spread in the area. Scarlato (1993) documented the beginning of this phenomenon in the 1960s, attributing it to the large availability of suitable soils, water sources and the implementation of large drainage works.

Spatially explicit land use/land cover (LULC) descriptions are a fundamental input for land-use planning and the promotion of conservation practices (Baeza et al., 2014; Hansen et al., 2000; Intergovernmental Panel on Climate Change (IPCC), 2019). Despite the fact that the Eastern Plains are one of the regions with the greatest conservation importance in Uruguay (Brazeiro et al., 2015) and the strong process of land use change that it has undergone, there is no LULC map that accounts for its natural grassland remnants, probably due to the difficulty of discriminating them in a particularly complex context. This complexity stems from the fact that the rice cultivation systems in Uruguay usually combine two consecutive years of rice followed by a period of two to four years of pastoral use, during which different types of management can occur, such as pasture sowing for cattle (with or without tillage) or spontaneous regeneration of the vegetation (Battello et al., 2013; Pittelkow et al., 2016). Consequently, a significant portion of the area is covered by post-agricultural fields with different stages of vegetal succession. These vegetal covers present similar spectral behavior to that of natural grasslands, which makes them difficult to discriminate with remote sensing and explains their classification as the same category in previous local and regional maps (see for example Baldi et al., 2008; Baeza and Paruelo, 2020).

In this work we mapped the natural grasslands remnants in the Easter Plains of Uruguay, combining a current detailed supervised classification with binary classifications that account for agricultural use in the recent past. We used the generated map to quantify grassland fragmentation and its spatial variability, and combined it with a set of biophysical and anthropogenic variables to identify the main drivers of the fragmentation process. We hypothesized that the degree of suitability for rice cropping determines spatial variation in grassland fragmentation. We expected that those areas where the conditions for rice cultivation are more attractive (e.g., areas with higher percentage of soils that facilitate the establishment of a flood plain; less slope; high density of hydrologic network; large paddocks; and areas near or with accessibility to rice logistics foci) would be the most transformed, with greater grassland fragmentation.

Materials and methods

Study area

Our analysis focuses in the Eastern Plains of Uruguay, the Southeast portion of the *Rio de la Plata Grasslands* (Fig. 1) (Soriano, 1991). The Eastern Plains have an extension of 743,600 ha covering a latitudinal range that goes from 32°28′S to 33°54′S. The average annual temperature is around 16.4 °C and the annual accumulated rainfall is approximately 1200 mm (INUMET, 2019). This area is traditionally devoted to rice cultivation as well as to extensive cattle raising (MGAP and DIEA, 2011). The predominant natural ecosystems are grasslands, wetlands and palm groves savannas (Achkar et al., 2012).

Land use/land cover (LULC) mapping

We carried out the LULC map in two stages. First, we made a supervised classification of a *Landsat 8* image from 2016 that
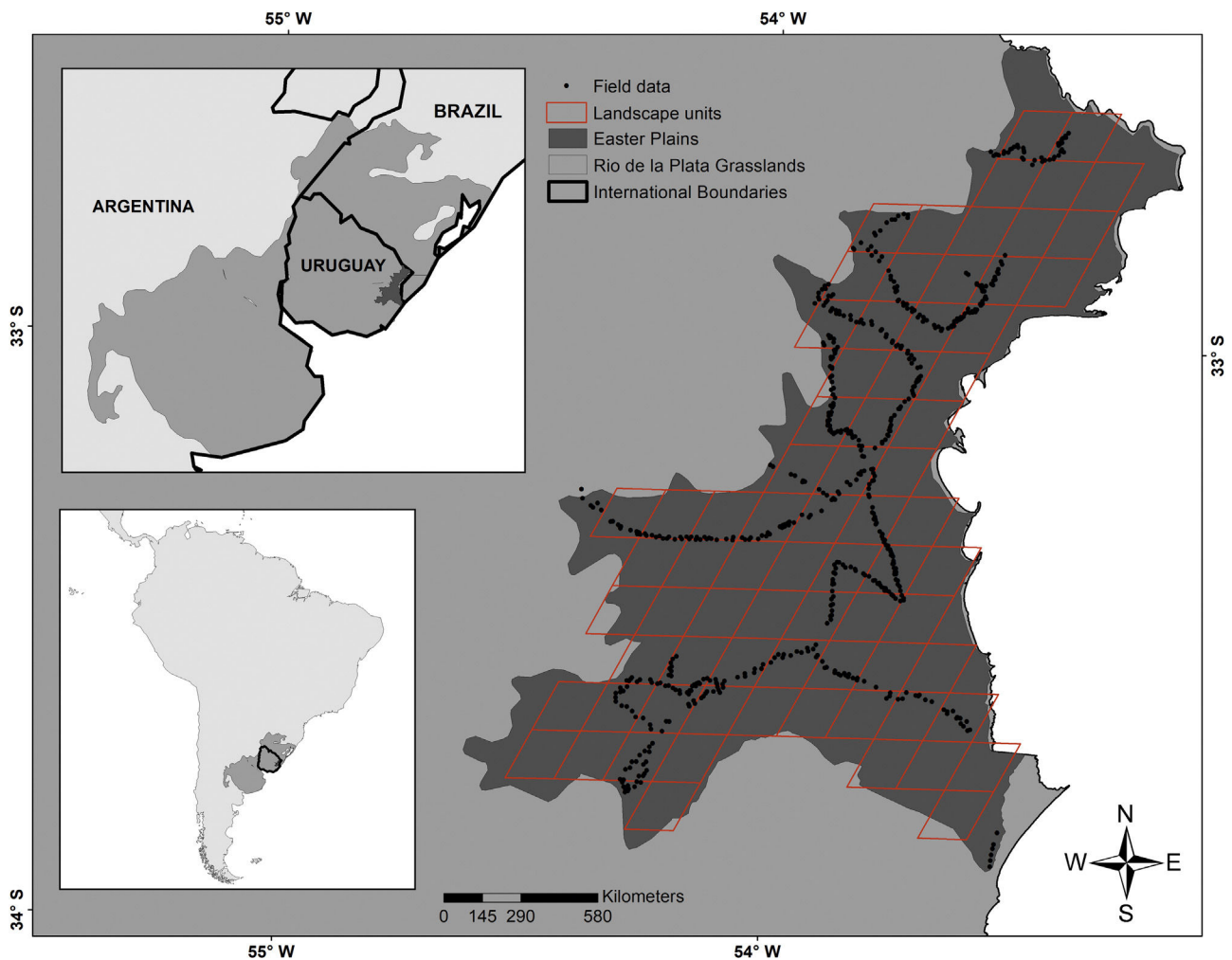
Fig. 1. Geographical location of the *Rio de la Plata Grasslands*, Uruguay and the Eastern Plains. Points in the Eastern Plains map represent the location of ground truth data and grid cells are the Landscape Units (10 × 10 km) for the landscape analysis.

discriminates among five categories (Section "Supervised classification"). Second, we made decision-tree classifications of two categories (bare soil and "other" uses) of each of the best images available from 2007 to 2016, in order to generate a multi-temporal cropland mask with all those pixels of the study area that had agricultural use at least on once in the mentioned period of time (Section "Cropland mask"). The final LULC map was generated by superimposing the cropland mask on the 2016 classification (Section "Final land use/land cover map").

Supervised classification

We made a supervised classification of the current LULC of the study area, using a cloudless *Landsat 8* image (*path* 222/*row* 083; 13/08/2016) close in time to the ground truthing date. We corrected the *Landsat* image atmospherically and radiometrically (Chander et al., 2007; Chander and Markham, 2003). Field information came from a trip during the first week of February 2017, where we obtained information for 658 paddocks. We confirmed and corrected their identity for the classification date, by visual interpretation of the false color composite (RGB: 4−3−2) of *Landsat* image and Google Earth (http://www.google.com/earth). The plots of the different classes were randomly divided into two subsets, 70% of them were used to train the classification algorithm and the other 30% were used later as ground truth to evaluate the final LULC map. The maximum likelihood classification algorithm was used for all reflective bands (Lillesand et al., 2014). In this

classification stage, the classes were: wetland, native forest, tree plantations, crop and forage resources. The last one includes natural grassland, sown pastures and rice stubbles in different stages of post-agricultural succession.

Cropland mask

We elaborated a mask of the agricultural use for the 2007–2016 period using twelve atmospherically and radiometrically corrected *Landsat 5 and 8* images. At least one image per year was selected on dates with the least cloud cover, trying to capture those moments of the year before sowing or after harvesting rice crop (except for the year 2012 since all the images presented more than 50% of cloud cover). As the main rice management practices in the study area imply the soil preparation long before planting (e.g., tillage, ground leveling, construction of irrigation channels), paddocks remain with very low or nil vegetation coverage most of the year. Based on this trait, we identified agricultural ground truth samples on each *Landsat* image through the visual interpretation of bare soil by means of infrared color composites (RGB: 4−3−2 or RGB: 5−4−3 in *Landsat* 5 and 8, respectively). For each image, we interpreted and digitalized at least 100 representative plots (polygon vectors of 1−5 ha) for each cover type (i.e., bare soil, wetland, forest, tree plantations and forage resources). As in the 2016 supervised classification, a 70%/30% of the plots of each year were used to train/evaluate each classification. We determined ranges of reflectance values of the pixels belonging to the "bare soil" class

Table 1
List of landscape metrics calculated for each of the 74 cells covering the study area.

Landscape metric	Equation	Minimum theoretical value	Maximum theoretical value
Percentage of landscape (PL)	$100 \dfrac{\sum_{i=1}^{n} A_i}{A_t}$	0%	100%
Number of patches (NP)	n	0	≈2645
Modified effective mesh size (EMS)	$\dfrac{1}{A_t} \cdot \sum_{i=1}^{n} (A_i . A_i^{cmpl})$	≈3.8 ha	≈10,000 ha
Nearest neighbor distance (NND)	$\dfrac{\sum_{i=1}^{n} (d_i)}{n}$	≈30 m	≈14,142 m

Abbreviations: n is the number of patches; A_i is the patch i area (ha); A_t total area of the landscape unit (ha); A_i^{cmpl} is the entire patch area of which A_i is a part (ha); d_i is the *Euclidean* distance from patch i to its nearest neighbor (m). The theoretical minimum and maximum for each metric are approximate values as they do not consider the Moser Modification (Moser et al., 2007) and are calculated using the grid cell size of 10×10 km as maximum area, which is not the exact value considered for the calculations of the landscape metrics due to the sinusoidal projection.

Table 2
Biophysical and anthropogenic variables included in the fragmentation drivers analysis and those included in the multiple linear regression model (MLRM).

Variable	Attribute	Description	Included in the MLRM	Data source
Road networks	Total density	Extension of all types of road in the cell, divided by the classified area	*	IDE[1]
	Secondary road density	Extension of internal roads in the cell, divided by the classified area		IDE
Cadastral parcels	Density	Number of cadastral parcels in the cell, divided by the classified area	*	DINOT[2]
Soil type	*Planosols* percentage	Cell Percentage which has *Planosols* as dominant soil	*	RENARE[3]
	Planosols and/or *Gleysols* percentage	Cell Percentage which has *Planosols* and/or *Gleysols* as dominant soil		RENARE
Hydrology	Hydrological network density	Hydrological courses extension in the cell, divided by the classified area	*	IDE
	Hydrological surface density	Accumulated surface of waterbodies in the cell, divided by the classified area		IDE
	Hydrological edges density	Edge extension of hydrological courses in the cell, divided by the classified area		IDE
Topography	Elevation range	Land height range above sea level in the cell	*	USGS[4]
	Average elevation	Average land height in the cell		USGS
	Standard deviation	Land height standard deviation in the cell		USGS
Space location	Latitudinal gradient	Y axis coordinates of the cell centroid.	*	Coordinate system UTM21S.
	Longitudinal gradient	X axis coordinates of the cell centroid.	*	Coordinate system UTM21S.

1: IDE: Spanish acronym for Uruguayan Spatial Data Infrastructure. 2: DINOT: National Directorate of Territorial Planning. 3: RENARE: General Directorate of Renewable Natural Resources, Ministry of Livestock Agriculture and Fisheries. 4: USGS ASTER GDEM: Advanced Spaceborne Thermal Emission and Reflection Radiometer, Global Digital Elevation Map.

* Variables included in the MLRM analysis.

and the "other" class, using reflectance values of all reflective bands of *Landsat* 5, *Landsat* 8 and the Normalized Difference Vegetation Index values (NDVI) (Tucker, 1979; Tucker et al., 1985) of training plots. We calculated the dispersion ranges and threshold values for each class using the maximum and minimum reflectance values for each class in each band, as well as the frequency histograms. Those threshold values that maximized the separation between classes were translated into simple rules of belonging or not to each class. We used these rules to implement simple decision trees in ENVI (Exelis Visual Information Solutions, Boulder, Colorado). ENVI is a software for processing and analyzing geospatial images and its decision tree method consist in assigning a class to each pixel based on its compliance or non-compliance with certain user-defined rules. The products of our decision trees were annual binary maps, which assigned value 0 to the "agricultural use" class and value 1 to all other. Our final mask for agricultural use was generated with the arithmetic product of the twelve binary maps and it has "0" value

for all those pixels that were classified as bare soil (i.e., agricultural use) at least in one of the analyzed images.

Final land use/land cover map

We obtained the final LULC map by intersecting the cropland mask with the 2016 supervised classification, allowing us to discriminate the following categories: "agricultural use" that includes the pixels classified as "crop" in the supervised classification and those masked in the second stage; "natural grassland" that includes the pixels classified as "forage resources" in the supervised classification and that were not masked in the second stage; wetland; forest; tree plantation; water bodies and urban centers. These last two classes did not result from the classification process, as they were obtained from official vector information collected by the National Direction of Territorial Planning (DINOT, by its Spanish acronym) and available in the Spatial Data Infrastructure of Uruguay (IDEUy: http://ide.uy/). The LULC map accuracy was eval-
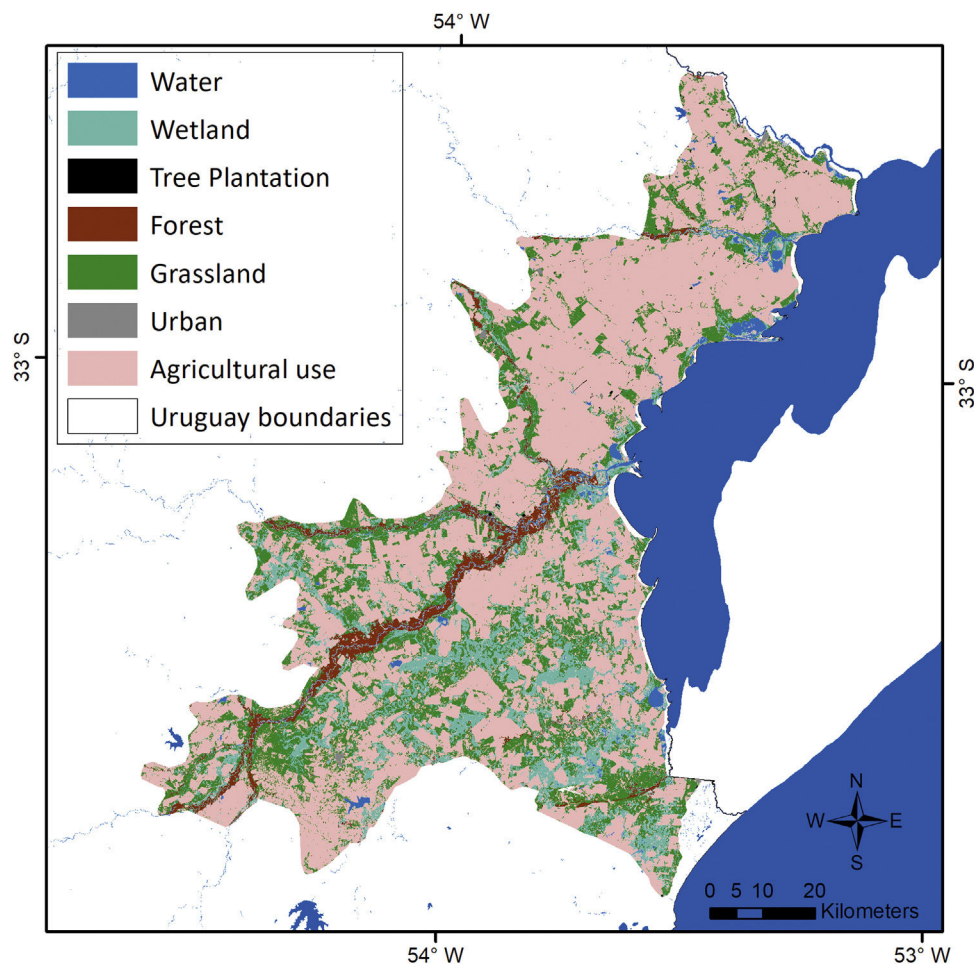
Fig. 2. Final land use-land cover (LULC) map of the Uruguayan Eastern Plains.

uated with a contingency matrix and omission/commission errors in the classification were calculated. The field truth used were those field data plots (corrected and reinterpreted for the image used in the 2016 classification) which were not masked.

Fragmentation characterization

The spatial variability of landscape patterns was explored through the intersection of LULC map with a 10×10 km cell size grid, each resulting cell was considered the "landscape unit" of the analysis. The study area comprises 74 cells that have at least 70% of its surface classified on the map (Fig. 1). For each cell, we quantified the percentage of grassland, wetland and agriculture use ("*Percentage of landscape*", PL) and estimated grassland fragmentation from three widely used metrics that can give good reference about grassland spatial structure and configuration, i.e., the *Number of patches* (NP), the *Effective Mesh Size* (EMS) and the mean *Nearest Neighbor Distance* (NND) (Table 1) (Jaeger, 2000; McGarigal and Marks, 1995). For the calculation of these metrics, we converted the LULC map from raster to vector format and eliminated all plots corresponding to urban, water bodies, and all those with an area smaller than 1,8 ha (equivalent to 20 *Landsat* pixels). The number of grassland patches, area and Euclidean distance were obtained with ArcGIS v.10.3. and the metrics were calculated manually in an excel spreadsheet. The PL, NP and NND are easily interpretable attributes that describe simple structural features of the landscape (Jaeger, 2000). However, they have the disadvantage of not necessarily reflecting the fragmentation processes, since two different landscape units could

have the same PL of some class, but have different division or isolation degree. The EMS, on the contrary, presents a more linear response to the different stages of the fragmentation process, even when fragmentation is not causing a marked decrease in habitat, like when the landscape is partially dissected by roads or other human infrastructures (Jaeger, 2000). It is calculated as an averaged size of the focus class weighted according to the class individual patch sizes. We made a mathematical modification of the EMS proposed by Moser et al. (2007) to eliminate what the author calls the "edge problem", which arises when considering the artificial edges that are generated in the limits of the landscape units.

Fragmentation drivers

To analyze the biophysical and human controls of fragmentation variability, we modeled natural grassland fragmentation considering the PL, EMS and the NND as dependent variables; and 13 independent variables (Table 2) from five datasets related to rice crop development aptitude. This comprised (Table 2): (1) anthropogenic variables, particularly the road network density (since a greater amount of roads tends to facilitates the human activities development) and cadastral parcels size (since rice activity tends to occupy the largest ones, facilitating logistic activities); (2) edaphic variables, like soil type (particularly *Planosols* percentage and *Planosols* and/or *Gleysols* percentage, which are the optimal soil types for rice activity in the region); (3) hydrological variables, particularly hydrological network density, water courses surfaces and edges density (due to the high water requirements of rice crops); (4)

Table 3
Contingency matrix of the final LULC map (expressed as percentage); classification omission and commission errors per class (expressed as percentage).

Classification Classes	Field truth (%)						Error (%)	
	Tree Plantation	Wetland	Forest	Agricultural use	Grassland	Total	Omission	Commission
Tree Plantation	**97.1**	0	0	0	0	7.7	2.9	0.1
Wetland	0.1	**98.7**	0.5	0.3	3.1	17.8	1.3	4.3
Forest	0	0	**99.5**	0.2	0	45.0	0.5	0.1
Agricultural use	0.5	0.1	0	**78.6**	0	10.4	21.4	0.5
Grassland	2.3	1.2	0	20.7	**96.9**	19.0	3.1	16.4
Total	100	100	100	100	100	**100**	–	–

Table 4
Average; standard deviation; maximum and minimum value of: agricultural use, wetland and grassland percentage (PL); grassland number of patches (NP); grassland effective mesh size (EMS) expressed in hectares; and grassland Euclidean distance to the nearest neighbor (NND) expressed in meters.

Metrics	Average	Standard deviation	Maximum	Minimum
Agricultural use PL (%)	60.85	20.32	96.59	17.75
Wetland PL (%)	12.59	11.07	47.58	0.15
Grassland PL (%)	20.66	11.20	53.82	1.79
Grassland NP (n°)	38	16	78	12
Grassland EMS (ha)	351	710	3870	0.4
Grassland NND (m)	152	68	387	71

topographic variables, particularly ground elevation and elevation variations (since low and flat lands facilitates the necessary flooding and drainage process of rice crop); and (5) spatial location variables (latitude and longitude) as aggregation indicators which may be associated with the presence of some industrial foci (Table 2). The set of independent variables has different spatial resolutions (ranging from pixels of 900 m^2 in the digital elevation model, to irregular units with an approximate median value of 1.500.000 m^2 in the soil types cartography) so they were summarised for each grid cell of the previous section, as shown in Table 2. Correlation analysis between all explanatory variables was performed by means of Pearson's coefficients. Finally, we explored the dependences of landscape metrics to the independent variables (biophysical and anthropogenic) by a stepwise multiple linear regression model. High correlated variables (significance value upper to 0.05 and correlation coefficient value equal or upper to |0.6|) were excluded.

Results

The mapped area covered 743,642 ha, 21% (155,021 ha) correspond to natural grassland, 60% agricultural use, 13% wetland, 4% forest and 2% water, while tree plantation and urban area were negligible (Fig. 2). The contingency matrix for the final LULC map showed an overall accuracy of 96% and commission-omission errors generally low and equitably distributed. The best discriminated category was forest, while the greatest confusion occurred between agricultural use and grassland. Grassland commission error was 16.4% since 20.7% of the ground truth pixels of agricultural use were misclassified within this class. Nevertheless 96.9% of grassland ground truth pixels were correctly classified (Table 3). The cropland mask evaluation showed very accurate results too since the decision tree classifications presented an average accuracy of 98% in the discrimination of the bare soil plots of the subset data reserved for the evaluation (see Table A1 in Appendix A).

The landscape analysis revealed a system characterized by an agricultural matrix (Table 4) with a variable presence of grasslands and wetlands, both less represented towards the Center and North of the study area (Fig. 3a–c). On average, the remaining grassland patches by cell are few (NP = 38 patches), small (EMS = 351 ha) and isolated from one another (NND = 152 m) (Table 4). The spatial distribution of landscape metrics shows better grassland conservation status in the southern of the study area, where cells showed more

grassland patches (Fig. 3d), bigger (higher EMS) (Fig. 3e) and more connected (lower NND) (Fig. 3d).

The multiple linear regression models showed that almost half of the variability of each landscape metric was explained by a small group of anthropogenic and biophysical variables: the cadastral parcels density, elevation range, total road density, hydrological network density and latitude (Table 5). Lower grassland percentages were found in larger cadastral parcels areas, flat topography and highest road network density areas. Consistently, the most fragmented areas (with lower EMS) were those with less irregular topography. Finally, grassland remnants were more isolated (higher NND) in areas with greater water availability, around certain particular points of the territory and where there are larger cadastral parcels.

Discussion

In this work we generated the first LULC map that discriminates the remnants of natural grassland in the Eastern Plains of Uruguay with precision and great level of conceptual detail using a novel methodology. The results showed a highly transformed landscape (one of the most modified in the country and the *Rio de la Plata Grasslands*) with a very low proportion of grassland and a high degree of fragmentation. This grassland fragmentation in the Eastern Plains is associated with a set of biophysical and anthropic factors related to the sites suitability for rice cultivation, the main agricultural activity in the region.

Mapping grassland remnants

Spatially and conceptually detailed data acquisition results essential to quantify subtle land cover changes in highly transformed landscapes with high biodiversity potential (Mallinis et al., 2011). Despite the fact that grasslands are among the most threatened and transformed biomes in the world, and the large-scale development of rice agriculture in the Eastern Plains, most of previous maps covering the study area did not attempt to discriminate between natural grasslands and other forage resources (Baeza and Paruelo, 2020; Graesser et al., 2015; Volante et al., 2015; Blanco et al., 2013; Clark et al., 2012; Friedl et al., 2010; Hansen et al., 2000). This is due to different objectives and scale analysis of these works, but also to the difficulty of discriminating natural grasslands from other herbaceous plant formations with satellite images. Map-
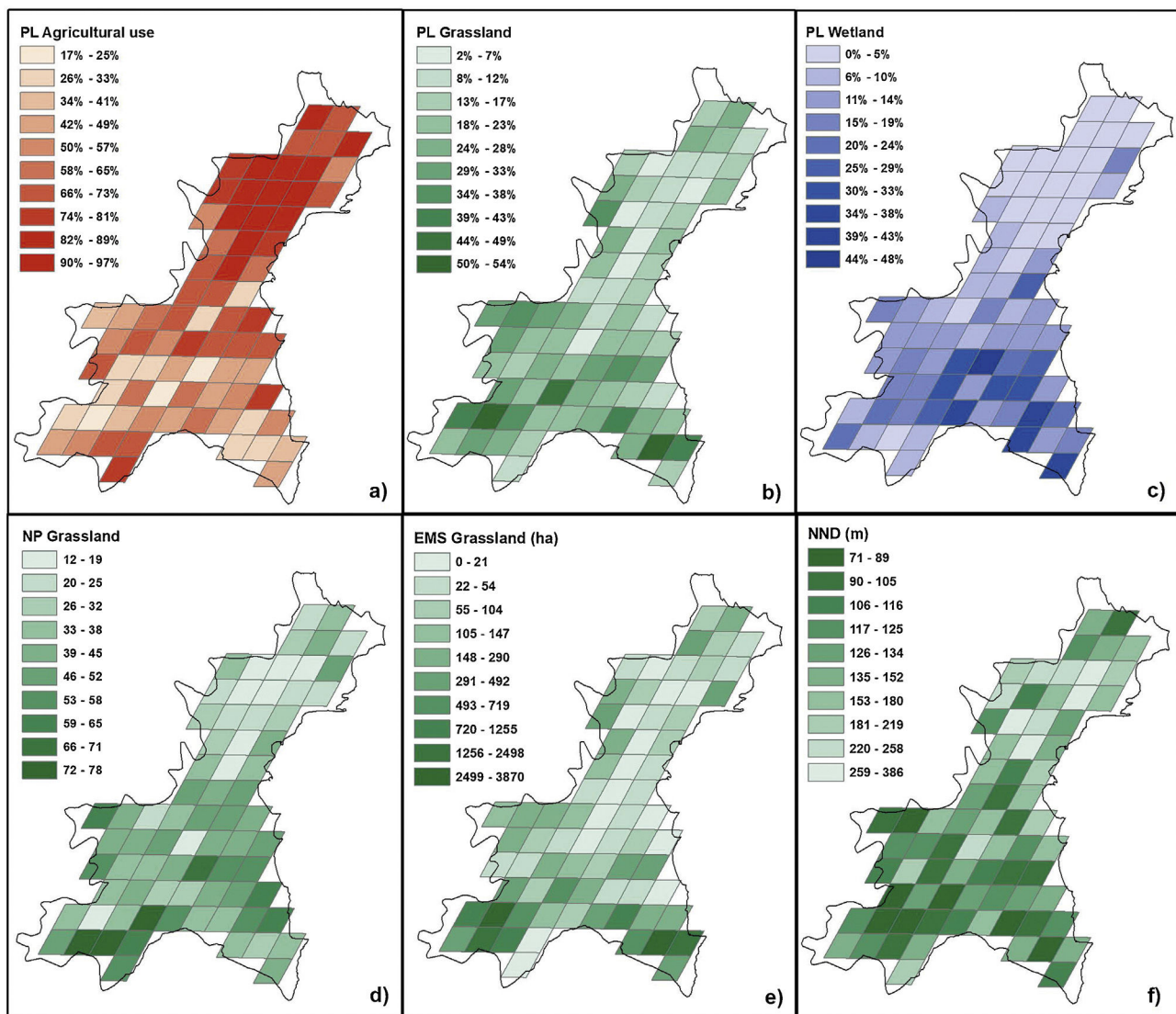
Fig. 3. Spatial variation of a) agriculture, b) grassland and c) wetland surface percentage (PL); and d) grassland number of patches (NP), e) grassland effective mesh size (EMS) and f) mean nearest neighbor distance (NND) of grassland patches.

Table 5

Partial coefficients of determination (partial r²); accumulated coefficients of determination (accumulated r²), standardized regression coefficients (β), unstandardized regression coefficients (B) standard errors, t-values, lower and upper bounds for each independent variable of the multiple linear regression models, for the landscape metrics included in the analysis (grassland PL, EMS and NND), all with statistical significance (< 0.05). Partial r² describes the proportion of the variability explained by each explanatory variable when the linear effect of all other variables is included in the model; the accumulated r² is the proportion of the variability explained by all the variables included in the model; and the β indicates the magnitude and sign of individual variables for every model.

Dependent var.	Independent var.	Partial r²	Accumulated r²	β	B	Standard Error	t-value	Lower bound	Upper bound
Grassland (%)	Cadastral parcels density	0.20	0.20	0.44	7266579.79	1509827.3	4.81	4255324.21	10277835.38
	Total road density	0.13	0.33	−0.34	−3773.94	1017.00	−3.71	−5802.29	−1745.59
	Elevation range	0.08	**0.41**	0.30	0.104	0.03	3.19	0.04	0.17
EMS	Elevation range	0.41	**0.41**	0.65	147744.13	20404.55	7.24	107068.4	188419.86
NND	Hydrologic network density	0.26	0.26	0.37	3162.975	769.20	4.11	1628.86	4697.09
	Cadastral parcels density	0.14	0.40	−0.36	−36669070.92	8780741.95	−4.18	−54181708.53	−19156433.31
	Latitudinal gradient	0.07	**0.47**	0.28	.001	0.0002	3.12	0.00018	0.00084

ping natural grasslands in the highly agriculturalised context of the Eastern Plains is not an easy task with the usual remote sensing techniques. Rotating system of rice production in Uruguay generates a wide variety of post-agricultural stages of vegetation as a consequence of different management practices, from sown pastures to different successional states of spontaneous vegetation growing after rice harvesting (i.e. crop weeds and other ruderal species). In spite of their structural differences (composition, diver-

sity, percentage of alien species, etc.) these vegetation stages have similar phenological behavior to that of natural grassland which generates an overlapping of spectral signals and impedes natural grassland discrimination (Baeza et al., 2014). In our work these difficulties were solved with a simple and replicable technique that discriminates natural grasslands based on a combination of a broad classification of forage resources and the identification of plots that had agriculture in the recent past. The reconstruction of recent

agricultural history has proven to complement the information provided by the current LULC classifications (Schmidt et al., 2016; Yan and Roy, 2014; Maxwell and Sylvester, 2012). Considering that paddocks dedicated to rice cultivation remain with very low or nil vegetation coverage most of the year, the agricultural history of the previous ten years was reconstructed from the detection of bare soil. Contrary to what happens with grasslands, bare soil before planting the crop or after harvesting has a very clear spectral signal, useful to discriminate areas that have had agriculture at some point and that allowed us to exclude them from grassland class in the final map. In a previous work, Maxwell and Sylvester (2012) combine intra- and inter-annual time series with spectral and temporal metrics to detect patterns in permanent cultivated lands and thus achieve accurate classifications. Other works combine time series with object-based analysis to generate automatic computational methodologies to distinguish cultivated areas (Schmidt et al., 2016; Yan and Roy, 2014). These techniques could not be applied in the study area due to the high clouds cover (even with years without a single useful image). Recent regional initiatives such Mapbiomas (Souza et al., 2020), particularly MapBiomas Pampa (https://pampa.mapbiomas.org/) has implemented the available technology to discriminate natural grasslands for other LULC. While their results remain to be validated, they are very similar to those found in our work.

Grassland conservation status in the Eastern Plains

Our results reveal how agricultural transformation has fragmented the natural grassland in the Uruguayan Eastern Plains, a fact observed in many regions of the *Rio de la Plata Grasslands* (Baeza and Paruelo, 2020; Clark et al., 2012; Baldi and Paruelo, 2008; Baldi et al., 2006; Guerschman et al., 2003). Only a 21% of the study area is covered by natural grassland remnants, which places the Eastern Plains as the most transformed region in the country so far. For comparison purposes, Baeza et al. (2019) mapped the natural grassland communities of the main livestock areas of Uruguay and reported that the percentage of natural grassland varied according to the region considered, from 39% in the South Central Region and 75% in the Basaltic Region (Baeza et al., 2019).

According to the conceptual scheme proposed by Forman and Gordón (1986) and modified by Jaeger (2000), natural grasslands in the Eastern Plains are in the most advanced stage of fragmentation process (i.e., shrinkage or attrition), being poorly represented in the landscape, and their remnants are highly divided into small patches. At regional level, Baldi and Paruelo, 2008 analyzed different regions of the *Rio de la Plata Grasslands* through the EMS and reported the most critical scenarios in the Flat Inland Pampa and Rolling Pampa, with values very close to those obtained in our work (EMS: 150 and 334 ha, respectively). The results obtained for the Eastern Plains are worrying, the degree of natural grasslands fragmentation is comparable to that of the historically most cultivated and transformed regions of the *Rio de la Plata Grasslands* (Baeza and Paruelo, 2018, 2020; Paruelo et al., 2005). These results contrast with those of Mittermeier et al. (2003), which consider the study area as one of the last wild areas in the world. Differences may be due to an increase in agricultural area in the first decades of the 21st century and/or differences in the conceptual resolution in their base maps, which do not discriminate natural grasslands from other forage resources. The evidence found in the Eastern Plains does not differ from the critical scenarios reported for other temperate grasslands in the world (Watson et al., 2016; Bond and Parr, 2010; Neke and Du Plessis, 2004) which once again places them as one of the most threatened natural biomes.

Drivers of grassland fragmentation

The results obtained from the multiple linear regression analysis support the hypothesis that factors that define the establishment of rice activity determine the spatial variation of grassland fragmentation in the Eastern Plains. The same has already been indicated in numerous works for other crops in Uruguay (Arbeletche et al., 2012; Arbeletche and Gutiérrez, 2010; Baeza et al., 2014; Hoffman et al., 2013; Paruelo et al., 2006) and in the region (Baldi et al., 2006; Baldi and Paruelo, 2008; Clark et al., 2012; Guerschman, 2005; Viglizzo et al., 2001). But unlike most of these studies, our results quantitatively demonstrate the relationship between agricultural suitability and the loss and fragmentation of natural covers. In our work, three variables turned out to be the main drivers of grassland replacement in the Easter Plains: the cadastral parcels density (therefore their size), the road network density and the topographical variation. Interestingly, topography explained 41% of the spatial variability of the EMS in the study area.

The places where natural grassland is more fragmented are those with flatter topography, with better suitability for rice cultivation due to easier access, management and final disposal of water (Battello et al., 2013; DIEA and MGAP, 2003, 2017). The areas with the lower percentage of grassland are concentrated in the North and Centre of the study region. In these places the average size of cadastral parcel is higher than in the South, which explains their lower density. A recent study shows that 80% of the rice planted in the Eastern Plains is on leased land, being more profitable the use of larger parcels (DIEA and MGAP, 2017). Since the main agro-industrial centers of rice are located there (Alegre et al., 2015; DIEA and MGAP, 2017), these areas have denser road networks that facilitate the movement of both production and machinery needed to implement the crop. In addition, the topographical variation is lower than in the South. Isolation of grassland patches is associated with similar variables; the NND variation is also explained by the size of cadastral parcels (finding more isolated patches in areas with larger parcels) and by the position in the landscape (closer to rice logistic foci). The density of hydrological network also explains the degree of isolation of grassland remnants, as more isolated patches are found in areas where there is a greater presence of water courses, probably due to the high water requirements of rice cultivation.

Several studies have affirmed that landscape composition in the *Rio de la Plata Grasslands*, and indirectly grassland fragmentation, are not random processes. There is a complex interaction between different variables that restrict agriculture expansion, relegating grassland to places where unfavorable characteristics for the development of this activity are combined (Guerschman et al., 2003; Viglizzo et al., 2001). Baldi et al. (2006) found that soil drainage explained the spatial distribution of agriculture and grassland surfaces in other regions of the *Rio de la Plata Grasslands*. This was very logical given that the greatest crops restrictions in their study sites are water stress and water excess (Hall et al., 1992). Unlike what was initially expected, the soil type does not explain the spatial variation of the fragmentation in our work, probably due to the scale of analysis (i.e., 10×10 km units). However, at smaller spatial scales, paddock edaphic characteristics are among of the main determinants of rice yield in the Eastern Plains (Tseng et al., 2021) and therefore in the choice of crop location. So probably, at a finer scale of analysis, other variables linked to suitability for rice crop will become more relevant in explaining spatial variation in fragmentation.

Implications for grasslands conservation and restoration

Our work highlights the high degree of grasslands lost in the Eastern Plains due to the replacement by crops or implanted pas-

tures, a situation that is repeated in temperate and subtropical grasslands around the world (Watson et al., 2016; Bond and Parr, 2010; Neke and Du Plessis, 2004). This replacement of natural habitats and the advanced fragmentation degree of grassland remnants imply a decline in native species diversity (Deák et al., 2021; Lampinen et al., 2018; Staude et al., 2018; Fahrig, 2003; Sala et al., 2000; Pimm and Raven, 2000). As patch size decreases, species richness may be reduced (Bennett and Saunders, 2010) because patches have become smaller than the minimum area required to support populations or individuals of species with larger range requirements (Fahrig, 2003). In addition, the loss of habitat corridors, increases the patches isolation, so a reduction in species diversity could be expected (Deák et al., 2021; Lampinen et al., 2018; Fahrig, 2003).

The current scenario of high grassland fragmentation in the Eastern Plains makes it of great importance to develop prompt conservation measures for the remaining natural areas, as well as restoration strategies for degraded sites. These actions are in line with international commitments taken by the country, such as the RAMSAR agreement for wetland conservation and the Aichi Biodiversity Targets for 2020 (https://www.cbd.int/aichi-targets/). Due to be a region where conservation and productive interests converge (Brazeiro et al., 2015; DIEA and MGAP, 2003) the compliance with the Aichi Targets, in particular point 7—which promotes the sustainable management of areas of agricultural use, guaranteeing the conservation of biological diversity – and point 15—which commits to increasing the resilience of ecosystems through conservation and restoration – assume particular relevance.

According Buisson et al. (2021), a critical step in the restoration process of grassland ecosystems is to have reliable information on the distribution of different grassland types, particularly pristine ones for use as reference ecosystems. The current LULC map generated here will allow us to describe and characterize the grassland plant communities in the remnant sites, their states and possible transitions to others, as well as evaluate their potential for post-agricultural restoration. The results of the landscape metrics obtained in our work also allow the recognition of sites with a higher and lower degree of fragmentation, which will be extremely useful for defining priority areas for conservation. In fragmented landscapes, conservation efforts have typically focused on the preservation of remaining large habitat patches that are intact and well connected (Fischer et al., 2009), but small patches may play a significant role in conserving remaining vegetation (Fischer and Lindenmayer, 2002). Particularly, plant communities present in grasslands remnants have proved to be an important source of natural diversity (Burkart et al., 2011). Increasing the quality of a focal habitat patch by ensuring proper management strategies can effectively compensate the losses in the total area (Otsu et al., 2017). Appropriate management of natural remnants (such as field margins, river and stream edges, and areas without optimal characteristics for cultivation) or suitable novel habitat patches (such as clearings under power lines, grasslands at dams) can also increase the amount of grassland and landscape connectivity (Lampinen et al., 2018; Bátori et al., 2020; Baum et al., 2004; Uezu et al., 2008; Tulloch et al., 2015).

Finally it is important to note that not all environmental changes can be detected through land cover transformation (Li and Wu, 2004; O'Neill et al., 1997). It is necessary to integrate this information with other field studies and link them with functional landscape properties to assess the state of its ecological resources (Li and Wu, 2004) and to devise management strategies to prevent further grasslands loss and promote their conservation.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A.

Table A1
Commission and omission errors and overall accuracy of binary maps (bare soil class and other classes) expressed in percentages, for each of the images used in the construction of the cropland mask.

Date	Class	Commission errors (%)	Omission errors (%)	Overall accuracy (%)
20/07/2007	BS	0,0	3,7	97,7
	others	5,9	0,0	
12/01/2008	BS	0,0	0,2	99,9
	others	0,2	0,0	
07/06/2009	BS	1,4	0,6	99,1
	others	0,5	1,2	
13/10/2009	BS	1,0	0,0	99,4
	others	0,0	1,7	
23/04/2010	BS	4,3	0,0	98,0
	others	0,0	3,7	
01/09/2011	BS	0,1	13,6	93,2
	others	11,9	0,1	
15/04/2013	BS	0,0	0,5	99,8
	others	0,5	0,0	
05/08/2013	BS	0,0	0,6	99,7
	others	0,6	0,0	
27/10/2014	BS	0,0	1,4	99,3
	others	1,4	0,0	
12/09/2015	BS	0,0	9,4	95,3
	others	8,6	0,0	
13/08/2016	BS	0,0	0,1	100,0
	others	0,1	0,0	
20/01/2017	BS	0,0	5,9	98,3
	others	2,3	0,0	

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