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Determinants of the spatial distribution of cultivated land in the North Argentine Dry Chaco in a multi-decadal study

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A B S T R A C T

Deforestation in the Northern Argentine Dry Chaco (NADC) has been mainly driven by soybean expansion and, more recently, by the expansion of implanted pastures. In areas with fast land use transformations, it is important to identify variables that determine the spatial distribution of land use change. The kinds of exploratory analyses that do so contribute to understanding the logic of deforestation agents and to identifying more probable sectors for land use change. We produced maps of cultivated land in NADC for different years (1972, 1991, 1997, 2002, 2007). Based on these maps, we evaluated the importance of environmental and accessibility variables over the spatial distribution of cultivated land in NADC using multiple and simple logistic regressions. Environmental variables (soil suitability for agriculture, rainfall, topography) and accessibility variables (distance to main roads, distance to main towns) were used to fit logistic regressions to the occurrence of cultivated land at different years as dependent variable. Goodness-of-fit was evaluated by the Relative Operating Characteristic (ROC) and Pseudo R2 indices. Results indicate that the main variables explaining the spatial distribution of cultivated land in 2007 are distance to main towns (ROC = 0.76; Pseudo R2 0.12) and soil suitability (ROC = 0.72; Pseudo R2 0.11). The capacity of environmental and accessibility variables to explain the spatial distribution of cultivated land decreased through time (ROC in 1972 = 0.91 and ROC in 2007 = 0.77). Results also suggest that rainfall has not been a major restriction to cropland expansion, and that the main limitations are imposed by infrastructure and services provided from main towns. A decreasing goodness-of-fit over time suggests that initial limitations have been overcome by cropland expansion and the consolidation of productive areas. Based on these results, we suggest that cropland expansion may generate positive feedbacks in infrastructure and services (i.e. agglomeration economies) that could explain why initial limiting factors related with distance to roads and towns have been gradually overcome.

1. Introduction

Understanding patterns and drivers of land use change is important for planning the use and conservation of natural resources. The most evident requirement of information is the area affected by land use change, but some characterization of its geographical patterns is also necessary (Nelson and Geoghegan, 2002). In particular, the study of spatial patterns and their control is valuable to understanding the proximate causes of change (Muller et al., 2012). Geographical patterns of land use change are the result of interaction between biophysical (e.g rainfall, soil, slope) and accessibility factors. These factors are taken into account by socioeconomic actors, i.e. the agents who make decisions about land use change, applying a logic framed by particular experiences, cultural values and perception. In consequence, different actors under similar biophysical and socioeconomic conditions may produce contrasting geographical patterns of land use.

One of the simplest and most established models to study geographical patterns of land use is the von Thünen model (von Thünen, 1966). This model proposes that for an area with spatially homogeneous agricultural yields (i.e homogeneous biophysical conditions and technology), the localization of cultivated land is a function of the distance to the market and of transport cost. In this way, the theoretic land use pattern shows a concentric distribution around markets (cities) with a gradient from the most

Abbreviations: NADC, Northern Argentine Dry Chaco; ROC, Relative Operating Characteristic (ROC); RN, National Road; SP, standardized parameters (SP).

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intensive land use (e.g horticulture) near the market to less intensive land uses (e.g extensive cattle) in the most remote areas. The general idea of the von Thünen model is the foundation for many spatial deforestation models based in accessibility and distance to road and cities (e.g. Chomitz and Gray, 1996; Nelson and Hellerstein, 1997; Walker, 2004. For more examples see the revision: Kaimowitz and Angelsen, 1998).

The emergence of globalization and the development of interconnected regions generate a different situation, in which markets and consumption in cities are sourced by distant places (Seto et al., 2012). In this situation, the logic of a central market sourced by surrounding areas should be modified. Cities and urban centers, however, still play an important role in articulating agriculture production as centers of logistic, administrative and economic activity. Agglomeration economies has been recently suggested as a valuable concept to understand the evolution of land use change. This framework define local land use as a consequence of the concentration and diversity of various supply chain actors in the region, not just yield potential and transportation cost as predicted by Thunian theory (Garret et al., 2013). The agglomeration economies concept points out that companies that operate in geographical proximity to each other benefit from positive externalities. These are created by a range of factors that promote a more efficient activity, including better access to market information, access to technology, increased specialization in value chain, or a labor pool (Fujita and Thisse, 2013). The concept of agglomeration economies takes into account the existence of circular causality (positive feedback) which reinforces the positive externalities of agglomeration, thus promoting the incorporation of more companies. This process was proposed to explain the existence of clusters of soybean production on Brazilian deforestation frontier (Garret et al., 2013).

In the last decades, deforestation patterns in South America shifted from occurring mostly in moist tropical forests to becoming more active in deciduous dry forests and savannas (Hansen et al., 2013; Aide et al., 2013). These changes in continental patterns of deforestation were accompanied by changes in the main actors involved (Rudel et al., 2009). During the last decades, deforestation in dry forests and savannas of South America has been promoted by medium and large agribusiness companies oriented towards global market agriculture commodities (mainly soybean) and intensive cattle ranching (Gasparri and le Polain de Waroux, 2014). This type of agribusiness-driven deforestation, has been less studied compared to the spatial patterns of small scale farmer-driven deforestation in moist tropical forests. The emergence of agribusiness companies as main agents of deforestation could represent changes in the spatial patterns of deforestation in contrast to deforestation by small-scale farmers with subsistence economies. Previous works exploring geographical patterns of agribusiness deforestation in Matto Grosso in Brazil (Jasinski et al., 2005) and *Santa Cruz de la Sierra* in Bolivia (Kaimowitz et al., 2002; Muller et al., 2011) showed that distance to roads and towns are the main factors explaining the localization of cultivated land expansion, suggesting the prevalence of factors related with production logistics.

The Chaco region has turned into one of the most dynamic deforestation areas in South America (Aide et al., 2013; Graesser et al., 2015). This process has been quantified for different sectors of Paraguay (Huang et al., 2009; Caldas et al., 2013) and Argentina (Zack et al., 2004; Boletta et al., 2006; Clark et al., 2010). Some of the previous studies also explored causes of change, including rainfall increase, technology change and soybean economy (Grau et al., 2005; Zack et al., 2008; Gasparri and Grau, 2009; Gasparri et al., 2013; Hoyos et al., 2013). However, at the moment, the geographical patterns of deforestation in the Dry Chaco and their main conditioning factors have not been described. In this work, we explore the relation between biophysical and accessibility factors and geographical patterns of cultivated land expansion from 1972 to 2001 in the North Argentine Dry Chaco. We evaluate the importance of different variables through time to explain the geographical distribution of cultivated land. Based on our results, we propose alternative mechanisms to explain past and current geographical patterns of cultivated land and the implications for future research and land use planning.

2. Methods

2.1. Study area

The Dry Chaco is the largest continuous patch of Neotropical dry forest (Portillo-Quintero and Sanchez-Azofeifa, 2010). The Northern Argentine Dry Chaco (22 °S–27 °S and 59.5 °W–65 °W; Fig. 1) includes the largest part of the Argentine Chaco. The area is characterized by flat relief and soils formed by eolian and fluvial sediments. Mean annual temperature ranges between 19 and 24 °C and rainfall between 400 and 900 mm year^{-1}, distributed in rainy summers and dry winters, with higher values in the West and East borders of the study area (Minetti, 1999). Vegetation is dominated by broadleaf, deciduous or semi-deciduous trees and the region is considered by some authors as a neotropical broadleaf dry forest (Gentry, 1995; Hoekstra et al., 2010). The region undergoes fast deforestation promoted by modern agriculture, which is well documented for Argentina (e.g. Zack et al., 2004; Boletta et al., 2006; Gasparri and Grau, 2009), but generalized in the whole region (Clark et al., 2010). The main roads of the study area are the national roads (RN in Spanish) number 34, 16 and 81 (Fig. 1b). RN34 is oriented in South-North direction towards the western sector of the study area. RN16 is oriented in west-east direction, crossing the region in the southern part (provinces of Salta, Chaco and Santiago del Estero). RN81 is also oriented in west-east direction but it crosses the region in the northerner part (provinces of Salta, and Formosa).

2.2. Cartography

Variables analyzed as conditioning factors of cultivated land expansion patterns in NADC were rainfall, soil suitability, slope, distance to main roads and distance to main towns. All variables were mapped in a raster format with the same spatial resolution. Different maps and data sources were converted and resampled to preserve spatial consistence in raster formats and the pixel sizes for the logistic regression analyses. Rainfall layers from WORLDCLIM were used as reference. Sources of information and a description of each variable can be found below:

2.2.1. Land cultivated maps

In order to prepare cultivated land maps, we identified cultivated land expansion as polygons in a vectorial format by visual interpretation of Landsat images for different dates: 1972 (MSS scenes from 08/1972 t to 05/1976), 1991 (TM scenes from 03/1989 to 02/1992), 1997 (TM scenes from 04/1997 to 01/1999), 2002 (TM scenes from 04/2001 to 09/2002), 2007 (ETM and TM scenes from 07/2007 to 08/2007). Although not all the images correspond to the exact years of reference, we set the reference year based in the majority of dates acquired and the date of those images which capture the most active sectors of deforestation. A list of the images used in our study is showed in Supplementary material SI. For the mapping of cultivated land, we used the standard procedures from the National Forests Resource Assessment Program (UMSEF, 2013) to generate binary maps of cultivated and non-cultivated land. These procedures generate maps previously assessed with an

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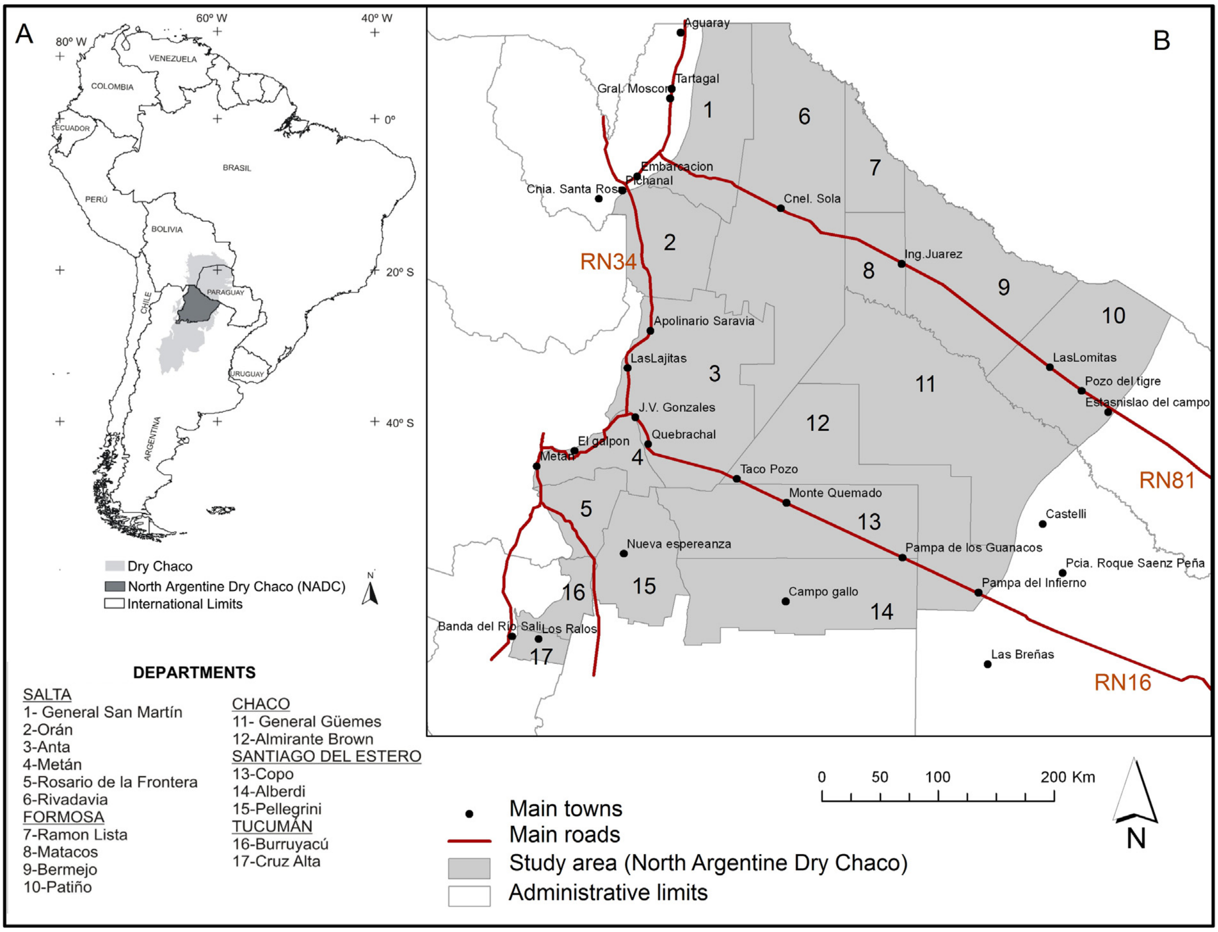

Fig. 1. Study area and departments included in analysis for the North Argentine Dry Chaco. A) Dry Chaco and NADC in South America. B) references for departments in the NADC; main roads and towns of the study area.

overall exactitude of 92% (Grau et al., 2005). The conversion of natural vegetation (mainly forest) to cultivated land is a discrete event and is easy to identify by visual interpretation of Landsat images based in spectral attributes, but also on the size and configuration of elements in the landscape.

In this work, we considered crops (e.g. maize, soybean) and implanted pastures as cultivated land. In the Dry Chaco, cultivated land replaced natural vegetation, including mostly dry forests, small portions of natural grasslands and some sectors previously affected by fires (this situation was more common in the early stages and towards the south east of the study area). For simplicity and considering that only exceptionally cultivated land replaces natural grasslands, we assume that cultivated land expansion is equivalent to deforestation in logistic regression analysis.

For the spatial patterns analysis, vector maps of cultivated land for different years were converted to raster format with a spatial resolution of 0.1 min (a 880 m pixel in our study area). Built up areas (i.e. towns) were not discriminated in these maps and were assigned to one of the two classes according to the dominance of the surrounding area. Water bodies were masked and excluded from the analysis. The resulting maps (Fig. 2a) were binary maps of cultivate lands (value 1) and natural vegetation (value 0), and they were used as dependent variables.

2.2.2. *Rainfall*

This variable was used as continuous data and derived from annual average rainfall layer in WORLDCLIM dataset (Hijmans et al., 2005) (Fig. 2b). Although there are alternative and more specific sources of information for the study area (e.g Minetti, 1999), their geographical coverage is limited. We therefore prioritized information consistency by using only one information source for the whole study area, and we chose a dataset that has been used in others studies in order to facilitate integration with these studies (e.g. Torres et al., 2014).

2.2.3. *Soil suitability for agriculture*

This variable was treated as binary data. The information source was the National Soil Atlas (Aeroterra et al., 1995), which includes the main limitations for agriculture use. We categorized cartography units with primary limitations related with salinity, sodic soils or acidity as unsuitable for agriculture (value = 0). Other conditions and situations were defined as suitable for cultivated land expansion (value = 1) (Fig. 2c). Similar criteria using global datasets were applied to estimate agriculture land reserve in the Chaco region (Lambin et al., 2013).

2.2.4. *Slope*

Slope was calculated and expressed in percent (%), based in the SRTM digital elevation model (Jarvis et al., 2008), using standard procedures in geographic information systems Areas with slope above 10% usually exhibit limitations for machinery operation and were labeled as unsuitable for cultivated land (value = 0), while all other sectors were labeled as suitable for cultivated land (value = 1) (Fig. 2d).

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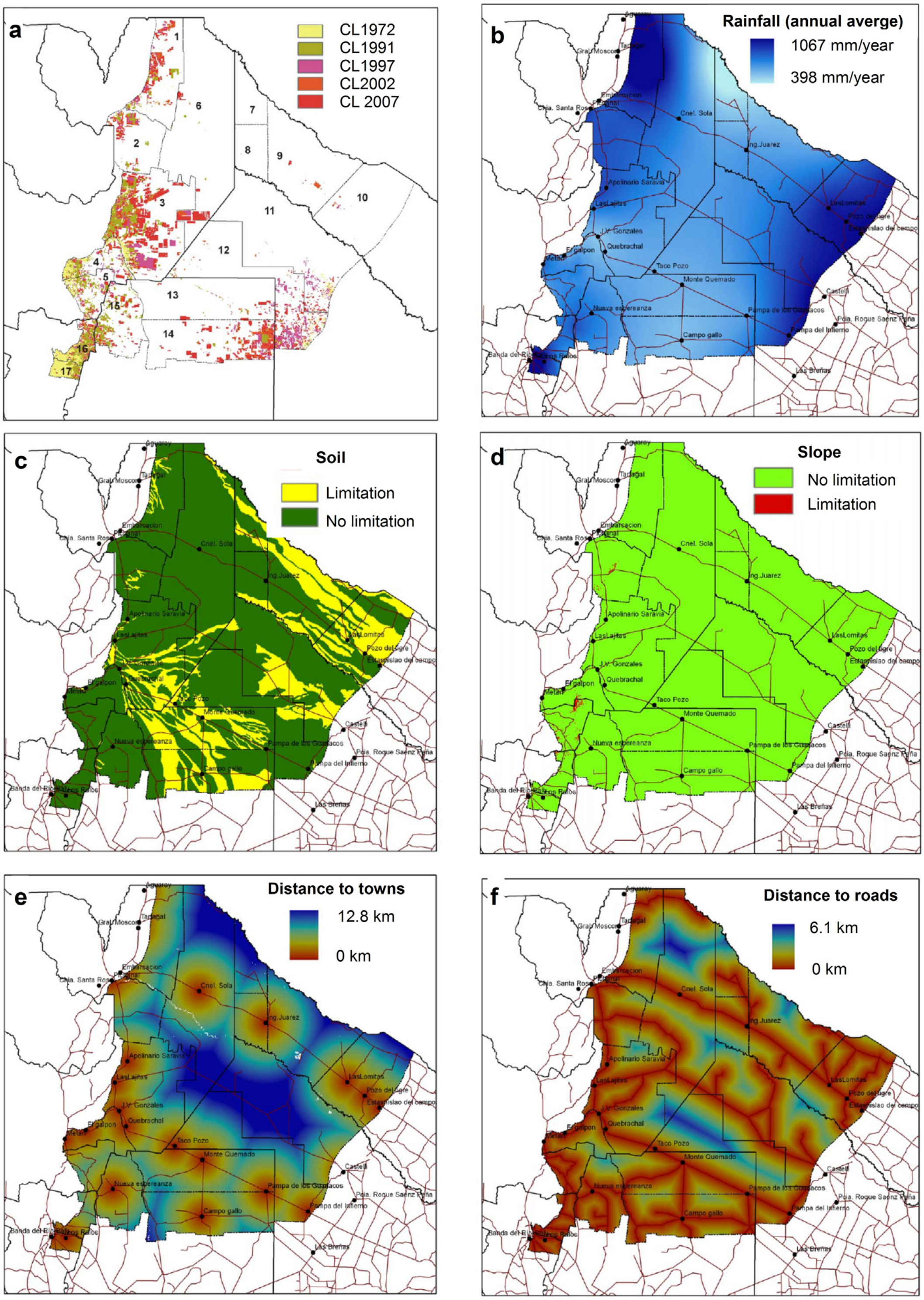

Fig. 2. Raster maps used to fit logistic regression models. a) cultivated land expansion; b) rainfall; c) soil agriculture limitation; d) slope limitation; e) distance to towns; f) distance to roads.

2.2.5. Distance to main towns

This variable was treated as continuous. We included all urban localities with more than 2000 inhabitants following the criteria and data of the National Population Census of 1991. We assumed that these towns remained as the most important urban centers throughout the study period. The majority of the towns considered are the administrative centers for the corresponding department (minimum policy units). We also included towns with influence over the study area that were located outside the limits (Fig. 1). The towns included were: Banda del río Salí and Los Ralos (Tucumán); J.V. Gonzalez, El Quebrachal, Las Lajitas, El Galpón, Apolinario Saravia, Embarcación, Pichanal, Colonia Santa Rosa, Tartagal, Salvador Maza, Gral. Mosconi, Aguaray, Coronel Sola (Salta); Estanislao del Campo, Ing. Juárez, Las Lomitas and Pozo del Tigre (Formosa);

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Castelli, Pampa del Infierno, Presidencia Roque Sáenz Peña, Las Breñas y Taco Pozo (Chaco); Pampa de los Guanacos, Nueva Esperanza, Campo Gallo y Monte Quemado (Santiago del Estero). Towns were represented as points in a vector format cover, digitalized on screen over the Landsat images used to mapping the cultivated land. Finally, a raster map of linear distance to main towns was prepared with standard geographic information system methods (Fig. 2e).

2.2.6. Distance to main roads

this variable was treated as continuous. Firstly, all national and provincial roads were identified in vial maps of *Automovil Club Argentino* (Fig. 2f). These roads were digitalized on screen over the Landsat images used to map cultivated land in order to preserve spatial consistence. Both national and provincial roads were selected because we assumed that their location is independent and unaffected by cultivated land distribution, a reasonable assumption since most roads in the area predated agriculture expansion. In consequence, we considered that national and provincial roads can be selected as independent variables (in contrast with secondary roads, see discussion). Since we analyzed a multidecadal situation, we decided not to discriminate between paved and unpaved roads because there is no available information about this condition for the 1972–2007 period. The vector national and provincial roads cover was converted into a raster lineal distance to roads map with a standard geographic information system method.

All maps used for the logistic regression in IDRISI software are presented in Fig. 2.

2.3. Analysis

We used logistic regression methods (Quinn and Keough, 2003) to explore regional patterns of cultivated land in NADC. We used the occurrence of cultivated land at different years as the dependent variable. In logistic regression, the probability of occurrence of an event follows a logistic curve. The limits of the function (values 0 and 1) can be removed by a *logit* transformation, and the binary variable is converted to a continuum variable with values between 0 and 1 that represent the probability of occurrence of the event. In our case, these values can be interpreted as the probability for one pixel to belong to the class "cultivated land". We suggest interpreting this value as an indicator of the potential of each pixel to be cultivated land, under the criteria applied for the region in the last decades. Under this logic, pixels with values next to 1 represent sites with similar conditions to those in pixels that have been converted to cultivated land in the past, under current conditions and criteria.

We fitted a multiple logistic regression (using all the variables in one function) for each date (1972, 1991; 1997; 2002 and 2007) to evaluate the influence of the selected variables over regional patterns of cultivated land at different times. Additionally, and as a measure of the importance of variables we also fitted simple logistic regressions (i.e. using only one independent variable) for each independent variable at each date. We excluded terrain slope from the single variable analysis the slope since, in the study area, only small portions exhibit slope limitations and accounting for slope as a single variable in the models generated an over-fit and did not provide any valuable information. However, slope information was included in the multiple logistic regression. We fitted twenty four simple logistic regressions (four variables and six dates) and six multiple regressions (six dates). Simple logistic regression models for assessing single variables importance were fitted using all the pixels. Multiple logistic regression models using all variables were fitted using a 10% stratified sampling to reduce spatial autocorrelation. All the logistic regression models were fitted using the IDRISI software (Eastman, 2006).

Logistic regression models were evaluated by the Relative Operating Characteristic (ROC) and Pseudo R^2. ROC can achieve values between 0 and 1; values above 0.5 indicate that the model is better than the random model (Pontious and Schneider, 2001) and values above 0.8 considered outstanding results (Lesschen et al., 2005). Pseudo R^2 is the logistic regression coefficient of determination and can be interpreted as the proportion of the variation in the dependent variables explained by the independent variables. In the case of logistic regression values of Pseudo R^2 above 0.2 can be considered a good model fit (Eastman, 2006).

Additionally, and in order to have a comparative measure of the importance of the different variables, we calculated the standardized parameters of the multiple regression of the year 2007. These are expressed in standard deviations units and were calculated using the formula proposed by Lesschen et al. (2005):

$$a)\ \ b^{*}yx = (byx)(Sx)(R)/S\ \mathrm{logit}(Y)$$

where b^{*}yx is the standardized parameter; *b*yx is the non standardized parameter; *S*x is the standard deviation of the x variable; R is the square root of the determination coefficient and *S* logit (Y) is the standard deviation of the y variable.

Finally, the function adjusted with 2007 cultivated land as the dependent variable was used to predict the probability of each pixel to belong to cultivated land map. This map can be interpreted as an index of the combination of conditions, in each pixel, that determine its potential to be converted to cultivated land under the criteria applied in the last decades.

3. Results

Cultivated land expansion from 1972 to 2007 was estimated at 1.94 million hectares, mainly over dry forests (i.e deforestation). Magnitude and temporal dynamics of this process are discussed in Gasparri et al. (2013). Cultivated land expansion map (Fig. 2a) shows a general pattern where expansion until 2002 occurred in the west border of the area oriented in the South-North direction and in the southeast border of the study area in the province of Chaco.

Simple logistic regressions (Table 1) show that *rainfall* and *distance to main roads* are the variables with least capacity of predicting localization of cultivated land in NADC. *Soil suitability for agriculture* shows intermediate values and *Distance to main towns* shows the highest values of model fitting (ROC and Pseudo R2) (see Supplementary material SII for fitted model details).

A multiple regression using 2007 cultivated land showed moderated fitting statistics but the Chi square test indicated that the model is statistically significant (SII). The resulting function was:

$$\begin{aligned} \mathrm{logit}\ (\mathrm{CL2007}) = & -3.0558 - 0.000044{*}\mathrm{Dtown.} \\ & - 0.000157{*}\mathrm{Droads} + 0.001569{*}\mathrm{rainfall} \\ & + 1.444770{*}\mathrm{slope} + 0.480221{*}\mathrm{soil\ suitability} \end{aligned}$$

where CL2007 is 2007 cultivated land; Dtown is *Distance to main towns*; Droad is *distance to main roads*.

The standardized parameters (SP) of the function showed that distance to main towns is the most important variable (SP = −1.307); followed by soil suitability for agriculture (SP = 0.225), distance to main roads (SP = −0.21), rainfall (SP = 0.178), and slope (SP = 0.073). Model parameters signs (positive vs. negative) were in agreement with the expected relations. Cultivated land expansion in NADC from 1972 to 2007 prioritized (in order of relevance) sites near towns without soil limitation, occurring near main roads and with higher

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Table 1
Fitting statistics for logistic regression.

Independent variable	Statistic	Dependent variable				
		CL1972	CL1991	CL1997	CL2002	CL2007
Rainfall	ROC	0.702	0.618	0.606	0.608	0.577
	pseudoR^2	0.0586	0.0151	0.0128	0.014	0.008
Distance to road	ROC	0.827	0.759	0.730	0.723	0.678
	pseudoR^2	0.0002	0.0002	0.0002	0.0002	0.0001
Distance to town	ROC	0.891	0.832	0.809	0.798	0.757
	pseudoR^2	0.2410	0.1879	0.1671	0.1589	0.1212
Soil	ROC	0.745	0.747	0.736	0.732	0.724
	pseudoR^2	0.0934	0.1153	0.1103	0.1100	0.1101
All the variables (multiple regression)	ROC	0.913	0.851	0.824	0.812	0.773
	pseudoR^2	0.3134	0.2256	0.1909	0.1804	0.1376

CL (cultivated land); ROC (Relative Operating Characteristic).

rainfall and no slope limitations. The map of probability prepared with the function adjusted with 2007 cultivated land as the dependent variable (Fig. 3) shows that high probability values present a clear concentric pattern in areas near towns. In particular, there are large areas with high probability to be converted to cultivated land in Formosa province associated with towns in the RN81. Other areas with high conversion probability correspond to remnants of natural vegetation in sectors with deforestation in the last decades on the western border of the study area in Salta and Tucumán.

4. Discussion

Logistic regression outputs indicate a good fit (ROC above 0.7 and Pseudo R^2 near 0.2) and were statistically significant (*Chi square* test in SII). These results clearly indicate that predictive variables have influenced past and current distribution of cultivated lands in NADC. The capacity of the environmental conditions and accessibility to explain geographical patterns of cultivated lands decreased in the last decades (from ROC in 1972 = 0.91; to ROC in 2007 = 0.77). Standardized parameters indicate that distance to main towns is the most important variable in explaining geographical patterns of cultivated lands, in agreement with economic models of bid-rent (Walker, 2004) or the more classic von Thünen (1966). However, we propose that the progressive concentration of cultivated lands near towns, is the spatial manifestation of soybean and cattle ranching agglomeration economy (described by Garret et al., 2013) in NADC. Most of the production in cultivated lands within the area (i.e soybean and beef) is oriented to exports or non-local markets. In consequence, towns are not the site of consumption of these products. The influence and relevance of distance to cities and towns for mechanized agriculture has also been observed in Bolivia (Kaimowitz et al., 2002; Muller et al., 2011, 2012) and Kenya (Serneels et al., 2001).

We suggest instead that towns are the places where positive externalities are obtained through agglomeration of activities and infrastructure development, such as grain storage, producers networking, transportation pools, machinery rent companies, etc. An example of positive externalities in the Chaco region is the water management project coordinated by agriculture producers in the Anta region (Murgida et al., 2014). In addition, a regional-coverage study conducted in Chaco region for the 90s, shows congruent patterns where agribusiness expansion promotes urban population growth and in some cases urban employment (Sacchi et al., 2013; Sacchi and Gasparri, unpublished data). This relation between agribusinesses expansion and urban population growth could be a manifestation of positive feedbacks associated with the development of supply markets, companies, and also labor demand to put new land into production, promoting immigration and population growth in towns. The interactions between agribusinesses expansion, deforestation and other socioeconomic factors in towns are complex and require future work, with particular attention to evaluating the impact of the cultivated land expansion on the economy and living conditions of the urban population.

One previous study in the Argentine Chaco region exploring geographical patterns of cultivated land expansion at the scale of political units (departments) indicated that road density and proximity to main ports (i.e Rosario) drove soybean expansion (Krapovickas, 2009). In this study we explored relations at a more local scale and the results indicate that distance to roads have moderate effects over spatial patterns of cultivated lands at this scale. National and provincial roads can be considered independent of the agricultural sector (exogenous variable) in terms of their planning. However, it is common that agribusiness actors build secondary road networks and integrate them to national and provincial roads. Under this situation, the agricultural sector progressively avoids accessibility limitations imposed by the main road network. We suggest that this situation is reflected in the decreasing statistics of the logistic regression fitting using distance to roads as independent variable (Table 1).

Biophysical variables, on the other hand, showed a moderate effect over geographical patterns of cultivated lands. The time dynamics of biophysical variables importance (evaluated with logistic regressions fitting at different years) suggest two situations: on the one hand, soil limitations showed stable statistics parameters in logistic regressions fitting at different dates (Table 1), suggesting that soil limitation remained as a restriction for cultivated land expansion for the whole study period. On the other hand, rainfall showed decreasing statistics in the logistic regression fitting (Table 1) suggesting that the rainfall between 1972 and 2007 acted as a limitation for cultivated land expansion but with decreasing relevance to define localization.

We propose that decreasing statistics in logistic regression fitting (Table 1) are the result of positive feedbacks associated with agriculture expansion. These positive feedbacks make the agricultural sector progressively gain independence from the initial constrains to expansion. It is likely that agricultural expansion in the area generates more experimentation in agronomic practices, seed selection and varietal development for local conditions, as described by Garret el al. (2013). In addition, agricultural expansion promotes the development of secondary roads networks and the consolidation and expansion of agriculture services and inputs provision from towns, a situation also described by Muller et al. (2011, 2012) in Bolivia. Another aspect is related with production unit size. We suggest that large farms with high capital availability have major capacity of facing production activity in more remote sectors from towns and roads. Large production units have the capacity of including larger infrastructure in farms (e.g fertilizer

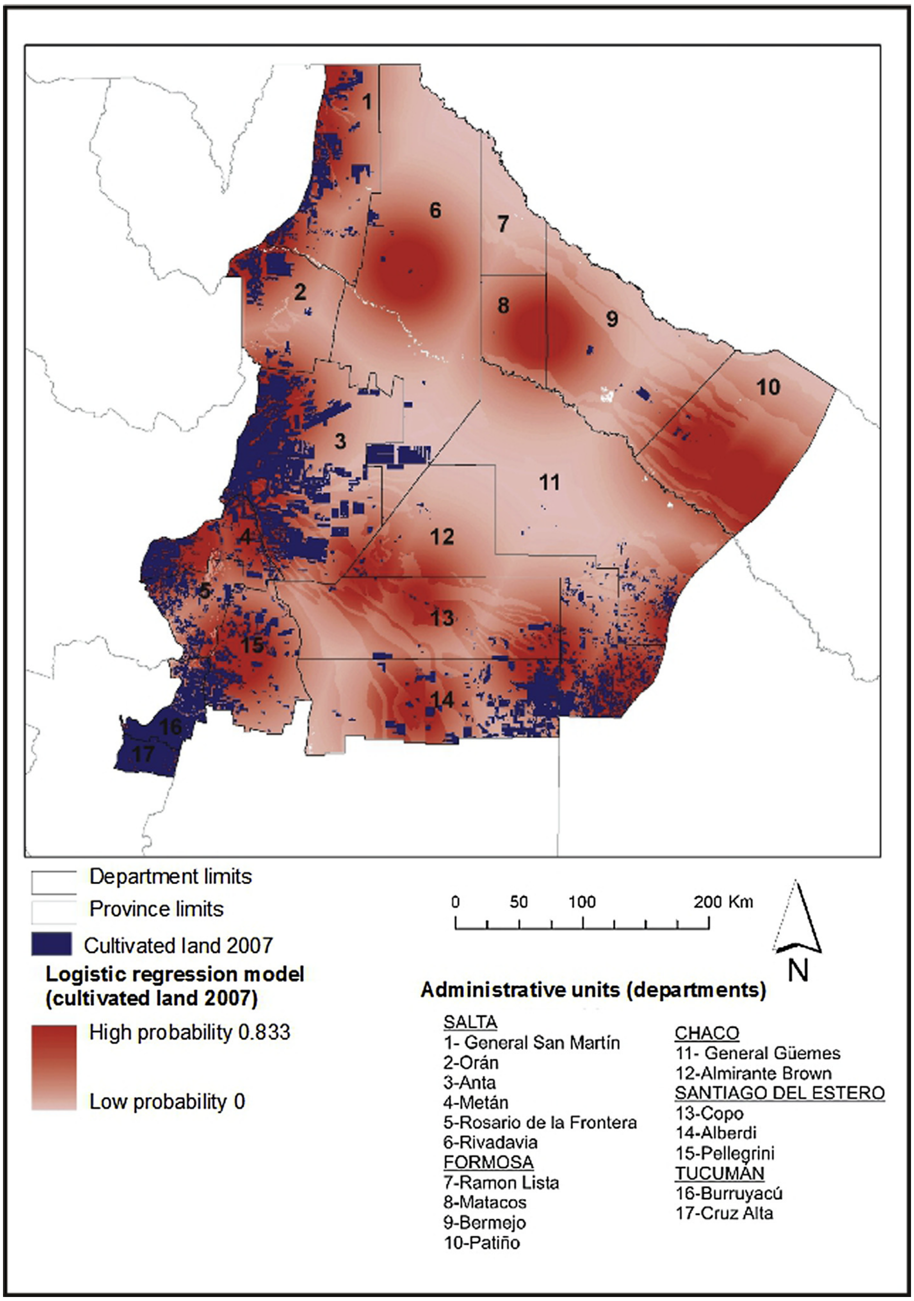

Fig. 3. Output map of the multiple logistic regression model with the cultivated land in 2007 as dependent variable. Numbers indicate departments (see Fig. 1).

storage) and have more capacity of capturing agriculture services. In the logistic regression model, large farms represent large tracks of cultivated land in suboptimal conditions (but not suboptimal under the capacity of the actor), and could be partially responsible for the decreasing of the logistic regression fitting. With time, these positive feedbacks promote a declining explanatory power of rainfall and distance to towns and roads.

There are others additional aspects worth taking into consideration to explain the decreasing statistics of logistic regressions over time, one of them being deforestation for implanted African drought-resistant pastures during the last years of the study. These pastures can be cultivated under drier conditions than crops and are less affected by rainfall limitations. Additionally, cattle activity is less intensive than agriculture with comparative fewer inputs requirements, therefore, being less affected by proximity to towns and logistic centers. In our opinion, future work oriented towards understanding of the spatial patterns and discriminating pastures and cropland and production units size, could be valuable to better understand the proximate causes of land conversion and the decision rules followed by different actors in NADC. In addition, we suggest that it is necessary to explore if there is a development of an agglomeration economy, and what its dynamic in time are.

The models based in logistic regression in this study do not aim at a precise prediction of future cultivated land expansion (either at pixel or farm level). The map of Fig. 3 represents the probability for one pixel of being converted to cultivated land applying the criteria of past transformation and this is not equivalent to agriculture suitability. Instead we used these models to explore relationships between regional patterns of cultivated lands and environmental and accessibility factors. We suggest that this map could be used as an guide to identifying future areas of cultivated land expansion. However, it is important to notice that if there are drastic changes in technology condition, actors' logic or market conditions, the map might not accurately predict future changes. The output map of the 2007 multiple logistic regression (Fig. 3) suggests that sectors near towns along the RN16 and RN81 (e.g Taco Pozo, Las Lomitas, Ing. Juarez) could be centers of new cultivated land expansion. At the same time, a progressive elimination of remnant fragments of natural vegetation (corresponding mainly to dry forests) in old production frontiers within the borders of the study area is clearly expected, especially in the west border along RN34 and the southeast border in the Chaco province. Cultivated land expansion from 2007 to 2011 (Gasparri et al., 2013) is overall in agreement with the expected patterns based in the multiple logistic regression models (Fig. 3).

5. Conclusions

Cultivated land expansion in NADC has been a very dynamic process in the last decades, which has been well documented in different sectors both in terms of magnitude and causes (e.g Grau et al., 2005; Zack et al., 2008; Gasparri et al., 2013). However, the spatial patterns of this process have received less attention. As a consequence, there is limited knowledge in relation to which factors constrain or promote cultivated land expansion in the Dry Chaco. In this work, we present a simple but informative analysis that contributes to advance in that direction.

We conclude that the main limitations of cultivated land expansion are more related to accessibility and logistic aspects than to environmental factors. Our results suggest that rainfall is relevant (Hoyos et al., 2013; Murgida et al., 2014), yet is not the main limitation for cultivated land expansion in NADC. Factors such as distance to towns show that logistics aspects might be more relevant. We believe that the strong influence of distance to towns in the cultivated land expansion could reflect the development of agglomeration economies in local towns and cities. The expansion of cultivated lands progressively gained independence from initial restrictions in the early 1970s, such as rainfall or distance to towns. We suggest the existence of a positive feedback related to agronomic technology and to the development of agglomeration economies in towns. In this sense, more cultivated land in the region implies more investment in agronomic technology and innovation for local use, and more services offer for the agribusiness production. Under this positive feedback, a progressive acceleration of cultivated land expansion could be expected.

The output map derived from the multiple logistic regression is an indicator of future sectors that might be more vulnerable to land conversion, rather than a precise predictive model of future land conversion occurrence. This map indicates that towns located along the east–west axis associated with RN16 and RN 81 could be the centers of new cultivated land expansion, in contrast with previous decades expansion in south–north axis, especially associated with RN9 and RN34 roads. If this scenario is realistic, as recent information suggests (Gasparri et al. 2013), the spatial continuity of large sectors of dry forest towards the South-North direction in NADC could be affected, with unknown consequences in terms of regional conservation, that need to be evaluated.

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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.2015.05.005.

References

Aide, T.M., Matthew, L., Clark, M.L., Grau, H.R., López-Carr, D., Levy, M.A., Redo, D., Bonilla-Moheno, M., Riner, G., Andrade-Núñez, M.J., Muñiz, M., 2013. Deforestation and reforestation of Latin America and the Caribbean (2001–2010). Biotropica 45, 262–271.
Aeroterra, INTA, ArgenINTA, 1995. Atlas de Suelos de la República Argentina. CDROM, Buenos Aires, ISBN 987-95542-0-5.
Boletta, P.E., Ravelo, A.C., Planchuelo, A.M., Grilli, M., 2006. Assessing deforestation in the argentine chaco. For. Ecol. Manag. 228, 108–114.
Caldas, M.M., Goodin, D., Sherwood, S., Campos Krauer, J.M., Wisely, S.M., 2013. Land-cover change in the Paraguayan Chaco: 2000–2011. J. Land Use Sci. 10, 1–18.
Chomitz, K.M., Gray, D.A., 1996. Roads, land use and deforestation: a spatial model applied to Belize. World Bank Econ. Rev. 10, 487–512.
Clark, M.L., Aide, T.M., Grau, H.R., Riner, G., 2010. A scalable approach to mapping annual land cover at 250 m using MODIS time series data: a case study in the Dry Chaco ecoregion of South America. Remote Sens. Environ. 114, 2816–2832.
Eastman, J.R., 2006. IDRISI Andes: Guide to GIS and Image Processing. Clark Lab.
Fujita, M., Thisse, J.F., 2013. Economics of Agglomeration: Cities, Industrial Location, and Globalization. Cambridge University Press, Cambridge.
Garret, R., Lambin, E.F., Naylor, R.L., 2013. The new economic geography of land use change: supply chain configurations and land use in the Brazilian Amazon. Land Use Policy 34, 265–275.
Gasparri, N.I., Le Polain de Waroux, Y., 2014. The coupling of South American soybean and cattle production frontiers: new challenges for conservation policy and land change science. Conserv. Lett. http://dx.doi.org/10.1111/conl.12121.
Gasparri, N.I., Grau, H.R., Gutiérrez Angonese, J., 2013. Linkages between soybean and neotropical deforestation: coupling and transient decoupling dynamics in a multi-decadal analysis. Glob. Environ. Change 23, 1605–1614.
Gasparri, N.I., Grau, H.R., 2009. Deforestation and fragmentation of Chaco dry forest in NW Argentina (1972–2007). For. Ecol. Manag. 258, 913–921.
Gentry, A., 1995. Diversity and floristic composition of Neotropical dry forests. In: Bullock, S.H., Mooney, H.A., Medina, E. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, Cambridge.
Graesser, J., Aide, T.M., Grau, H.R., Ramankutty, N., 2015. Cropland/pastureland dynamics and the slowdown of deforestation in Latin America. Environ. Res. Lett. 10, 034017.
Grau, H.R., Gasparri, N.I., Aide, T.M., 2005. Agriculture expansion and deforestation in seasonally dry forests of north-west Argentina. Environ. Conserv. 32, 140–148.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.
Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Clim. 25, 1965–1978.
Hoekstra, J.M., Molnar, J.L., Jennings, M., Revenga, C., Spalding, M.D., Boucher, T.M., Robertson, J.C., Heibel, T.J., Ellison, K., 2010. The Atlas of Global Conservation: Changes, Challenges and Opportunities to Make a Difference. University of California Press.
Hoyos, L.E., Cingolani, A.M., Zak, M.R., Vaieretti, M.V., Gorla, D.E., Cabido, M.R., 2013. Deforestation and precipitation patterns in the arid Chaco forests of central Argentina. Appl. Veg. Sci. 16, 260–271.
Huang, C., Kim, S., Song, K., Townshend, J.R.G., Davis, P., Altstatt, A., Rodas, O., Yanosky, A., Clay, R., Tucker, C.J., 2009. Assessment of Paraguay's forest cover change using Landsat observations. Glob. Planet. Change 67, 1–12.
Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled Seamless SRTM Data V4. International Center for Tropical Agriculture (CIAT). http://srtm.csi.cgiar.org.
Jasinski, E., Morton, D., De Fries, R., Shimabukuro, Y., Anderson, L., Hansen, M., 2005. Physiscal Landscape Correlates of the Expansion of Mechanized Agriculture in Mato Grosso, Brazil. Earth Interactions 9.016. http://EarthInteractions.org.
Kaimowitz, D., Mendez, P., Puntodewo, A., Vanclay, J., 2002. Spatial regression analysis of deforestation in Santa Cruz, Bolivia. In: Wood, C.H., Porro, R. (Eds.), Land Use and Deforestation in Amazon. University Press of Florida.
Kaimowitz, D., Angelsen, A., 1998. Economic Models of Tropical Deforestation: a Review. Bogor. Center for International Forestry Research, Indonesia. http://www.cifor.cgiar.org/publications/pdf_files/Books/model.pdf.
Krapovicas, J., 2009. Cambio socio-ambiental en el Chaco Argentino y su relación con la expansión de soja en la década de 1990. Tesis de magistratura en estudios territoriales y de la población. Universidad Autónoma de Barcelona.
Lambin, E.F., Gibbs, H.K., Ferreira, L., Grau, H.R., Mayaux, P., MeyFroidt, P., Morton, D.C., Rudel, T.K., Gasparri, N.I., Munger, J., 2013. Estimating the world's

potentially available cropland using a bottom-up approach. Glob. Environ. Change 23, 892–901.
Lesschen, J.P., Verburg, P.H., Staal, S.J., 2005. Statistical Methods for Analysisng the Spatial Dimension of Change in Land Use and Farming Systems. LUCC report series Nº 7. International livestock research institute, Naerobi, Kenia and LUCC focus 3 office. Wageningen University, The Neteherlands.
Minetti, J.L., 1999. Atlas climático del Noroeste Argentino. Laboratorio Climatológico sudamericano. Fundación Zon Caldenius, Tucumán.
Muller, R., Muller, D., Schierhorn, F., Gerold, G., 2011. Spatiotemporal modeling of the expansion of mechanized agriculture in the Bolivian lowland forests. Applayed Geogr. 31, 631–640.
Muller, R., Muller, D., Schierhorn, F., Gerold, G., Pacheco, P., 2012. Proximate causes of deforestation in the Bolivian lowlands:an analysis of spatial dynamics. Reg. Environ. Chang. 12, 445–459.
Murgida, A.M., González, M.H., Tiessen, H., 2014. Rainfall trends, land use change and adaptation in the Chaco salteño region of Argentina. Reg. Environ. Chang. 14, 1387–1394.
Nelson, G.C., Hellerstein, D., 1997. Do roads cause deforestation? Using satellite images in econometric analysis of land use. Am. J. Agric. Econ. 79, 80–88.
Nelson, G.S., Geoghegan, J., 2002. Deforestation and land use change: sparse data environment. Agric. Econ. 27, 201–216.
Pontius Jr., R.G., Schneider, L.C., 2001. Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. Agric. Ecosyst. Environ. 85, 239–248.
Portillo-Quintero, C.A., Sanchez-Azofeifa, G.A., 2010. Extent and conservation of tropical dry forests in the. Am. Biol. Cons. 143, 144–155.
Quinn, G.P., Keough, M.J., 2003. Experimental Design and Data Analysis for Biologists. Cambridge University Press.
Rudel, T.K., DeFries, R.S., Asner, G.P., Laurance, W.F., 2009. Changing drivers of deforestation and new opportunities for conservation. Conserv. Biol. 23, 1396–1405.
Sacchi, L., Gasparri, N.I., Paolasso, P., 2013. La deforestación y su relación con las dinámicas demográfica urbanas en la región chaqueña durante los 90. In: IV congreso nacional de geografía de universidades públicas y XI jornadas cuyanas de Geografía. Mendoza 10/2013.
Serneels, S., Lambin, E.F., 2001. Proximates causes of land use change in Narok district, Kenya: a spatial statistical model. Agric. Ecosyst. Environ 85, 65–81.
Seto, K.C., Reenberg, A., Boone, C.G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D.K., Olah, B., Simon, D., 2012. Urban land teleconnections and sustainability. Proc. Natl. Acad. Sci. U. S. A. 109, 7687–7692.
Torres, R., Gasparri, N.I., Blendinger, P., Grau, H.R., 2014. Land-use and land-cover effects on regional biodiversity distribution in a subtropical dry forest: a hierarchical integrative multi-taxa study. Reg. Environ. Chang. 14, 1549–1561.
UMSEF (Unidad de manejo del Sistema de Evaluación Forestal), 2013. Monitoreo de la superficie de bosque nativo de Argentina. www.ambiente.gov.ar/?idarticulo=311.
von Thünen, J.H., 1966. Der isolierter staat in beziehung der landwirtschaft und nationalökonomie. In: Hall, P. (Ed.), Von Tünen Isolated State. Pergamon press, Oxford.UK.
Walker, R., 2004. Theorizing land-cover and land-use: the case of tropical deforestation. Int. Reg. Sci. Rev. 27, 247–270.
Zack, M.R., Cabido, M., Hodgson, J.G., 2004. Do subtropical seasonal forests in the Gran Chaco, Argentina, have a future? Biol. Conserv. 120, 589–598.
Zack, M.R., Cabido, M., Cáceres, D., Díaz, S., 2008. What drives accelerated land cover change in central Argentina? Synergetic consecuences of climate, socioeconomic, and technological factors. Environ. Manag. http://dx.doi.org/10.1007/s00267-008-9101-y.