

Transformation dynamics of the natural cover in the Dry Chaco ecoregion: A plot level geo-database from 1976 to 2012



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ABSTRACT

The aim of this work was to characterize the spatial and temporal dynamics of the transformation of the natural cover in the Dry Chaco ecoregion from 1976 to 2012. Dry forests in this region have one of the highest deforestation rates in the world. We analyzed 44 Landsat scenes, including part of Argentina, Paraguay and Bolivia. The analysis was based on tracking individual transformed plots of the entire Dry Chaco region for over more than three decades using the same protocol. Until the end of 2012 15.8 million ha of the original habitats of the Chaco were transformed into croplands or pastures. Our study showed that the greater annual rates of transformation were observed in Paraguay, where deforestation increased dramatically in the last decade, reaching values higher than 4.0% in 2010, the highest historical value in the entire region. The size of the transformed plots increased significantly through the studied period both in Argentina and Paraguay, while in Bolivia decreased. At the landscape level, the use of several fragmentation indices showed the disruption of the continuity and connectivity of the original vegetation. The spatially explicit description of the dynamics of transformed areas is an indispensable tool for natural resources management, territorial planning and deforestation impacts assessment. The developed geo-database is available online at <http://monitoreodesmonte.com.ar/> for further analyses and use.

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1. Introduction

South American Dry Chaco is going through a new phase of agricultural expansion and intensification that is increasing exponentially the production of commodities, but that may also compromise the provision of ecosystem services (Paruelo et al., 2011). Clearance of xerophytic forests and other native vegetation types for agriculture or cattle ranching is the dominant transformation of the landscape (Gasparri and Grau, 2009; Volante et al., 2012; Caldas et al., 2013; Volante and Paruelo, 2015). Deforestation rates are one of the highest in the world (Hansen et al., 2013), which generates a worldwide concern on the conservation of the woodlands and on the sustainability of the production systems. Land use

and land cover changes in Dry Chaco forests have become a major issue for policymakers and an area of intense political dispute (Paruelo et al., 2011; Seghezzo et al., 2011; García-Collazo et al., 2013; Redaí, 2012).

Different governmental and non-governmental organizations of South American countries promote the sanction of legal instruments aimed to regulate the use of natural resources, and to support forest conservation. In December of 2004 the Congress of Paraguay sanctioned the Law No. 2524, also known as Zero Deforestation Law, which banned forest transformation in the eastern part of the country. Argentina issued Law No. 26,331, Native Forest Protection Act in November 2007, to promote the territorial planning and regulate the conservation and management of native forest (García Collazo et al., 2013). The Law No. 1700 of the Plurinational State of Bolivia, New Forest Act (issued in July 1996), was aimed to regulate property rights on forest areas for local actors. Despite these regulation attempts through legal mechanisms

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deforestation in the region follows. Moreover, there is a widespread concern on illegal deforestation and logging in Argentina (Redaf, 2012), Paraguay (Fundación Avina, 2012) and Bolivia (Andaluz and Mancilla, 2006). The ongoing land transformations generate, on the one hand, a loss of natural habitats and on the other, a fragmentation of the landscape (Gasparri and Grau, 2009). Both, in turn, have large impact on ecosystem functioning (Volante et al., 2012; Alcaraz-Segura et al., 2013a). The degree of fragmentation provides critical information to infer ecosystem characteristics (O'Neill et al., 1997). Changes in the landscape structure have direct consequences on biodiversity (Fahrig, 2003), biogeochemical cycles (Saunders et al., 1991), atmospheric dynamics (Pielke and Avissar, 1990) and water exchange (Briant et al., 2010). Land clearing increase carbon emissions (Gasparri et al., 2008), groundwater recharge and onset salt mobilization in areas where forests are replaced by annual croplands (Amdan et al., 2013).

There is a great international pressure to monitor long-term changes in forest cover (GCOS, 2004; GOCF-GOLD, 2007) and the main efforts are focused on tropical rainforests (Achard et al., 2002; Shimabukuro et al., 2004; INPE, 2008). Nevertheless, deforestation rates are particularly high in subtropical dry forests areas (FAO, 2009; Hansen et al., 2013). Several studies evaluated forest cover transformation in the Dry Chaco ecoregion (Supplementary material Table S.1); however, most of these studies had low temporal resolution or extension. A plot level geo-database for the entire Dry Chaco region that covers long term periods—more than three decades—based on the same protocol is not available. Such database is an essential input not only for basic research on the characteristics and consequences of land use and land cover change, but also for applied issues related to law enforcement or land planning.

In this paper we characterized the spatial and temporal dynamics of natural cover transformation in the South American Dry Chaco ecoregion from 1976 to 2012, using a geo-database developed with Landsat satellite imagery observation. Changes were quantified at the individual plot level. We analyzed land transformation dynamics focusing on the total transformed area, the plot size patterns and the landscape patterns of the transformed land. The developed geo-database is available for further analyses and use at <http://monitoreodesmonte.com.ar/>.

2. Study area and methods

2.1. Study area

The South American Dry Chaco is a vast plain comprising northwestern Argentina, western Paraguay and southeastern Bolivia, integrating an area of approx. 787,000 km² (Olson et al., 2001). The South American Dry Chaco ecoregion includes 3 countries (primary administrative units, Argentina, Bolivia and Paraguay), 18 secondary political and administrative units (called provinces in Argentina and departments in Bolivia and Paraguay) and 175 tertiary administrative units (called departments in Argentina, municipalities in Bolivia, and districts in Paraguay). Of the total area of the Dry Chaco, 62% is located in Argentina, including part of the provinces of Salta, Santiago del Estero, Jujuy, Tucumán, Formosa, Chaco, Catamarca, Córdoba, Santa Fe, La Rioja, San Juan and San Luis; 22% in Paraguay, including part of the departments of Alto Paraguay, Boquerón and Presidente Hayes; and 16% in Bolivia, including part of the departments of Santa Cruz, Chuquisaca and Tarija.

The Chaco region is one of the flatter plains of the planet (Jobbágy et al., 2008). This region is part of the Río de la Plata Basin and is crossed by the Pilcomayo, Bermejo, Juramento and Salado rivers. The climate of the Chaco is semiarid and is characterized by a

strong seasonality, with high temperatures in summer and winter frost. Annual mean temperature varies from 18 °C in the southern part of the ecoregion to 26 °C in the north, and annual mean rainfall varies from 400 mm/year in the center to 1000 mm/year in the eastern and western extremes (Minetti, 1999). Because of its continental climate there are large variations in temperature between winter and summer. The months of maximum precipitation coincide with those of higher temperatures (Berbery and Barros, 2002). Rains occur in summer, from October to March, and the driest months are July and August. The predominant natural vegetation of the Chaco is open woodland or thorn forest, interspersed with grasslands (Morello et al., 2012).

This region has a significant productive potential (Lambin et al., 2013), a large biodiversity and cultural richness (TNC, 2005), but also presents high levels of poverty and inequality (Bolsi and Paolasso, 2009; Paolasso et al., 2012). Around 7.5 million people live in the Chaco, coexisting aboriginal populations with descendants of European immigrants (*Criollos*) (Naumann, 2006). Indigenous people and “*criollos*” practice a subsistence economy, including small scale agriculture, extensive ranching, hunt and gathering (Leake and De Economo, 2008). In the last decades, the area is undergoing into a rapid transformation to agribusiness (Grau et al., 2005; Gasparri et al., 2008).

2.2. Image processing and database development

Landsat satellite images were examined in order to identify land-clearing transitions in the period 1976–2012. Images were obtained from CONAE (National Commission on Space Activities, from Argentina), INPE (National Institute for Space Research, from Brazil) and USGS (U.S. Geological Survey, from USA). The whole area includes 44 Landsat scenes. For years prior to 2000 three periods were analyzed: 1976–1986, 1986–1996 and 1996–1999. From 2000 to 2012 land transformation dynamics was evaluated annually. We selected images with low presence of clouds, preferably corresponding to December (because most of the clearings occur during the driest winter months). Images were selected, georeferenced, ordered by date and displayed in high contrast false color composite (RGB band combination: 4-5-3) in Quantum GIS 1.8.0-Lisboa. About seven hundred Landsat images have been analyzed. A list of the used images is available at <http://monitoreodesmonte.com.ar/metodologia>.

Landsat Multispectral Scanning (MSS) 1–3 imagery (launched at 1972 and terminated at 1983, with 60 m spatial resolution and 4 spectral bands) was used to detect land transformations before 1976. Scene size and path-row designations from Landsat MSS 1–3 imagery differs from that of subsequent releases. Landsat Thematic Mapper (TM) 4–5 imagery (launched at 1982 and terminated in 2013, with 30 m spatial resolution and 7 spectral bands) was used to detect transformations at 1986, 1996, and from 2000 to 2012. Images from Landsat Enhanced Thematic Mapper Plus (ETM+) 7 (launched at 1999 and still active, with 30 m resolution and 8 spectral bands, operating with scan line corrector disabled since 2003) were used to detect transformations from 2000 to 2012, as an alternative to the use of Landsat 5.

The transformed plots were manually digitalized by visual interpretation of the last Landsat image of the study period (2012). Each individual plot was incorporated as a polygon shape into the GIS. The criterion to define plots by visual interpretation was the disruption of spatial continuity with strong evidences of human action. Transformed plots by human action are regularly shaped and have defined limits, while transformations due to natural agents (e.g. fire) are irregularly shaped. In some cases where the size of the patches was significantly large but with small defined plots inside, without hedgerows presence between them (e.g. plots

with sugarcane in west of Tucumán transformed before 1976), plot limits were automatically traced using segmentation methods (Bhanu et al., 1995). The parameters of the segmentation methods were case defined by region according to the similarity to the real shape and size of the plots, and were revised and corrected manually afterwards.

Once the limits of the plots were drawn, the year of transformation of each plot was defined by overlaying sequentially previous Landsat images, starting from the oldest (1976). Thus, plots were identified (in the attribute table) by its year of transformation. If a polygon identified in 2012 as unit was partially transformed in several years, the 2012 plot was divided into as many plots as clearance processes occurred.

The classification was validated using high spatial resolution historical imagery from Google Earth. Five thousand random points were distributed in the study area to compare high resolution imagery with the database obtained in our study. The area covered by high spatial resolution imagery in the Dry Chaco region is 410,703 km² (aprox. 52% of the total Dry Chaco area). The first high resolution image available in the region is from 2002. The random points were classified into 4 categories for each year from 2002 to 2012: i) Land Transformation in both the database and Google Earth (Tdb-Tge); ii) Land Transformation in the database and natural cover in Google Earth (Tdb-Nge); iii) Natural cover in the database and Google Earth (Ndb-Nge); iv) Natural cover in the database and land transformation in Google Earth (Ndb-Tge). We also compared

our database with published data and contrasted transformation area estimates with the area estimated in this work.

2.3. Data analysis

The term “transformation” is used when there is a replacement of natural vegetation (forests, grasslands, wetlands, savannas or shrublands) by cultivated pastures or crops. The rates of transformation were calculated for five periods (pre 1976, 1976–1986, 1986–1996, 1996–2006, and 2006–2012) to evaluate tendencies. We estimated the Annual Rate of Transformation using the methodology proposed by the Food and Agriculture Organization (FAO, 1995):

$$q\% = 1 - \left[\left(\frac{A_2}{A_1} \right)^{\frac{1}{t_2 - t_1}} - 1 \right] * 100$$

Where $q\%$ is the Annual Rate of Transformation in percentage, and A_1 and A_2 represent the areas of natural habitats at dates t_1 and t_2 respectively. For the first period of analysis, we considered $t_1 = 1940$ as the year when natural vegetation removal started in the region (Morello et al., 2005). The original natural areas in the region were calculated after discounting urban areas, lakes, rivers and salines to the total area of the political administrative units. Because it is not possible to know the original forest cover of a given transformed area, $q\%$ does not represent the Annual Rate of Deforestation, but

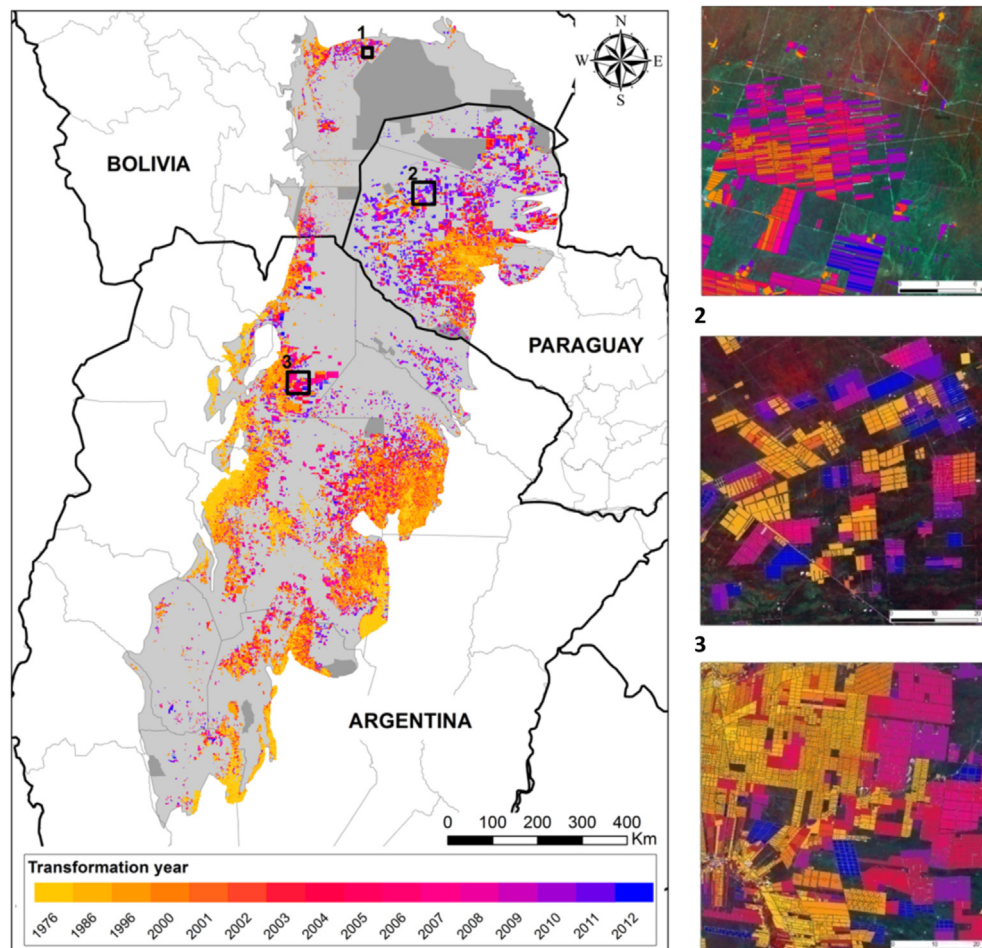


Fig. 1. Left panel: Spatial distribution of transformed areas from 1976 to 2012 in the South American Dry Chaco ecoregion. Darker gray color corresponds to protected areas inside the region. Right panel: Detail of the transformed plots in three zones from Bolivia (1), Paraguay (2) and Argentina (3).

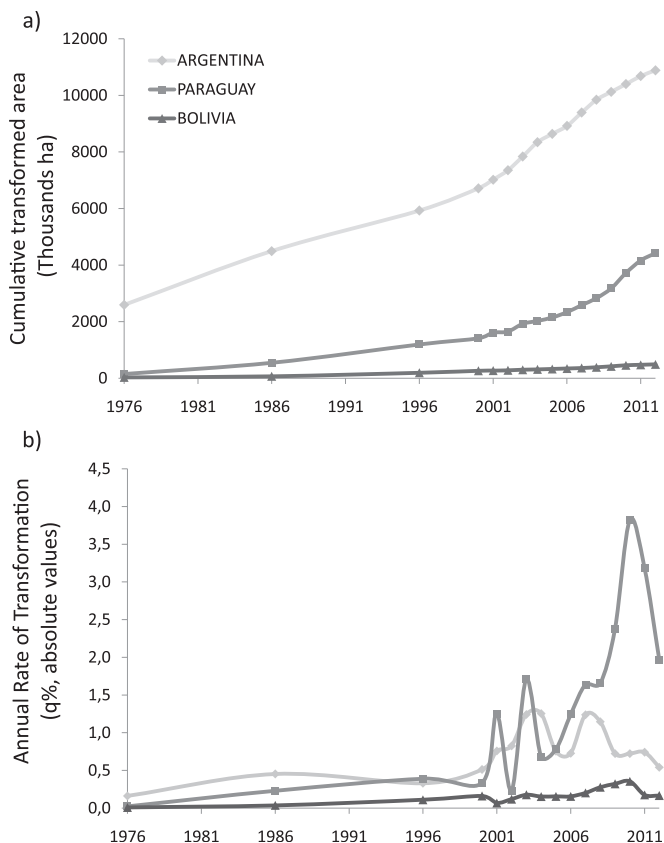


Fig. 2. (a) Cumulative transformed area and (b) Annual Rate of Transformation “ $q\%$ ” (FAO, 1995) as a function of the time from 1976 to 2012 at country level in South American Dry Chaco ecoregion.

the Annual Rate of Transformation. We employ $q\%$ as positive values for a better representation and understanding. $q\%$ is a widely used rate, as it weights the transformed area by the initial natural area and allows comparing rates in other locations around the world. We evaluated trends according to the best fit model based on the coefficient of determination for primary and secondary administrative units.

Plot-scale level analysis was performed by analyzing individual Plots (productive units, in most of the cases). Landscape patterns were analyzed observing transformed land patches dynamics for each period. Patches are Plots aggregated at 200 m, i.e. without considering hedgerows between transformed Plots.

Landscape fragmentation refers to a disruption in the continuity of natural cover. It is the process where a landscape matrix is progressively subdivided into smaller and more isolated patches (Baldi et al., 2006; Gasparri and Grau, 2009). Landscape patterns of the transformed land were quantified using several indices, since no single metric can capture the complexity of the spatial arrangement of the patches (Riitters et al., 1995). Metrics to measure landscape fragmentation usually make reference to the changes in a matrix of the natural cover, but in this case, the metrics refer to the transformed Patches, what gives an idea of the accumulated impact of the transformations. Analysis of the landscape dynamics was based on a set of “Patch-based” landscape metrics at country level: total area transformed (TA), mean patch size (MPS), percentage co-variation of MPS (PSCOV), number of patches (NUMP), density of patches (DENS), total edge (TE) and Mean Shape Index (MSI) (McGarigal et al. 2002; Pinto-Ledezma and Ruiz, 2010). This metrics encompass essential aspects of ecosystem structure

and functioning. TA of patches has effects on water, energy and nutrients cycling. MPS, NUMP have implications on the disruption of landscape continuity and connectivity, and the minimum area requirement for species survival and ecosystem functioning. PSCOV is a measure of the variability and distribution of the patches size. DENS is defined as the number of patches per unit area, which facilitates comparisons among landscapes of varying size, and is a good indicator of fragmentation (McGarigal et al., 2002). TE has implications for interior sensitive species and ecosystem integrity (Broadbent et al., 2008). MSI describe shape complexity and the compactness of patch shape. Specifically, MSI quantifies the amount of edge present in a class relative to what would be present in a class of the same area but with a circular shape. Thus, the index equals 1 for circle patches of any size and increases without limit as the patch becomes increasingly irregular.

3. Results

3.1. Evaluation of the database

The overall accuracy of the classification was 97.8%. User's and producer's accuracies are balanced for “Transformation” and “Original Cover” classes. Accuracy for individual years, varied between 95.6% and 99.2%. The estimated error matrix and accuracy for each year are shown in the Supplementary material (Table S.2 and S.3).

We compiled 18 published articles or reports that include classifications of transformed, deforested or cultivated area in the Dry Chaco ecoregion in this work (Table S.1 of the Supplementary material). These classifications cover different spatial and temporal extensions than our database. Fifteen of the classifications were realized using Landsat imagery, while three of them were based on MODIS imagery. Ten classifications resulted from visual interpretation, and the remaining by digital classifications, either they were supervised (5), unsupervised (2) or a combination of both (1).

Only two deforestation databases are available online: the global maps of forest cover change made by Hansen et al. (2013), which is available in raster format; and the data produced by Guyra Paraguay (Fundación Avina, 2012; Cardozo et al., 2013; Caballero et al., 2014), which is available in KMZ format but without an accuracy assessment.

The different spatial and temporal extensions of the analysis precluded a comparison with each single available product of land transformation. We made a comparison with the data provided by Hansen et al. (2013), Clark et al. (2010) and Boletta et al. (2006). For the same area (the Dry Chaco) the transformed area in our database was 10.0% higher than the reported by Hansen et al. (2013) (6.0% when polygons were rasterized at 30×30 m pixel size), 1.5% higher than Clark et al. (2010), and 0.2% smaller than Boletta et al. (2006) (See Table S.1 Supplementary material).

3.2. Dynamic of land transformation

The total transformed area in Dry Chaco by the end of 2012 totaled 15.8 million ha (Fig. 1). This area corresponds to the 20.7% of the natural area in the whole ecoregion. Natural areas transformed in Argentina, Paraguay and Bolivia represent the 68%, 27% and 4% respectively, of the total area transformed (Fig. 2a). The Annual Rate of Transformation $q\%$ had the highest values in Paraguay since 2009, reaching values over 4.0% in 2010, the highest historical value in the entire region (Fig. 2b).

Considering the second level administrative units, Santiago del Estero contributed with 23% of the total transformed area, followed by Boquerón, Salta, Chaco and Alto Paraguay, which contributed respectively with a 17%, 12%, 10% and 8% of the total transformed

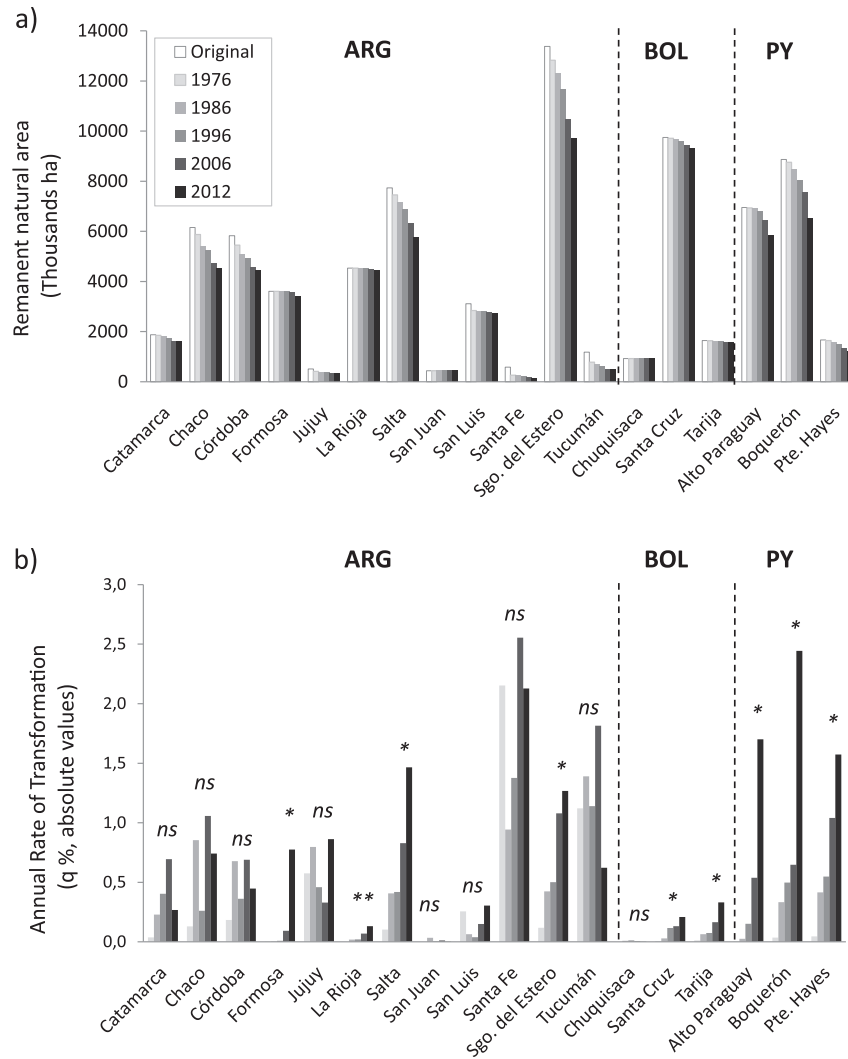


Fig. 3. (a) Remaining natural area (Thousands ha) and (b) Annual Rate of Transformation “q%” (FAO, 1995) for five periods (1940–1976; 1976–1986; 1986–1996; 1996–2006; 2006–2012) at secondary administrative units in South American Dry Chaco ecoregion. For each secondary administrative unit, trends were evaluated according to the best fit model based on the coefficient of determination. ns: not significant regression, **: linear regression, *: second order polynomial regressions.

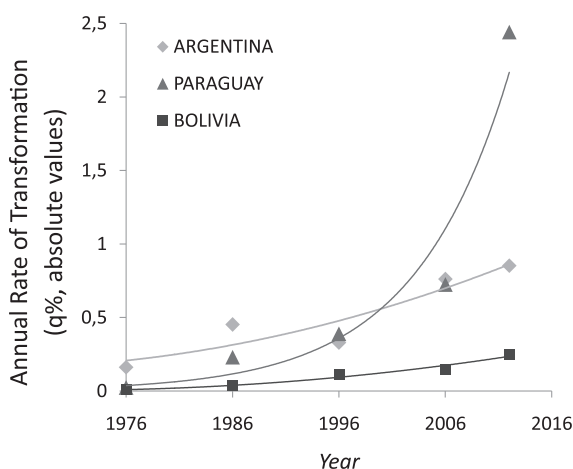


Fig. 4. Annual Rate of Transformation “q%” (FAO, 1995) for five periods (1940–1976; 1976–1986; 1986–1996; 1996–2006; 2006–2012) at country level in South American Dry Chaco ecoregion.

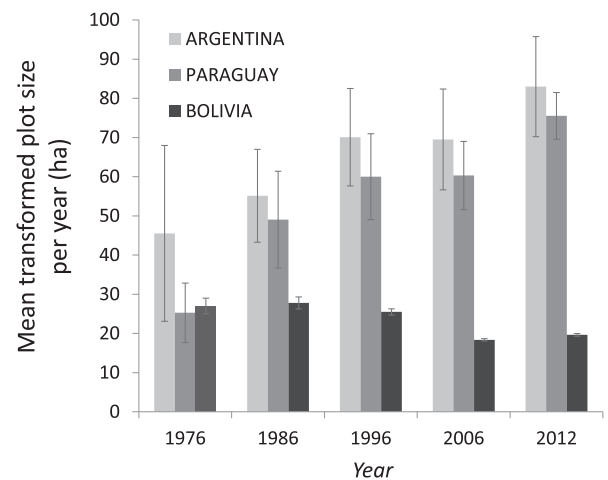


Fig. 5. Mean transformed plot size per year evolution from 1976 to 2012 at country level in South American Dry Chaco ecoregion. Error bars represent SE.

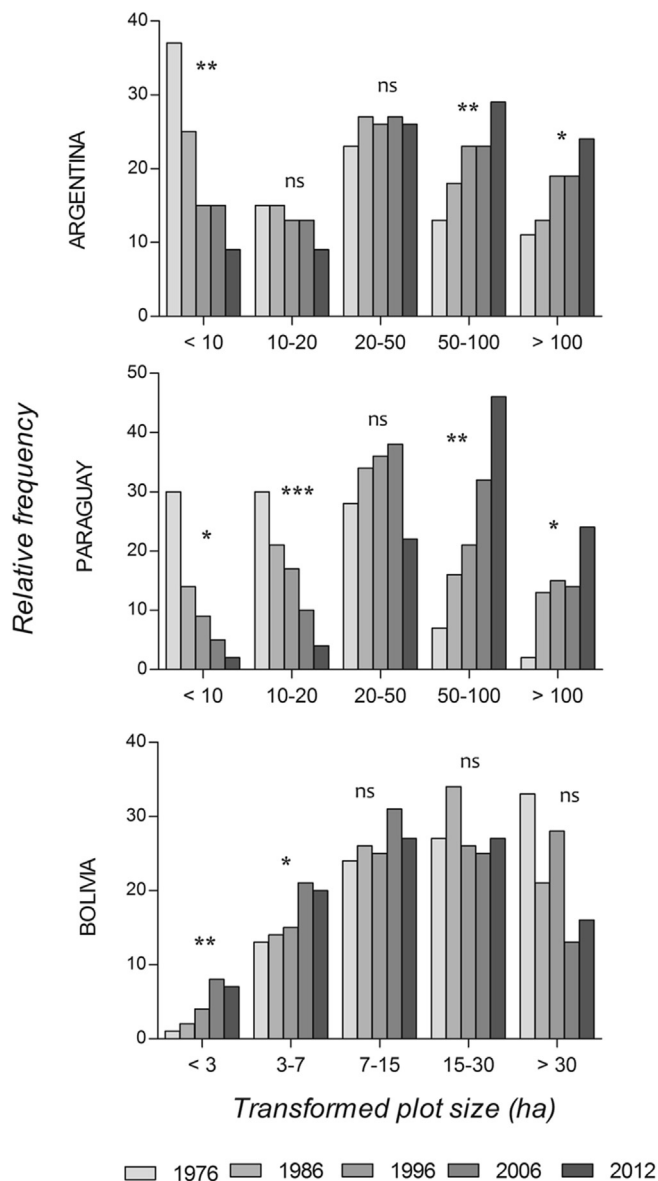


Fig. 6. Relative frequency (to each year) distribution for different plot sizes categories of transformed areas from 1976 to 2012 at country level in South American Dry Chaco ecoregion. ns: not significant regression, *: $p < 0.5$, **: $p < 0.05$, ***: $p < 0.01$.

area respectively (Fig. 3a). The Annual Rate of Transformation $q\%$ showed a significant increasing trend from 1976 to 2012 in Formosa, La Rioja, Salta, Santiago del Estero, Santa Cruz, Tarija, Alto Paraguay, Boquerón and Presidente Hayes. Except for La Rioja (showing a linear increase), trends were exponential (Fig. 3b).

An increasing positive trend of $q\%$ values was observed for the entire region, resulting in averages increments since 1976 of about 0.026% per year. Paraguay showed an exponential growth in $q\%$, presenting average increments of about 0.07% per year. Argentina and Bolivia presented averages increments in $q\%$ of about 0.02% and 0.01% per year, respectively (Fig. 4).

3.3. Plot size patterns at country level

Mean plot size (MPS) was, on average, bigger in Argentina (61.99 ± 0.29 ha) than in Paraguay (54.03 ± 0.27 ha) and Bolivia (33.39 ± 0.25 ha). Moreover, MPS had a positive trend from 1976 to

2012 for Paraguay ($b_1 = 1.13 \pm 0.02$ ha/year) and Argentina ($b_1 = 0.82 \pm 0.02$ ha/year), while for Bolivia, had a negative one ($b_1 = -0.52 \pm 0.03$ ha/year) (Fig. 5).

The relative frequency of small plots (less than 20 ha) decreased and the relative frequency of large plots (more than 50 ha) increased throughout the study period (1976–2012) for Argentina and Paraguay. For Bolivia the trends were the opposite, besides plot sizes were smaller than in the other countries (Fig. 6).

3.4. Patch-scale level analysis of the transformed area at the country level

On average, Paraguay had larger Patch size (3513 ± 742 ha), than Argentina (1284 ± 115 ha) and Bolivia (361 ± 70 ha). Patch size at landscape level was 10 times bigger in Paraguay than in Bolivia, and 3 times bigger compared to Argentina. The Number of Patches, its co-variation, and the Density of Patches (patches per unit area) increased as the Total Area transformed increased from 1976 to 2012. Mean Patch Size (ha) and the Total Edge (m) showed also an increasing trend, except between the first and second period analyzed for Bolivia. The Mean Shape Index showed high values in the first period for Bolivia and Paraguay—indicating increases in complexity of patches—, and the opposite pattern for Argentina (Table 1).

The relative frequency of small patches of transformed areas (from 10 to 100 ha) showed a positive trend, while large patches tended to increase in number in the period analyzed in Argentina and Paraguay. For Bolivia, trends were not evident (Fig. 7).

4. Discussion

We developed a comprehensive spatially and temporally coherent database on land use transition covering the Dry Chaco region. The database was constructed identifying individual plots through time and using the same identification protocol from 1976 to 2012. The spatially explicit description of the dynamics of transformed areas is an indispensable tool for natural resources management, territorial planning and deforestation impacts research, among others. This geo-database has already been used in academic studies, to detect illegal deforestation (Redaf, 2012), and to support legal disputes in aboriginal territories in Argentina (see bestp.agro.uba.ar/), among other uses. The database is available online at <http://monitoreodesmonte.com.ar/> for further studies.

The original vegetation, particularly dry forests, of the Dry Chaco is being rapidly replaced by extensive croplands and pastures at an alarming rate (Volante et al., 2012; Hansen et al., 2013). Our study revealed that the rates of deforestation had an increasing trend from 1976 to 2012 (Figs. 2, 3 and 4). In the last period analyzed the Annual Rate of Transformation $q\%$ for the entire region increased 1.7 times, from 0.62% to 1.02%. Changes in $q\%$ were spatially heterogeneous. Although at the country level trends were always positive, the magnitude of the increase in the last six years varied: in Paraguay $q\%$ increased 3.4 times (from 0.72% to 2.44%), in Bolivia increased 1.7 times (from 0.15% to 0.25%), and in Argentina increased 1.12 times (from 0.76% to 0.85%) (Fig. 4). Changes were also variable at the second administrative level analyzed. In the last period analyzed the Annual Rate of Transformation was still increasing in Argentina in several provinces (Formosa, Jujuy, Salta, San Luis and Santiago del Estero). In Formosa the Annual Rate of Transformation increased 8.2 times in the last decade (from 0.09% to 0.8%), and in Salta, 1.6 times (from 0.86% to 1.40%) (Fig. 3b). Other provinces showed decreasing trends in the Annual Rate of Transformation (Catamarca, Chaco, Córdoba, Santa Fe and Tucumán). These decreasing trends in deforestation may be associated with two facts: a) much of the remaining forest lands in those provinces

Table 1

Spatial indexes from patches of transformed areas at landscape level (200 m aggregation, mean hedgerows with) in South American Dry Chaco ecoregion, for 1976, 1986, 1996, 2006 and 2012 in Argentina, Paraguay and Bolivia. Gray bars represent the relative differences between years in a particular index and country. TA = total area (ha), MPS = mean patch size (ha), PSCOV = percentage co variation (%) of MPS, NUMP = number of patches, DENS = density of patches (patches/10 km²), TE = total edge (m), MSI = Mean Shape Index.

	Year	TA (ha)	MPS (ha)	PSCOV (%)	NUMP	DENS	TE (m)	MSI
ARGENTINA	1976	2.543.280	715	10	3.556	0,76	11.598	1,51
	1986	4.520.474	872	12	5.182	1,11	13.584	1,55
	1996	5.845.509	1.130	12	5.172	1,11	15.935	1,57
	2006	9.046.075	1.577	14	5.738	1,23	18.650	1,55
	2012	11.010.087	1.828	14	6.023	1,29	20.385	1,54
BOLIVIA	1976	31.885	375	2	85	0,07	10.441	1,64
	1986	70.541	226	6	312	0,26	6.261	1,50
	1996	198.764	251	12	792	0,65	6.319	1,52
	2006	362.310	364	11	994	0,81	7.366	1,54
	2012	526.281	474	11	1.110	0,91	8.718	1,56
PARAGUAY	1976	220.791	1.110	6	199	0,11	26.286	1,86
	1986	864.945	2.016	9	429	0,25	33.710	1,72
	1996	1.919.700	2.344	13	819	0,47	30.604	1,65
	2006	4.491.473	3.790	13	1.185	0,68	42.856	1,71
	2012	7.381.943	4.605	13	1.603	0,92	47.446	1,68

are located in areas with topographic, edaphic or climatic limitations for agriculture; b) the implementation of the Native Forest Protection Act—Law No. 26,331—, in November 2007, which restricted deforestation in some areas of high and medium conservation value. These results are consistent with those found by UMSEF (2012).

The Dry Chaco has large areas with suitable conditions for producing highly demanded commodities: crops such as soybean and maize, and meat from cultivated pastures (Aizen et al., 2009; Glatzle, 1999). The sharp increase in the prices of these commodities in the last fifteen years (FAOSTAT, 2010; Gasparri et al., 2013; Aide et al., 2012) has led to a rapid expansion in the region. Additionally, changes in local currency exchange rates, the availability of technological packages (no-tillage system and genetically modified crops), and regional increases in precipitation (Boletta et al., 2006; Gasparri et al., 2008; Zak et al., 2008) prompted abrupt changes in the rates of deforestation.

Different groups of land users have a strong imprint on the configuration of landscapes (Killeen et al., 2008; Baldi et al., 2015). The transformation plots size gives an idea of the management unit and it is a proxy of the economic dimension of the actors driving the transformation. In Argentina and Paraguay, where there is a predominance of capitalized farmers and ranchers (Gasparri et al., 2013; Baldi et al., 2015), large plots predominate (Fig. 5), and its size increased from 1976 to 2012 (Fig. 6). This pattern suggests the operation of large land holdings (Steininger et al., 2001; Killeen et al., 2008; Gasparri et al., 2013) and a high level of mechanization for deforestation and sowing (Pacheco and Mertens, 2004; Huang et al., 2009). In Bolivia the situation differed from Argentina and Paraguay because the areas deforested for agriculture are managed by a more diverse group of stakeholders (Pacheco, 2004; Redo et al., 2012). The Chaco region of Bolivia, where there is a predominance of aboriginal groups and non-mechanized Mennonite settlers (Baldi et al., this issue), presented a significantly smaller mean plot size (Figs. 1 and 5) than the Argentine and Paraguayan Chaco. In Bolivia a significant increase in

the relative frequencies of small transformed plots throughout the period studied was observed (Fig. 6).

The spatial configuration of the transformed patches (plots aggregated at 200 m) changed substantially during the study period between 1976 and 2012. The mean patch size, the number of transformed patches, the density of patches and the total edge increased considerably as the total area transformed increased (Table 1). These results are consistent with other analyses of landscape changes of dry forest areas (Steininger et al., 2001; Gasparri and Grau, 2009; Pinto-Ledezma and Rivero Mamani, 2013). Mean shape index was higher for Paraguay than for Argentina and Bolivia, indicating more complexity (i.e. less compactness) in the deforested patches. Big patches tended to augment in Paraguay, while in Argentina and Bolivia patch size was more stable. The increase in the size of deforested patches suggests a homogenization of the landscape (Fig. 7). The total transformed area, the size of the deforested patches, the total edge and the shape of the patches have large impact on ecosystem functioning (Volante et al., 2012), on local populations, due to habitat loss (Macchi et al., 2013), and on local climate (Camargo and Kapos, 1995; Alcaraz-Segura et al., 2013b).

Large-scale conversion of Dry Chaco forests into pastures or annual crops accelerates climate changes (Agrawal et al., 2011), alters the ecosystem functioning (Volante et al., 2012) and lead to social problems (Redaf, 2012). In the Dry Chaco more than 20 native ethnic groups coexist. These groups have no definitive tenure of their lands (Leake and De Economo, 2008) and are being displaced from their homeland by the agricultural expansion, increasing territorial conflicts associated to the process that Harvey (2003) defined as “accumulation by dispossession”. Monitoring is a key element to start solving the territorial conflict installed by agricultural expansion. On one hand a proper description of the spatial and temporal patterns of land transformation would allow to identify the biophysical, social, political and economic drivers of changes. On the other hand monitoring is essential to develop and enforce land use planning and management policies.

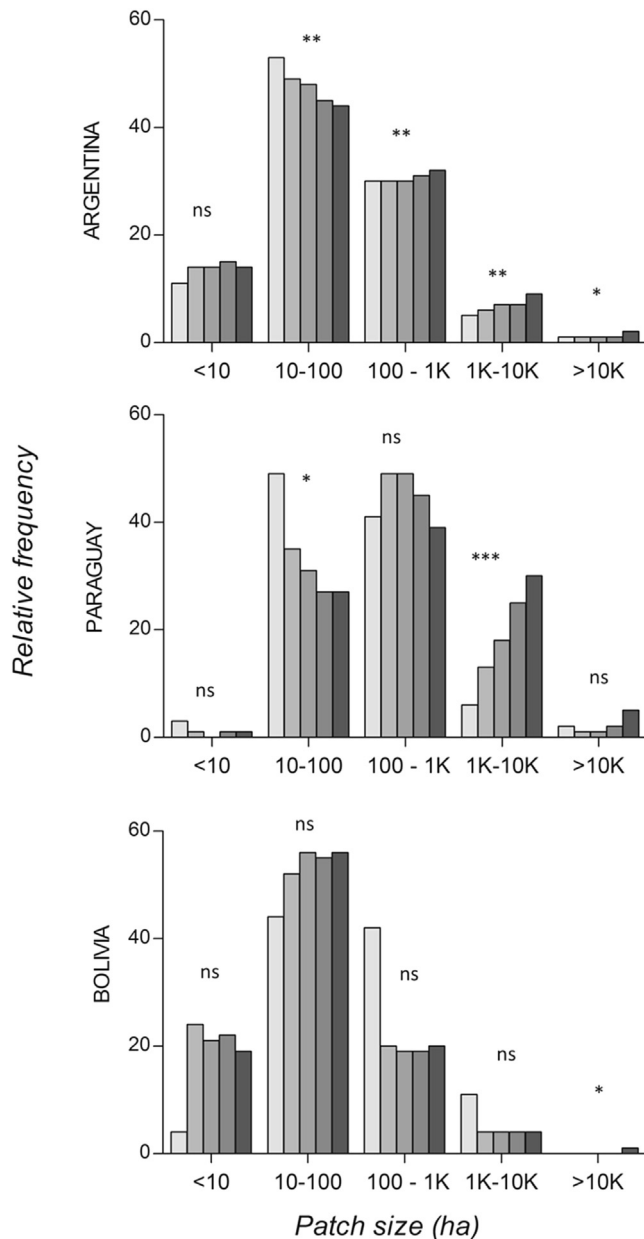


Fig. 7. Relative frequency (to each year) distribution for different patch sizes categories of transformed areas (plots aggregated at 200 m) at landscape level from 1976 to 2012 at country level in South American Dry Chaco ecoregion. ns: not significant regression, *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jaridenv.2014.11.009>.

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