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Characterizing fragmentation in temperate South America grasslands

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Abstract

In the last century, the grasslands of southern South America were rapidly converted to croplands, starting a fragmentation process that is still ongoing. Almost no information is available on the spatial patterns and environmental controls of these processes. Our objective was to characterize the degree of fragmentation and to analyze the environmental controls of landscape composition of the Río de la Plata grasslands, in southern South America. We classified land cover types using three Landsat TM scenes and we analyzed landscape structure using six metrics. Grassland is still the predominant land cover type in the Pampas, occupying 65.5% of the analyzed area. The abundance of the original land cover varied regionally, being higher in the south east (Flooding Pampa) and lower in the northern part of the area studied (Rolling Pampa). Landscape fragmentation was determined by crop production, therefore, was highest in the Rolling Pampa and lowest in the Flooding Pampa. The fragmentation patterns were associated to both climatic and edaphic factors. Fragmentation of native vegetation was mainly regulated by soil drainage, as in poorly drained soils, crop production is almost unfeasible.

Keywords: Pampas; Land use; Remote sensing; Fragmentation; Spatial metrics

1. Introduction

The concept of fragmentation refers to the transformation of the landscape, often driven by disturbances, from a uniform to a more heterogeneous and patchy situation (Kouki and Löfman, 1998). Transformations include both changes in area and patch configuration. Such changes over time lead to different stages: incision, perforation, dissection, dissipation, shrinkage and attrition (Forman, 1995; modified and extended by Jaeger, 2000) (Fig. 1). Fragmentation is not a random process, as the clearing of native vegetation occurs in areas where agriculture or intensive cattle raising are profitable economic activities (Kemper et al., 2000). The degree of fragmentation provides critical information to infer ecosystem changes, even when the details of all ecological process affected are unknown (O'Neill et al., 1997). Such changes have important consequences on biodiversity and water and C fluxes both at local and regional levels (Herkert et al., 2003).

Native grasslands of temperate and subtropical regions of the world have been used as rangelands or have been transformed into croplands due to the aptitude of their soils. Only a small fraction of the arid and semiarid grasslands of the world remain in a relatively undisturbed state (Hannah et al., 1995). In southern South America, the extensive plains named "Río de la Plata Grasslands" (Soriano, 1991), started to be transformed with the arrival of the first Europeans to the region, in the first half of the 16th century (Báez, 1944). The influence of cattle grazing has been especially important during the first three centuries, while agriculture became an important disturbance in the 20th century (Vervoorst, 1967; Hall et al., 1992). In the last decades, the rate of agricultural expansion increased considerably due to technological

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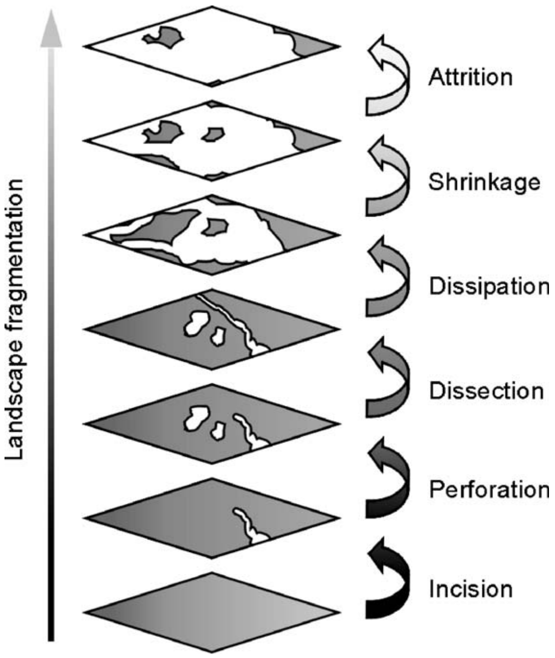

Fig. 1. Schematic representation of the fragmentation process and its different stages (modified from Forman, 1995 and Jaeger, 2000). In gray it is represented the original land cover, and in white the anthropogenic or new land cover.

changes (i.e., non tillage techniques, genetically modified crops) and market conditions (the increase in the demand of soybean by Asian countries) (Paruelo et al., 2005), imposing a serious threat to the still large areas of grasslands of the region.

Despite the importance of agriculture in the Argentine Pampas, land use and land cover descriptions are particularly poor (Paruelo et al., 2004a). Only county level statistics are generated by official agencies. Such statistics are based in not well-defined protocols that introduce serious uncertainties on the estimates. Spatial explicit descriptions of the land cover and land use types are only available for particular areas of the region (Alperín et al., 2002; Demaría et al., 2003; Guerschman et al., 2003a).

Landscape fragmentation studies have been concentrated in forests (e.g. Skole and Tucker, 1993; Blanco Jorge and García, 1997; Roy and Tomar, 2000; Saatchi et al., 2001; Jaeger et al., 2001; Riitters et al., 2002), but recently this kind of analyses have been extended to other natural systems, like shrublands (Kemper, 2000), grasslands (Coppedge et al., 2002; Egbert et al., 2002) and even aquatic environments (Bell et al., 2001). The relatively few studies on grassland fragmentation might be due not only to the long history of land cover conversion of these systems, but also to the traditional lack of recognition of the conservation value of grasslands (Risser et al., 1981; Joern and Keeler, 1995). Landscape fragmentation in the Río de la Plata Grasslands has only been quantified before for a small particular area in the western Pampas (Demaría et al., 2003). Krapovickas and Di Giacomo (1998) highlighted the negative consequences of landscape fragmentation on biodiversity over the main subregions of the Río de la Plata Grasslands: the Pampas and the Campos.

At a landscape scale, topography and agroclimatic potential are the key determinants of land use patterns changes (Veldkamp and Lambin, 2001). Several authors pointed out that the prairies and steppes of the Río de la Plata Grasslands persisted only in areas where particular edaphic or climatic conditions restricted the expansion of the agriculture (León et al., 1984; Viglizzo et al., 2001; Guerschman et al., 2003b). The underlying hypothesis is that landscape composition, and thus indirectly landscape fragmentation, is a non-random process, and will result from a complex interplay of environmental factors, that constrains transformation, and technological changes.

The objectives of this article were: (1) to characterize grassland fragmentation in the Río de la Plata Grasslands and (2) to analyze the correspondence between environmental factors (edaphic and climatic) and landscape composition. To achieve these objectives we first characterized the land cover patterns performing classifications of remotely sensed data. Land cover and land use types discrimination was based on the differential phenology of the land cover types. We described landscapes using a small set of metrics which span the relevant dimensions of pattern and process, summarizing the information at the level of phytogeographic district. The correspondence between environmental factors and landscape composition was studied using multiple regression models.

2. Materials and methods

2.1. Description of study areas

The Río de la Plata Grasslands cover more than 700,000 km^2 in the large plains of center-east Argentina, Uruguay and Southern Brazil, located between the 28° and 38° South (Soriano, 1991; Paruelo et al., in press) (Fig. 2a). Several phytogeographic units or districts can be distinguished according to geomorphology, soils, drainage, physiography and vegetation characteristics: the *Rolling Pampa*, the *Southern Pampa*, the *Flooding Pampa*, the *Inland Pampa* (with two subunits, *Flat* and *West*), the *Mesopotamic Pampa*, the *Southern* and the *Northern Campos* (León y Marangón, 1980; León et al., 1984; León, 1991). We focused our analyses on the first four districts, incorporated in three study areas (Fig. 2b). Mean annual temperature varies from 17 °C in the North to 13 °C in the South and mean annual precipitation varies from 1200 mm in the Northeast to 600 mm in the Southwest. Mollisols are the dominant soils, with Alfisols, Lithosols and Oxisols occupying smaller areas (INTA-SAGyP, 1990). Prairies and steppes, codominated by C_3 and C_4 *Poaceae* species, are the main vegetation types (Burkart et al., 1998). Land use practices deeply converted and modified the original land

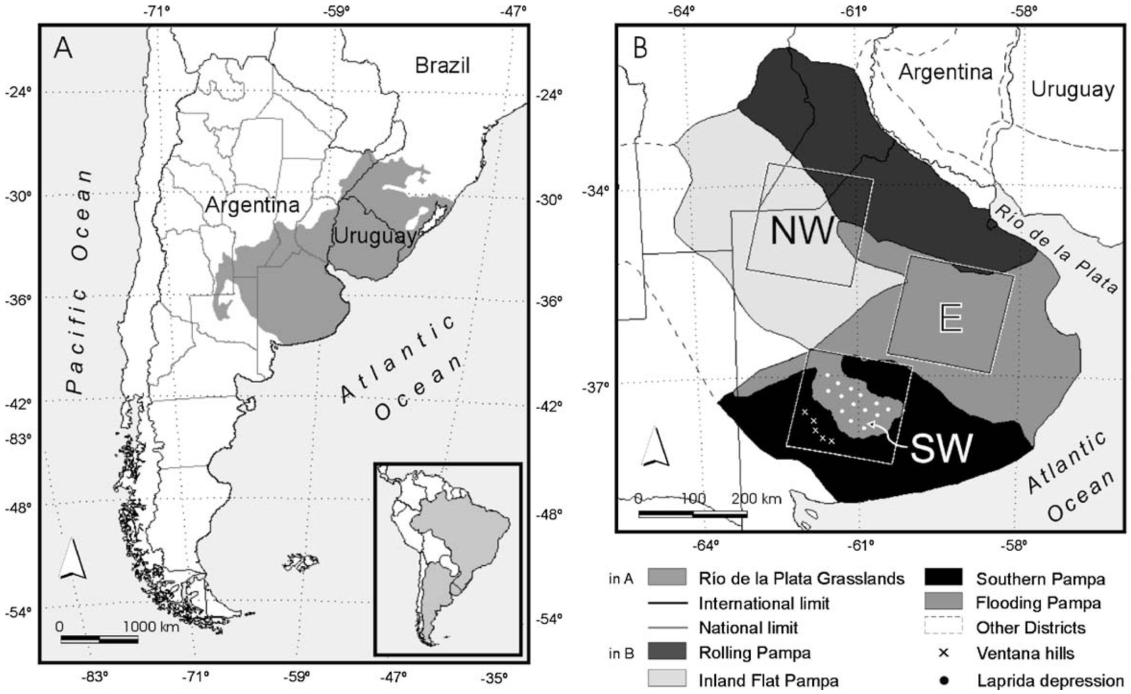

Fig. 2. (A) Geographic location of the Río de la Plata Grasslands (in gray). Adapted from Soriano (1991). (B) Details of the phytogeographic districts and the study areas (Landsat scenes). *NW*, *SW* and *E* refer to the *Northwest*, *Southwest* and *East* scenes.

cover in a relatively short period of time. The more humid areas have been grazed for more than 400 years (Soriano, 1991) and cultivation became a major disturbance in the sub humid and humid grasslands a century ago, and particularly in the last 20 years (Hall et al., 1992; Paruelo et al., 2005). In the *Rolling*, *Flat Inland* and *Southern Pampas*, agriculture replaced most of the native vegetation, while in the *Flooding Pampa* croplands cover is lower (León, 1991). The main annual crops are soybean, maize, sunflower, wheat and oat. Perennial crops include pastures, used for direct grazing or for hay production (Guerschman et al., 2003a).

2.2. Land cover and land use characterization

We characterized land cover and land use from the analysis of normalized difference vegetation index (NDVI) temporal series derived from Landsat TM images following the methodology proposed by Guerschman et al. (2003a). The NDVI is computed as: $\text{NDVI} = (\text{NIR} - \text{R})/(\text{NIR} + \text{R})$, where the NIR is the near infrared (band 4 of Landsat TM) and R is the red (band 3 of the same sensor). Many authors found a strong relationship between the NDVI and functional characteristics of vegetation (particularly with the fraction of absorbed radiation and then with net primary production) (Tucker et al., 1985; Box et al., 1989; Sellers et al., 1992; Paruelo et al., 1997; Paruelo et al., 2000) and it has been proposed as a remote sensing surrogate for leaf area index (Running et al., 2000). Lloyd (1990) showed that NDVI temporal series can track phenological differences among land cover types. Our classification scheme is based then on the phenological signatures of the different land cover types. We selected three study areas that cover 103,000 km^2 (Fig. 2b). Each area corresponds to one Landsat scene. We refer to the areas as *Northwest* (path-row 227/084), *East* (225/085) and *Southwest* (226/086). The dates of the images correspond to the same growing period and they capture the main changes in the interception of radiation from the vegetation (*NW* 9/10/96, 12/1/96 and 2/1/97; *E* 10/8/96, 1/2/97 and 3/7/97; *SW* 10/7/96, 12/24/96, 2/10/97 and 3/30/97). The classification of *Northwest* scene is based on Guerschman et al. (2003a) analysis.

We discriminated eight land cover classes: summer crops, winter crops, double crops (areas where winter and summer crops are sown in the same growing period), prairies, grass steppes, vegetated and non vegetated ponds and urban areas. The class ‘‘prairies’’ included natural and seminatural prairies and implanted pastures. The ‘‘grass steppes’’ class included steppes located on shallow or halomorphics soils. The original eight classes were recoded according to the degree of anthropogenic modification and the presence of native grassland species. The final classes were: croplands, grasslands, water bodies and urban areas (Table 1). Urban areas were not considered in the classification process; they were digitized and used as a mask in the post classification analysis.

Ground truth information was available for the NW and SW areas, based on records of land use on individual plots. Data were obtained from farmer's associations (AACREA). We performed supervised classifications using approximately 50% of the ground truth pixels and applying the maximum likelihood algorithm (Lillesand and Kiefer, 1994). The accuracy of the classifications was evaluated using the remaining pixels. We calculated the overall

Table 1
Reclassification scheme and characteristics of the principal classes

Original classes[a]	Principal classes[b]	Characteristics
Summer crops Winter crops Double crops	Cropland (Cl)	High modification and low or null native species presence
Prairies Grass steppes	Grassland (Gl)	Moderate or low modification and moderate or significant native species presence
Vegetated ponds Non vegetated ponds	Water body (WB)	Lack of grasslands coverage

[a] Derived from land use and land cover maps.
[b] Used for landscape analyses.

Table 2
Climatic and edaphic variables included in the multiple regression analyses

Environmental control	Source	Abbreviation
Mean annual temperature (°C)	FAO	MAT
Mean annual precipitations (mm)	FAO	MAP
Drainage	INTA-SAGyP	DRN
Soil depth (cm)	INTA-SAGyP	DEP
Percentage of clay (%)	INTA-SAGyP	CLA
Percentage of silt (%)	INTA-SAGyP	SIL
Percentage of sand (%)	INTA-SAGyP	SAN
Salinity	INTA-SAGyP	SAL
Alkalinity[a]	INTA-SAGyP	ALK

Abbreviations: FAO, Food and Agriculture Organization of the United Nations; INTA-SAGyP, Instituto Nacional de Tecnología Agropecuaria – Secretaría de Agricultura, Ganadería y Pesca – Argentina.
[a] This variable was omitted in the analyses.

accuracy and the producer and the user accuracy for each class by the generation of a contingency matrix (Congalton, 1991). The overall accuracy is calculated by dividing the number of pixels correctly classified (i.e. the sum of the diagonal axis) by the total number of pixels included in the evaluation process. The producer accuracy is a measure of the omission error and indicates the percentage of pixels of a given land cover type that are correctly classified. It is calculated by dividing the number of pixels of the *i*th class correctly classified by the total number of pixels of the *i*th class included in the evaluation. The user accuracy is a measure of the commission errors and indicates the probability that a pixel classified into a given class actually represents that class on the ground. It is calculated by dividing the number of pixels of the *i*th class correctly classified by the total number of pixels classified as the *i*th class. For the *East* scene field data were not available. We followed, then, an indirect approach to perform the supervised classification. We interpolated the phenological signatures (derived from the seasonal dynamics of the NDVI) of each class of the NW and SW scenes to the dates of the East scene. These new signatures were used to classify the *East* scene. Classification results for this scene were consistent with our knowledge of the distribution of land cover types in the area. Finally, we applied a moving window majority filter (7 × 7 pixels) in order to eliminate the ‘‘salt and pepper’’ appearance of the classifications. For image processing we used the software ERDAS Imagine, Version 8.2 (Leica Geosystems, Atlanta, Georgia, USA).

2.3. Relationship between environmental variables and landscape composition

We compiled a database of nine environmental variables (Table 2). Climatic data was extracted from the FAO’s ‘‘Agroclimatological data for Latin America and the Caribbean’’ (FAO, 1985) and edaphic information from the ‘‘Soil Atlas of Argentina’’ (INTA-SAGyP, 1990; based on Soil Survey Staff, 1975). We used data from 21 meteorological stations, inside a buffer region of 220 km surrounding the study area and we generated maps for the climatic variables by spatial interpolating the point data. All the edaphic variables, with the exception of *soil depth*, were categorical. We transformed them to a quantitative scale as follows: *drainage* had 7 categories, from ‘‘very poorly drained’’ (1 in our scale) to ‘‘excessively drained’’ (100 in our scale), *salinity* from ‘‘non saline’’ (1 in our scale) to ‘‘moderate salinity’’ (100 in our scale) and *alkalinity* from ‘‘non alkaline’’ (1 in our scale) to ‘‘high alkalinity’’ (100 in our scale). To obtain the *percentage of silt*, *clay* and *sand* we transformed the textural classes (e.g. ‘‘silty clay’’) to particle sizes percentage using the soil textural triangle. Thus, *drainage*, *salinity* and *alkalinity* were adimensional, and the *percentage of silt*, *clay* and *sand* were percentages. For climatic and edaphic variables, we summarized the information into a hexagonal grid (with a cell size of 6400 ha), to describe their spatial variation over the region. We used hexagons because they are the geometric shape more similar to the circle that allows generating a tessellation (Sahr et al., 2003). For the climatic variable, we calculated the mean value for each cell of the grid. For the edaphic variables, we calculated a mean value weighted with the area occupied by each soil type polygon inside each grid cell.

We used a forward stepwise multiple regression analysis to relate environmental variables and landscape composition of grasslands, croplands and water bodies (Paruelo and Lauenroth, 1995; Verburg and Chen, 2000; Paruelo et al., 2001; Guerschman et al., 2003b). Independency between variables is a prerequisite of the method and several measures were taken to reduce the effects of multicollinearity as much as possible (Verburg and Chen, 2000). The first step was to eliminate those variables that were redundant, based on the results of their correlation. For each pair of variables with a module of the correlation coefficient ($|r|$) greater than 0.80, one was eliminated of the analysis, and for the pairs with a coefficient greater than 0.50, only one was allowed to enter in the regression model. The remaining set of environmental variables was used to generate the regression models. We stopped adding variables when the increase in the adjusted coefficient of determination (R^2) was less than 2%. The standardized regression coefficients (β_{st}) indicated the magnitude and sign of individual variables for every model. The partial determination coefficients (r_p^2) described the proportion of the variability explained by each explanatory variable when the linear effect of all other variables was included in the model. The introduction of an environmental variable into a regression model allows us to detect an association with the dependent variable, but this does not imply a causal relationship.

2.4. Grassland fragmentation analysis

Grassland fragmentation patterns were quantified using several indices, since no single metric can capture the complexity of the spatial arrangement of the patches (Riitters et al., 1995). We vectorized the land cover maps and discarded for the fragmentation analysis croplands, water bodies and urban polygons. Grassland polygons smaller than 3,600 m^2 (four Landsat pixels) were eliminated because they did not represented pure grassland polygons. We intersected the vectorized map with a grid of hexagons of 6400 ha. Six spatial metrics were calculated to characterize landscape composition and configuration (Table 3). The *effective mesh size* (Jaeger, 2000; Jaeger et al., 2001; Saura, 2002) is an index that simultaneously considers the patch size and the level of dissection, and, additionally, it is not sensitive to the omission or inclusion of small patches. It reflects structural changes and has a monotonous response through to different fragmentation stages (the greater the effective mesh size, the lower the fragmentation level). The *percentage of landscape* is perhaps the most important and useful information to describe a landscape (McGarigal and Marks, 1995). The *number of patches* is an intuitive and simple measure of the degree of subdivision of a land cover type. However, it presents a unimodal relationship with the amount of disturbance leading to possible misinterpretations. The *mean patch size* is a simple and commonly used metric in the spatial pattern analysis. These two last metrics are very sensitive to changes in the minimum mapping unit, i.e., the smallest area entity to be mapped as a discrete area (Saura, 2002). The *Edge Density* is the total length of the edge of patches within a landscape and it is useful to compare landscapes of identical size, but it has also the disadvantage of presenting a unimodal relationship with the amount of disturbance (McGarigal and Marks, 1995; Hargis et al., 1998). The metric *area weighted mean shape index* quantifies aspects related to the shape of the patches, weighted with their area. As the analysis of the shapes of the intersected patches would be meaningless since in many cases the intersected polygons would not represent the real shape of the patch, we performed a slightly different analysis compared with what we did for the previous metrics. We measured the *shape index* over the original patches and then we intersected the patches with the hexagons grid. We weighed the values by the area that the particular shape occupied in the corresponding hexagon. Each hexagon was assigned to the corresponding phytogeographic district, in order to make comparisons among them.

3. Results

3.1. Land use and land cover characterization

The maps generated from the supervised classifications (eight land cover classes, not shown) were recoded into a second map showing the distribution of grasslands, croplands and water bodies. Urban areas were overlapped to this map (Fig. 3). This map is the only available description of the land cover and land use types distribution in the Río de la Plata Grasslands at a resolution and extent compatible with landscape studies. The *Flooding*, *Southern* and *Inland Pampas* were dominated by grasslands (78.6, 56.8 and 55.7% respectively, Table 4 and Fig. 4b), while in the *Rolling Pampa* croplands were the prevalent land cover type (55.2%, Table 4 and Fig. 4b). For all the districts the percentage of water bodies was lower than 12% and the urban areas lower than 0.4% (Table 4 and Fig. 4b).

The evaluation of the land cover and land use classifications for the *Southwest* and *Northwest* scenes showed a high degree of accuracy. For the *Southwest* scene, croplands, grasslands and water bodies exhibited a high

Table 3
List of the six landscape metrics

Landscape index	Abbreviation	Formula
Percentage of landscape	PLAN	$\mathrm{PLAN} = 100\frac{\sum_{i=1}^{n} Ai}{At}$
Number of patches	NUMP	$\mathrm{NUMP} = n$
Mean patch size	MNPS	$\mathrm{MNPS} = \left(\frac{1}{10{,}000}\right)\frac{\sum_{i=1}^{n} Ai}{n}$
Edge density	EDGD	$\mathrm{EDGD} = \frac{1}{At}\sum_{i=1}^{n} Pi$
Area weighted mean shape index	AWMS	$\mathrm{AWMS} = \frac{\sum_{i=1}^{n}((Ppi/2\sqrt{\pi Api})(Ai/At))}{n}$
Effective mesh size	EFMS	$\mathrm{EFMS} = \frac{\sum_{i=1}^{n}(Ai)^2}{At}$

Abbreviations: *Ai*, patch area; *Api*, original patch area (before intersecting with the grid); *At*, total area of the landscape unit; *Pi*, perimeter of each patch; *Ppi*, perimeter of each original patch (before intersecting with the grid); *n*, number of patches.

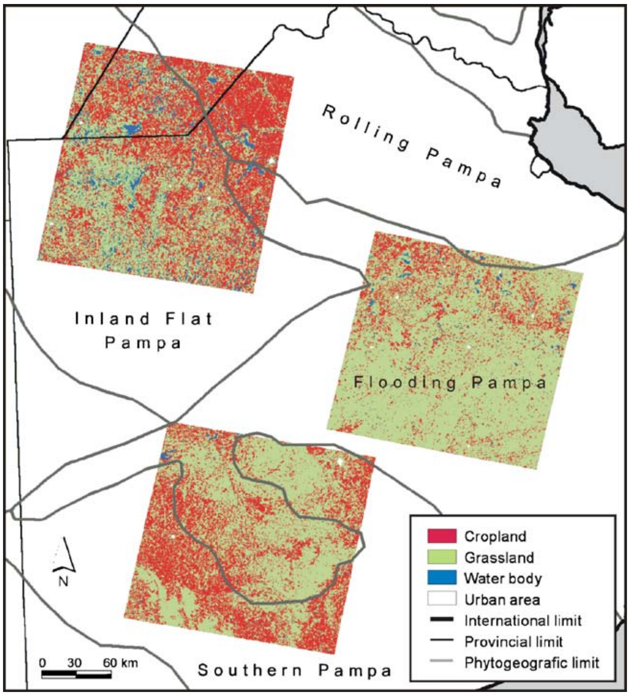

Fig. 3. Land use and land cover maps for the principal classes: grasslands (in green), croplands (in red) and water bodies (in blue). The urban areas (in white) were digitalized and overlaid in the map. The gray lines indicate the phytogeographic districts limits of the region.

precision both in terms of producer's (Cl 89.8%, Gl 90.4% and WB 92.2%) and user's accuracy (Cl 75.3%, Gl 97.0% and WB 71.6%). Similar results were found for the *Northwest* scene (producer accuracy: Cl 88.5%, Gl 83.4% and WB 97.9%; user accuracy: Cl 84.1%, Gl 76.1% and WB 99.6%). The overall accuracy of the classification after recoding (90.3% in the *Southwest* and 95.6% in the *Northwest*) provides us enough confidence on our description of the spatial composition and configuration.

3.2. Relationship between environmental variables and landscape composition

Only one pair of environmental variables (*alkalinity* and *salinity*) had a correlation coefficient ($|r|$) higher than 0.80 ($p < 0.05$). In the Río de la Plata Grasslands, saline soils tend to be also alkaline due to the presence of soluble sodium carbonates in phreatic waters (Lavado et al., 1992). As a consequence, we did not include the variable *alkalinity* in the regression analyses. Four pairs of variables had $|r|$ higher than 0.50 ($p < 0.05$): *mean annual temperature* and *mean annual precipitation* ($r = 0.69$), *percentage of silt* and *percentage of sand* ($r = -0.78$), *soil depth* and *mean annual temperature* ($r = 0.63$) and *percentage of sand* and *mean annual temperature* ($r = 0.54$). Consequently, we eliminated one of the variables of each pairs for the generation of the regression models.

A 43% of the spatial variance in grassland (Gl) and a 37% in cropland (Cl) cover was explained by environmental variables ($p < 0.001$, Table 5). The standardized regression coefficients (β_{st}), showed that Gl were negatively related to *drainage*, *mean annual temperature* and *percentage of silt* and positively related with *salinity* and *percentage of clay*, indicating that that the original land cover persisted in areas with poorly drained clayed and salty soils, and with low *mean annual temperature*. Cl were positively related to *drainage* and negatively to *percentage of sand* and *percentage of clay*, indicating that the areas suitable for crop production are those with a well-developed drainage system, and a silty soil texture (Table 5). The partial determination coefficients (r_p^2) showed that *drainage* was the most important explanatory factor of the land cover composition (for Gl $r_p^2 = 0.17$, for Cl $r_p^2 = 0.33$), while the contribution of the other variables to the models was low for Gl (as the sum of the r_p^2 for the other variables is 0.21) and very low for Cl (as the sum of the r_p^2 for the other variables is 0.05) ($p < 0.001$; Table 5).

3.3. Landscape fragmentation analysis

The *effective mesh size* (EFMS, Fig. 4a) summarize the degree of landscape fragmentation of a system (the greater the effective mesh size, the lower the fragmentation level). Our results for grasslands indicated that the *Flooding Pampa* was the district with the highest mesh size and thus the lower landscape fragmentation (41 km^2). The *Rolling Pampa* had the opposite pattern, showing the lowest mesh size and thus the greatest level of landscape fragmentation (4.7 km^2). The *Southern* and *Inland Pampas* had intermediate mesh sizes (21.4 and 20.0 km^2, respectively; Fig. 4a). The *percentage of landscape* (PLAN), the *mean patch size* (MNPS), and the *number of patches* (NUMP) where used as complementary

Table 4
Area of each principal class in the analyzed phytogeographic districts

Class	Inland Pampa		Flooding Pampa		Southern Pampa		Rolling Pampa		Total	
	ha	%	ha	%	ha	%	ha	%	ha	%
Gl	1579361	55.7	3968718	78.6	986613	56.8	250187	34.1	6784879	65.5
Cl	934715	32.9	920648	18.2	733910	42.2	404656	55.2	29939295	28.9
WB	319925	11.3	159238	3.2	14204	0.8	74843	10.2	68210	5.5
UA	3808	0.1	3297	0.1	3381	0.2	2992	0.4	13478	0.1
Total	2837810	100.0	5051902	100.0	1738109	100.0	732679	100.0	10360500	100.0

Abbreviations: Gl, grasslands; Cl, croplands; WB, water bodies; and UA, urban areas.

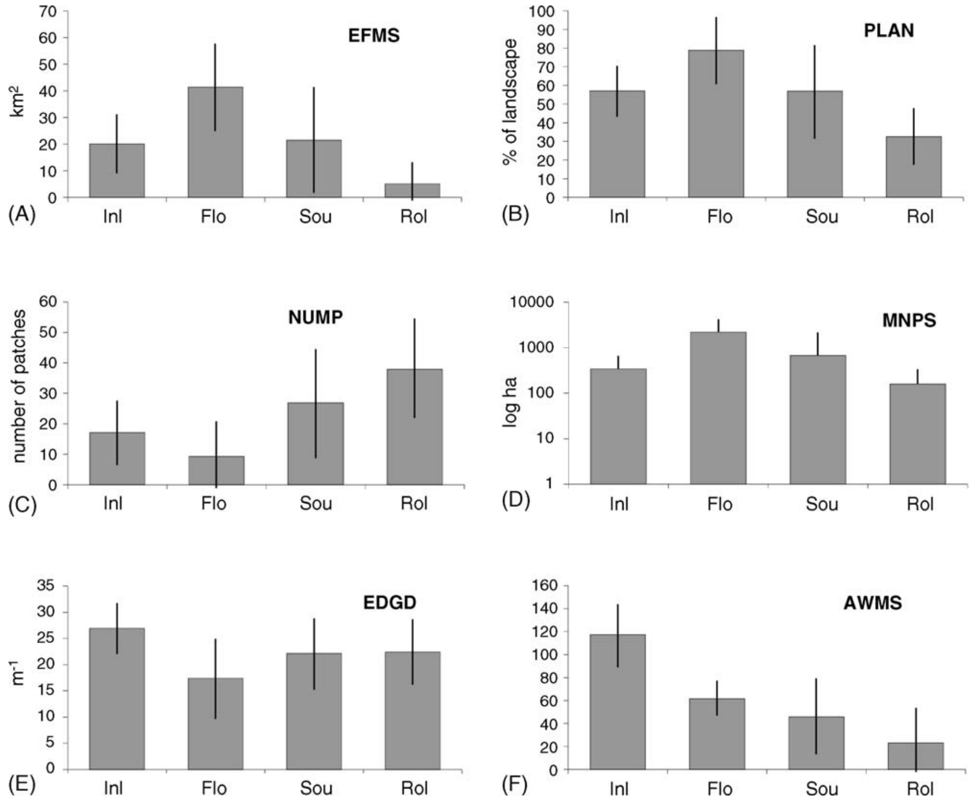

Fig. 4. Mean values for each of the metrics discriminated by phytogeographic district. Vertical bars represent the standard deviation. Abbreviations: Inl: Inland Pampa, Flo: Flooding Pampa, Sou: Southern Pampa, Rol: Rolling Pampa. EFMS: effective mesh size, PLAN: percentage of landscape, NUMP: number of patches, MNPS: mean patch size, EDGD: edge density and AWMS: area weighted mean shape index.

metrics of the EFMS, as they show simple landscape attributes, and are easier to interpret (Table 4 and Figs. 4b–d). We found that the *Flooding Pampa* had the highest *percentage of landscape* covered by Gl (78.8%) and the lowest by Cl (18.1 %). This extensive Gl cover was characterized by a low level of dissection (9.3 patches) and very large units (2199.3 ha). On the contrary, the *Rolling Pampa* exhibited the highest value of Cl cover (60.5%) and the lowest value of Gl cover (32.6 %). The high *number of* Gl *patches* (37.9 patches) and their small size (MNPS = 158.4 ha) indicated that the grass cover in the district was highly dissected.

Landscape metrics were particularly variable in the *Southern Pampa* (Fig. 3) were three major subregions could be identified: the Ventania Hills (in the SW of the scene), the poorly drained plains located between the central sector of the *Flooding Pampa* and The Laprida Depression (NE portion of the scene) and the well-drained plains occupying most of the district intercepted by the Landsat scene. For the entire unit, Gl were the dominant cover (56.8%), followed by Cl (41.2%). We found a high *number of patches* per grid unit (26.9 patches), and an intermediate patch size (668.4 ha), indicating a high degree of dissection of the original land cover. These results denoted an intermediate situation of grasslands fragmentation between the *Flooding* and the *Rolling Pampas*.

The *Interior Pampa* had a high percentage of grasslands (57.0%), an important proportion occupied by Cl (33.6%) and the highest value for water bodies (8.2%). The low *number of* Gl *patches* (17.1 patches) denoted a low dissected cover. The *mean patch size* was small (341.0 ha) and similar to that found for the *Southern Pampa*. The lower variability

Table 5
Standardized regression coefficients (β_{st}), partial determination coefficients (r_p^2) and coefficients of determination (r^2) of the models

	Class	MAT	MAP	DRN	DEP	CLA	SIL	SAN	SAL	r^2
β_{st}	Gl	−0.23	–	−0.43	–	0.13	−0.23	–	0.22	0.43
r_p^2		0.07	–	0.17	–	0.03	0.06	–	0.05	–
β_{st}	Cl	–	–	0.62	–	−0.09	–	−0.18	–	0.37
r_p^2		–	–	0.33	–	0.01	–	0.04	–	–

Abbreviations: Gl, percentage of grasslands; Cl, percentage of croplands; MAT, mean annual temperature; MAP, mean annual precipitations; DRN, drainage; DEP, soil depth; CLA, percentage of clay; SIL, percentage of silt; SAN, percentage of sand; and SAL, salinity.

of the *Inland Pampa* compared to the *Southern Pampa* resulted from a interspersed pattern of croplands, grasslands and water bodies within the individual cell instead of spatial segregation at a broader scale of land cover, as in the case of the *Southern Pampa* (see maps of landscape metrics in the Appendix A).

The other two metrics, the *edge density* (EDGD, Fig. 4e) and the *area weighted mean shape index* (AWMS, Fig. 4f) provided additional information on the landscape configuration. They allowed us to discriminate between the *Inland* and the *Southern Pampas*, as the first district presented grassland patches with a higher surface of contact with other land cover types than the second (EDGE, 26.9 m^{-1} for *Inland Pampa* and 22.1 m^{-1} for *Southern Pampa*), and thus a more complex geometry (AWMS, 117.2 for *Inland Pampa* and 45.3 for *Southern Pampa*), reinforcing the differences stated above. Maps of all landscape metrics are shown in the Appendix A.

4. Discussion

4.1. Land use and land cover characterization

In the last century, native grasslands of temperate South America have been transformed into croplands due to the aptitude of their soils and the adequate climatic conditions. Nowadays, the rate of agricultural expansion rises considerably due to technological changes and market circumstances (Paruelo et al., 2005). The Río de la Plata Grasslands ecosystem supports a large amount of the gross product of Argentina, Uruguay and Brazil. Surprisingly, no quantitative data on the patterns and rates of land cover changes are available (Paruelo et al., 2004a). The lack of organized attempts to measure these changes and to develop a land use scheme, impose a serious threat to the still large areas of grasslands of the region. The analyses presented in this study provided a first regional description of the Río de la Plata landscapes, allowing us to identify their landscape configuration and composition heterogeneity. Besides, this study provided a baseline to analyze the profound changes that took place during the last decade.

Most of the original vegetation has been replaced by croplands in the *Rolling Pampa* and in parts of the *Southern Pampa* (24% of the grid units of the first district and 5% of the second, presented a Cl cover higher than 75%). Rangelands dominated the landscape in most of the *Flooding Pampa* and parts of the *Southern* and *Inland Pampas* (94% of the grid units of the first district, 29% of the second and 10 % of the third, presented a Gl cover above 75 %). Even though rangelands represent the closest situation to the original vegetation, both in structural and floristic terms, they are used intensively. In 2001, more than 22.5 million of domestic herbivores grazed these rangelands in the Buenos Aires province (Instituto Nacional de Estadística y Censos – INDEC-, 2001). The structure and functioning of the original ecosystems were deeply modified by grazing (Sala et al., 1986; Rusch and Oesterheld, 1997; Altesor et al., 1998; Rodríguez et al., 2003; Altesor et al., 2005). Though it would be desirable to discriminate rangelands based on their structural characteristics (physiognomy, floristic composition) our classification approach only allowed us to detect differences associated to short time influences of grazing pressure.

4.2. Relationship between environmental variables and landscape composition

Our results showed that a few climatic and edaphic variables account for a substantial proportion of the spatial variability in land cover composition ($r^2 = 43$ % for Gl and $r^2 = 37\%$ for Cl). The models developed provided quantitative hypotheses on the environmental controls of grassland fragmentation (as the degree of fragmentation depends on land cover composition) and agreed with the available knowledge on the edaphic and climatic constraints of agriculture. The relative importance of edaphic variables was higher than the climatic variables, being *drainage* the most important determinant factor of the croplands and grasslands cover ($r_{\mathrm{p}}^2 = 0.17$ for Gl and $r_{\mathrm{p}}^2 = 0.33$ for Cl). Hall et al. (1992) pointed out that the main constrains for crop production in the Pampas are water stress and surplus. Water deficits and surplus may occur even in different seasons of the same year generating important reductions in crop yields (López Pereira and Trápani, 2004). Even though the importance of soil salinity/alkalinity in determining cropping suitability of an area, the proportion of variance explained by this variable was low. Soil texture variables (*percentage of clay*, *sand* and *silt*) had a marginal explanatory power both for Cl and Gl, but their effect was consistent with the requirements of loam or clay loam soils of the main crops of the area (Satorre and Slafer, 1999). Though some important periods of water deficits may occur, most of the studied area presents favourable conditions regarding *mean annual precipitation* (Satorre and Slafer, 1999). Consequently, the explanatory power of this climatic variable was also marginal. In areas where summer water deficits are frequent, farmers avoid the unfavourable months sowing crops as early as thermal conditions are satisfied (Otegui and López Pereira, 2003).

Social, economical, technological and political factors may contribute to improve our models on the controls of land use patterns and landscape configuration. However, a basic problem to include them in a model is their spatial and temporal resolution and the chance of represent them spatially. As the very best, economic and social variables are available at a county level. Many of the economic variables (crop prices, exchange rates, etc.) have an even coarser grain (the country). Other important factors that constrains agricultural activities (and determine landscape patterns) could be identified only at a lower scale than the one used in our study. For example, technological facilities (i.e., non tillage techniques, genetically modified crops) determine the cropping possibilities of an individual plot (Paruelo et al., 2005) and are suitable to be applied all over the region. Moreover, inadequate technologies applied by individual farmers, can facilitate the erosion by water and wind of the top soil layers, the development of a plough sole or the crusting and sealing of the soil. These characteristics play, then, a fundamental role in determining landscape patterns in the region (Hall et al., 1992). The net effect of at least some socioeconomic variables could be distinguished from the effect of environmental variables by the comparison of land use patterns over environmental uniform areas shared by two or more political units (e.g. provinces, countries). Expanding the study to the whole Río de la Plata Grassland region would allow including three countries and at least five Argentine provinces. Such change in extent would allow testing the influence of social, economical, technological and political variables as potential drivers of land use patterns. Understanding the drivers of changes in landscape structure would allow scientists to improve land use/land cover change models and to evaluate scenarios of changes in biophysical or human factors (Verburg et al., 1999; Veldkamp and Lambin, 2001).

4.3. Landscape fragmentation analysis

Our analyses suggest that grassland fragmentation heterogeneity over the region should be primary due to crop development. Other causes of grasslands fragmentation, i.e., transportation network or urban settlements, appear to have a small effect in the area studied. The density of roads is similar over the study area, with an average value of 0.15 km/km^2. Moreover, contribution to fragmentation due to urban development is negligible, as we showed that urban cover was smaller than 0.4% of the region. This situation contrasts to those found in some areas of North America, Europe and East Asia, in where these fragmentation factors play a major role (e.g., von Haaren and Reich, in press; Matsushita et al., in press).

Based on the analysis of different landscape metrics that capture fundamental and independent components of spatial pattern (Riitters et al., 1995), we identified a situation of grasslands shrinkage or attrition in the entire *Rolling Pampa* and in the South and West portions of the *Southern Pampa*, characterized by the occurrence of small ($MNPS \approx 200$ ha.), simple-shape ($AWMS \approx 35$) and isolated ($NUMP > 40$ patches) grassland remnants (Figs. 3 and 4 and Appendix A). In particular, the *Rolling Pampa* presented a high level of fragmentation ($EFMS = 5.06\ km^2$) due mainly to two reasons. First, the *Rolling Pampa* is one of the most suitable areas in Argentina for crop production (Hall et al., 1992), with lands capable of sustaining a double crop production system for several years (Hall, 1992). Second, the region has a long history of use (Hall et al., 1992; Ghersa and León, 1998); cropping activities become important in this region since the lasts decades of the XIX century (Gaignard, 1989). In the last century, the pattern of crop plots superimposed on a grassland matrix gave place to the opposite pattern (small grassland patches surrounded by a cropland matrix) as described in this study. Cropland areas in the *Southern Pampa* have also a long history of use (Gaignard, 1989). Though these areas have a high potential for wheat and sunflower production, the implementation of a double crop cycle is unfeasible due to thermal restrictions (Hall, 1992). A difference between the *Southern* and the *Rolling Pampa* was not detected by landscape metrics: in the first case the landscape is composed by a matrix of croplands and isolated pasture plots, while in the *Rolling Pampa* the cropland matrix is dissected by well connected seminatural grassland associated to water streams (Fig. 3). Hilly areas of the *Southern Pampa* (Ventana hills) presented a particular case of study because grassland fragmentation was in an incision stage; grid units in this hilly system presented a few ($NUMP < 10$ patches) and large ($MNPS \approx 2000$ ha) patches (Figs. 3 and Appendix A). The disturbance in the future of these hilly grasslands is unlikely because the important environmental constraints (like rock outcrops, pronounced slopes, etc.) restrict the expansion of cropland in this subunit of the *Southern Pampa*. The *Interior Pampa* was in a stage of dissection or dissipation, as very complex patches ($EDGE = 26.9\ m^{-1}$ and $AWMS = 117.2$), small ($MNPS = 341$ ha) but interconnected ($NUMP = 17$ patches) patches led to a situation of marked landscape heterogeneity. The district was historically devoted to agriculture and grazing. The distribution of both activities is clearly associated to topography, the main determinant of drainage (the main explanatory variable in our model). The lack of an integrated drained system (Paruelo et al., 2005) determines an intricate distribution of well and poorly drained areas. Grasslands dominate in lowlands though some perennial pastures are sown in well drained areas as part of a rotation with crops (Hall, 1992). In recent years, due to the adoption of non-tillage techniques and changes in market conditions, agriculture expanded and reduced the area devoted to pastures in well drained areas. Fragmentation is probably still in progress in the *Inland Pampa*. Grasslands in the *Flooding Pampa* and in the Northeast portion of the *Southern Pampa* were on an initial stages of fragmentation (incision or perforation) ($EFMS \approx 40\ km^2$; see Appendix A Figure) as they constitute a ubiquitous ($PLAN > 80\%$) and non dissected land cover ($NUMP < 10$ patches, $MNPS \approx 2200$ ha). The grass cover of these areas is only interrupted by lines of communication (roads, railways), small agricultural plots, short streams, artificial channels and ponds (Fig. 3). Comparisons among these results and those found for other grasslands systems of the world are difficult due to the low number of publications on grassland fragmentation and the differences in grain and extent on the existing ones.

Finally, as fragmentation varied over the region, we could expect parallel effects on ecosystem functioning and

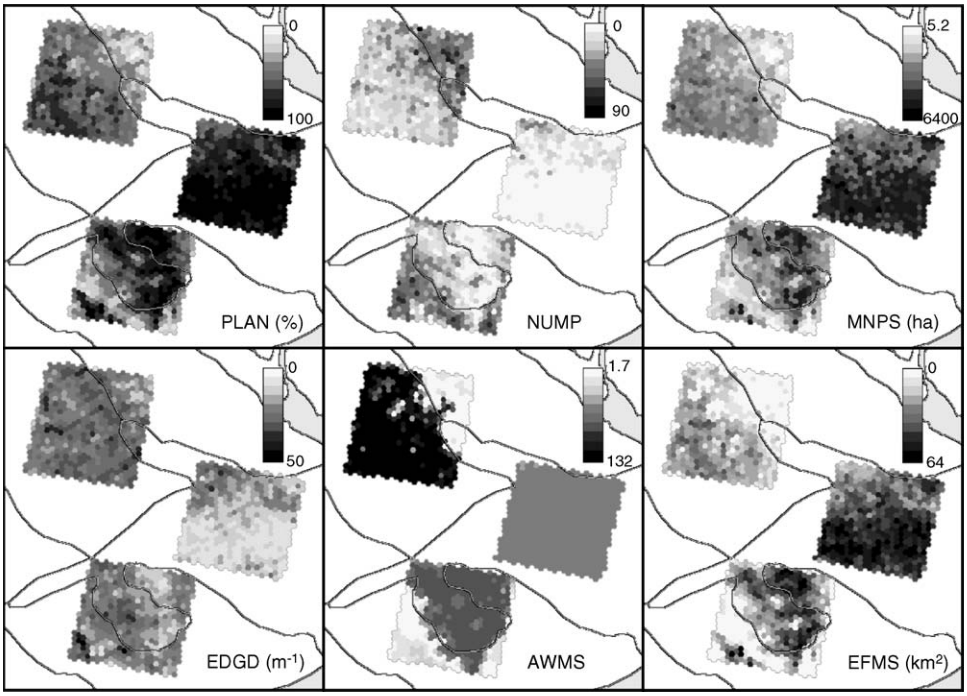

Fig. A.1.

biodiversity. Changes in the landscape structure have direct consequences on energy and water exchange between the surface and the atmosphere (Pielke and Avissar, 1990; Paruelo et al., 2000, 2004b; Guerschman et al., 2003b) and on biogeographical processes (Saunders et al., 1991). Such changes affect the provision of ecosystems goods and services, as biodiversity maintenance and carbon sequestration (Sala and Paruelo, 1997; Daily et al., 2000). In terms of production and conservation, not all the region has the same importance. In areas where almost all the land is privately owned, governments have serious economic constraints to develop environmental programs because traditional conservation objectives are almost unfeasible (Forman and Collinge, 1996). Therefore, conservation plans need to be tuned with production activities. A proper description of landscape structure provides a key element in the process of developing sustainable systems aimed to achieve a balance between agriculture, cattle raising activities and the conservation at different levels of organization, from genes to ecosystems.

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Appendix A

Maps of the six landscape metrics analyzed. The metrics were calculated for grassland polygons inside each 6400 ha hexagon cell. The lines indicate the phytogeographic districts limits of the Río de la Plata Grassland region.

See Fig. A.1

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