Land Use Policy 55 (2016) 154–165

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Agricultural expansion in the Semiarid Chaco: Poorly selective contagious advance

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form 26 February 2016
Accepted 14 March 2016
Available online 8 April 2016

Keywords:
Deforestation
Land use change
Models
Dry Chaco
Remote sensing

ABSTRACT

Clearance for agriculture or cattle ranching was the dominant land-cover change during the last two decades in the South American Dry Chaco. The Argentinean portion has been particularly affected, presenting greater deforestation rates than the continental and global averages. Little is known on the control factors of the location and the spatial clearance patterns. In this article we studied (a) deforestation dynamics in the Argentinean Dry Chaco and the factors determining land clearing locations for the last 25 years; (b) changes in the relative impact of those factors through time and space; and (c) the effect of regulations aimed to control the location and magnitude of land transformation. We also tested the “expansion of the agricultural frontier” hypothesis for the Argentinean Chaco. To identify the factors that defined agricultural expansion we used binomial logistic models that were fitted to a set of independent variables (bio-physical, infrastructure and political factors) that could eventually influence the distribution of new agricultural areas. Results indicate that the Forest Law devised by the Argentinean federal government to control the clearing process was insufficient to restrict both the area transformed per year and clearance locations. Agriculture is expanding over marginal areas and land clearing dynamics have been increasingly associated to the proximity to already cleared areas, defining a frontier—advancement pattern which gives the idea of a contagion process. According to our results, the relative importance of the anthropic factors associated to the agricultural expansion in the region increased through time.

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1. Introduction

In South America, dry forests and grasslands clearance for agriculture or cattle ranching is the dominant land-cover change. During the last decade, the Chaco region has become one of the largest of the three global deforestation hotspots, surpassing the Amazon basin (Hansen et al., 2013). The Gran Chaco Argentinean portion showed greater deforestation rates (0,89%) (UMSEF, 2007) than averages at the national, continental and global levels (0.82%, 0.51% and 0.13%, respectively) (FAO, 2011). Consequences include fragmentation of remaining patches (Gasparri and Grau, 2009; Volante et al., 2012; Caldas et al., 2013; Volante and Paruelo, 2015), changes in productivity (Volante et al., 2012), carbon balance (Gasparri et al., 2008) and biodiversity (Piquer-Rodríguez et al., 2015). Deforestation also increased the proportion of primary production dissipated as fire (Verón et al., 2012).

In general, there are five types of controls influencing the dynamics of land-use changes (Geist et al., 2006; Verburg et al., 2006) particularly in the South American deforestation process (Kirby et al., 2006; Müller et al., 2010): (a) biophysical features (i.e., slope, elevation, climate, soil characteristics and drainage conditions), (b) socio-cultural aspects (i.e., demography, lifestyle, diet, legacies and path dependence), (c) economic factors (i.e., market structure, accessibility and existing infrastructure, consumer demands, governmental incentives, subsidies and taxes), (d) political measures (i.e., those related to nature conservation, infrastructure and defense), (e) technological factors (i.e., agricultural machinery, genetic material and organizational issues).

In particular for the Chaco region three underlying issues were considered as the main causes of land-use/land-cover changes observed during the last 30 years: (1) the introduction of Roundup Ready soybean cultivars (RR soybean) in 1997 which allowed the

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http://dx.doi.org/10.1016/j.landusepol.2016.03.025
0264-8377/Published by Elsevier Ltd.

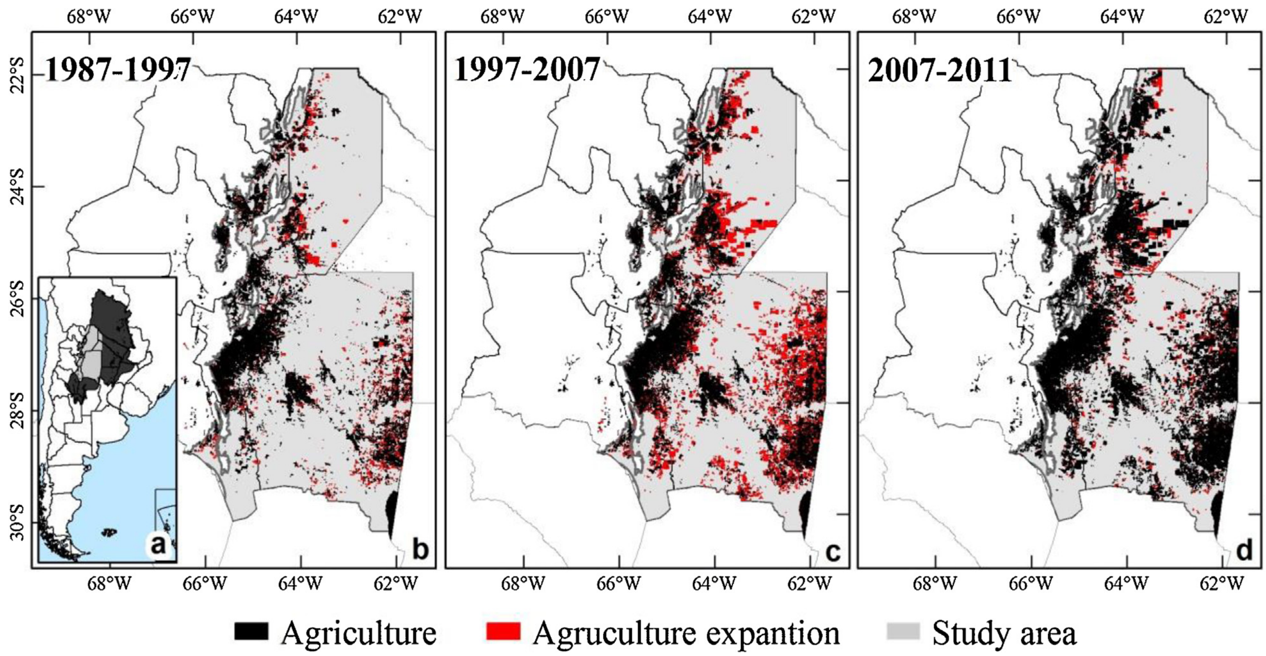

Fig. 1. (a) Study area (light gray), Chaco ecorregion (dark gray); (b), (c) and (d), time periods of agricultural land-use changes between 1987 and 2011 where black is agriculture at the beginning of each period, and red is new agriculture during that period.

expansion of non-tillage systems (Grau et al., 2005b; Gasparri and Grau, 2009), (2) an increase in mean annual precipitation (Zak et al., 2004; Grau et al., 2005a) and (3) economic factors, both at local (changes in currency exchange rates) and global scales (commodities price increases) (Zoomers and Goldfarb, 2013). Concerns regarding to deforestation rates during the first years of the century contributed to the emergence of a fourth control factor in Argentina: (4) the "Native Forest Law" passed in 2007 (Seghezzo et al., 2011; García Collazo et al., 2013). This national law provided a general framework under which each province produced its own forest-protection zone map with three colored categories: areas where forest could be cleared for agriculture (green zones), areas where forest could not be cleared but only managed (yellow zones) and areas dedicated only to conservation purposes, where forest could not be cleared (red zones).

In NW Argentina, interactions between the above mentioned factors define a spatial growth pattern named "agricultural frontier expansion". This term describes the way new agricultural lands are located near or adjacent to already transformed areas (Barsky and Gelman, 2009; Viglizzo et al., 2012; REDAF, 2013). This concept has an embedded hypothesis: there would be a continued growth of the agricultural area that would generate an aggregated pattern of agricultural plots, which gives the idea of a contagion process.

Understanding the processes that underlie the land use/land cover spatial patterns is a requirement for land-use planning. Empirical models on land transformation (Lesschen et al., 2005; Verburg et al., 2006; Rossiter and Loza, 2012) help to identify the processes behind the observed patterns, to rank the importance of driving factors, to define land transformation scenarios and to locate special risk areas (Müller et al., 2010; Diogo et al., 2014).

In this article, we sought to answer the following questions concerning the land transformation dynamics in the Argentinean Dry Chaco: (a) which were the factors that determined the location of land clearance for the last 25 years (b) did these factors vary through time? (c) was the Native Forest Law effective in controlling the location and magnitude of land transformation? We also tested the "agricultural frontier expansion" hypothesis for the Argentinean Chaco, where "contagion" is the main control of new clearings. To answer these questions and to evaluate the hypothesis, we characterized land transformation with remote sensed data and we used binomial logistic models to identify factors that defined agricultural expansion for the past 25 years in NW Argentina.

2. Materials and methods

2.1. Study area

The study region was located between parallels 22 and 30° S and meridians 61° and 66° W and included 28.3×10^6 ha of northern Argentinean provinces (Fig. 1). Most of the area is in the Semi-arid Chaco, a land dominated by Xerophytic Subtropical Forests (Cabrera, 1976; Morello et al., 2012) except for a small NW portion which corresponds to the Yungas ecoregion, covered by Humid Subtropical Forests (Cabrera, 1976; Morello et al., 2012). The area is part of the South American subtropical belt, where mean annual temperature varies from 20 to 22 °C (Appendix B Fig. B1) and annual rainfall at the center of the area is 500 mm, increasing eastward, westward, and southward reaching up to 700–900 mm (Figure B1), providing conditions for rainfed agriculture (Morello et al., 2012). Traditionally, native inhabitants and Criollos (descendants of European immigrants) practiced subsistence economy, including small scale agriculture, extensive ranching, hunt and gathering (Leake and Ecónomo, 2008). However, in recent decades natural vegetation has experienced a rapid and extensive clearing for industrial agriculture and livestock production on sowed pastures (Volante et al., 2006; Gasparri and Grau, 2009).

2.2. Modeling strategy

We used logistic regression models to identify and evaluate the factors associated to land clearing and to generate spatially explicit models of land transformation (Lesschen et al., 2005). In this case, logistic regression is the most suitable regression tool since the dependent variable is binary (clearing presence/absence). The dependent variable was regressed against a set of independent variables, including bio-physical, socio-economic and political fac-

Table 1
Hypothesized independent variables selected *a priori* to analyze agricultural expansion in Argentina NW region during three periods (1987–1997, 1977–2007 and 2007–2011). Variables that remained after applying a set of analyses to avoid multicollinearity and over-especification are highlighted in bold (see Appendix C).

Variable type	Variable name	Meaning	Units
Bio-physical	**Precipitation**	**Mean annual precipitation**	**100 mm**
	Water deficit	Difference between mean annual precipitation and Mean annual potential evapotranspiration	100 mm
	Evapotranspiration	Mean annual potential evapotranspiration	100 mm
	Temperature	**Mean annual temperature**	**°C**
	Topography	**Mean slope**	**%**
		Standard deviation of slope	%
	Molisol Alfisol Entisol	**Percentage of the area of the soil taxon in the unit of analysis**	**10%**
Socio-economic	**Distance to small localities**	**Distance to nearest town of 2 thousand inhabitants)**	**Log (distance in m)**
	Distance to medium localities	**Distance to nearest town of 4 thousand inhabitants)**	**Log (distance in m)**
	Distance to large localities	**Distance to nearest town of 8 thousand inhabitants)**	**Log (distance in m)**
	Distance to local markets	**Distance to the cities of 50 thousand inhabitants**	**Log (distance in m)**
	Paved roads	**Distance to nearest paved roads**	**Log (distance in m)**
	Roads (paved and unpaved)	**Distance to nearest paved and unpaved roads**	**Log (distance in m)**
Landscape	**Distance to prior deforestation**	**Distance to edge of agricultural enterprises at the beginning of each period.**	**Log (distance in m)**
	Density clearings at close range	**Area occupied by agriculture in a circle of radius of 2 km**	**%**
	Density clearings medium distance	**Area occupied by agriculture in a circle of radius of 5 km**	**%**
	Density clearings long range	**Area occupied by agriculture in a circle of radius of 10 km**	**%**
Political	**Administrative limits**	**Provincial administrative limits**	**Nominal categorical variable**
	Native Forest Law	**Conservation categories defined in Act 26,331 (The Native Forest Law)**	**Nominal categorical variable**

tors. The resulting regression coefficients indicate the direction and strength of each independent variable's influence on forest conversion and allowed us to rank the importance of each one (Lesschen et al., 2005; Müller et al., 2012). The critical steps in the application of our approach are: (1) the selection of a set of variables that represent well defined hypothesis of agriculture expansion in the NW Chaco region; (2) the use of a statistical approach that allows to test the regression assumptions in the hypothesized variables (Lesschen et al., 2005); (3) the mitigation of spatial autocorrelation in the construction of the dependent variable samples; and (4) if existing, the quantification of the relationship between deforestation and its potential controls and the prediction of spatial growth patterns.

2.3. Dependent variable

We used a spatially explicit database of agricultural fields cleared in three periods (a) 1987–1997 (before the introduction of RR soybean and non-tillage systems), (b) 1997–2007 (since the introduction of RR soybean up to the Native Forest Law implementation; (c) 2007–2011 (after the "Native Forest Law" implementation). The database was built using Landsat TM images obtained from CONAE (Argentinean National Commission on Space Activities), USGS (United States Geological Service) and INPE (Instituto Nacional de Pesquisas Espaciais do Brasil) for 1987, 1997, 2007 and 2011 (Appendix A, Table A1). Agricultural fields were detected by visual interpretation of Landsat mosaics (RGB band combination 4-5-3), scale: 1:75000.

Detailed maps of agricultural areas (30 m spatial resolution) (Fig. 1) were aggregated into 1 km^2 pixels. This cell size allowed us to capture changes at a landscape level. One km^2 cell maps were obtained by overlapping detailed resolution maps with a regular 1 km-side grid cell (Mitchell, 2005). The study region included a total of 283,514 cells. For each 1 km^2 cell we calculated the agricultural area (cleared area) in percentages. Afterwards, three categories were defined: cleared area >90% (category 1); cleared area <90% and >10%; and cleared area <10% (category 0). In order to study highly contrasting situations, the first and third categories (1 and 0) were only considered.

To monitor global deforestation (FAO, 2009) of land transformed into croplands every year, we estimated the annual rate of change "q" in the study area, according to the Food and Agriculture Organization (FAO, 1995):

$$q = [(A_2/A_1)^{1/(t2-t1)} - 1] * 100$$

Where "q" is the Annual Rate of Change in percentage of the study area; and A_1 and A_2 represent the areas of natural habitats at date t1 and t2, respectively.

2.4. Independent variables

The independent variables are hypothesized factors acting as driving forces of deforestation (Table 1). They were selected *a priori* based on previous modeling deforestation works undertaken worldwide (Geist and Lambin, 2002; Lambin et al., 2003; Walker, 2004; Lambin and Meyfroidt, 2010; Baumann et al., 2011), in Latin America (Kirby et al., 2006; Grau and Aide, 2008; Zak et al., 2008; Müller et al., 2012) and also based on the authorsí experience on the field (Volante et al., 2006; Laterra et al., 2011; Seghezzo et al., 2011).

2.4.1. Bio-physical factors

2.4.1.1. Climate. Rainfall and temperature are determining factors for farming; therefore they are important location controls for agricultural enterprises. Four climate variables were included in the analysis: mean annual temperature, mean annual rainfall, mean annual potential evapotranspiration and water deficit (Appendix B, Fig. B1). Data were obtained from 44 weather stations distributed in the study area (Bianchi and Yáñez, 1992; Bianchi et al., 1994, 2002). Because no significant changes were found between the studied periods nor in rainfall or temperature, we decided to work with long-term average climate map sets (1934–1990) which captured the spatial climate variations of the region (Bianchi and Yáñez, 1992; Bianchi et al., 1994, 2002).

2.4.1.2. Topography. High slopes and rough terrain are limiting factors for agricultural production. Maps of slope mean and standard deviation within the 1 km^2 cell were derived from the Digital Elevation Models from the Shuttle Radar Topography Mission (SRTM) as a measure of terrain roughness (Appendix B, Fig. B2).

2.4.1.3. Soils. Soil type is determinant for agricultural activity and therefore it operates as an important location cause of land clearings. Soils were characterized based on the proportion of three soil orders (Mollisols, Alfisols and Inceptisols) inside each-cell. Deep, well drained soils with high organic matter content, such as Mollisol, are desirable for agriculture. Data were obtained from the "Soils Atlas of Argentina" (INTA, 1990), E.: 1:500,000, which describes the types of soils according to the USDA's Taxonomy (United States Department of Agriculture) (Appendix B, Fig. B3).

2.4.2. Social factors and infrastructure

2.4.2.1. Demography. Urban areas act as centers for labor and services provision and, depending on their size, they may also operate as local markets for agricultural production. Distance to these centers is an important aspect in the land value and the agricultural profitability. We evaluated the effect of urban populations based on the distance to different sizes towns (more than 2, 4, 8 and 50×10^3 inhabitants). Information was obtained from maps of the Instituto Geográfico Nacional (E: 1:250,000) (IGN, 2012) (available at: http://www.ign.gob.ar/sig250). Population Census data of 1991, 2001 and 2010 (INDEC, 1991, 2001, 2011) were used to estimate population in the different periods. The input variables were the log distances of each map cell to the nearest town (of 2, 4, 8 and 50×10^3 inhabitants) (Appendix B, Fig. B4 and 5).

2.4.2.2. Roads. Accessibility, represented by the presence and type of roads, is critical for industrial agriculture. The influence of accessibility was evaluated through the variable distance to roads at two levels: distance to paved roads and distance to paved and unpaved roads. As a source of information we used SIG-250 digital maps (E: 1:250,000) (AutoMapa, 1990, 2000, 2010; IGN, 2012) updated to years 1990, 2000 and 2010 to represent the situation at the beginning of the periods 1987/1997, 1997/2007 and 2007/2011, respectively. To avoid endogenous effects, we only took into account provincial and national roads, excluding rural roads (Appendix B, Fig. B6).

2.4.3. Landscape configuration factors

Proximity to agricultural areas: Distances or density measurements, which quantify the degree of landscape agriculturization, are frequently included to develop land-use change models (Zhou and Liebhold, 1995; Theobald and Thompson Hobbs, 1998; Lambin et al., 2003; Müller and Munroe, 2008; Müller et al., 2012; Prishchepov et al., 2013).

Two types of aspects were evaluated at the beginning of each period: (a) distance to prior deforestation and (b) density of land-clearing. The first variable measures the linear distance between each cell to the edge of the nearest cleared areas. The second one measures the percentage of agricultural land within a circle of radius n. Maps were generated as a result of the measurement taken from a moving window with focal point in each map cell. The influence radios evaluated were 1, 5 and 10 km, calculated as "deforested area in the circle"/"circle area" $\times$ 100. Distances and densities were measured in *ad hoc* agricultural maps generated at the beginning of each period, i.e., 1987, 1997 and 2007 (Appendix B, Figs. B7 and 8).

2.4.4. Political and administrative factors

Administrative boundaries and the Native Forest Law: In Argentina, natural resources such as soil, water, flora and fauna are under provincial jurisdiction. This means that conservation and agricultural production policies vary between provinces and therefore there may be different influences in the agriculture expansion degree. A specific example of the above mentioned is the Act 26,331 (Forest Law) application for which each province defines its own forest zones.

Provinces were considered as categorical multinomial variables to assess the degree of differential influence of political particularities between the five provinces involved in the analysis (IGN, 2012). These types of variables can be included in the logistic models by transforming the categories of the original variable in n-1 dummy dichotomous variables (presence/absence), where n is the number of categories in the original variable, leaving one of them as reference variable. Afterwards, the province variable was transformed into 4 dummy variables (Tucumán, Santiago del Estero, Catamarca and Jujuy) while Salta Province was taken as the reference variable. We have also included (as dummy variables) the category of the zone map created by each province under the "Native Forest Law" 26,331 framework. This variable was only considered for the 2007–2011 period (after the act was issued). Each map cell was labeled with a unique code (areas where transformation is allowed, managed forests and conservation areas) using as majority criteria (Appendix B, Fig. B9).The Native Forest Law variable was transformed into 2 dummy variables (red and yellow zone) while the green zone was taken as the reference variable.

2.5. Selection of variables to perform the logistic regression

Before performing the logistic regression models, we carried out a statistical analysis to test problems caused by over-specification and multicollinearity (see Appendix C. Supplementary statistical analysis). Two of twenty-one variables selected *a priori* (Table 1) (*Inceptisol* and *Aridisol* soil type) were rejected to avoid over-specification problems (in those variables no significant differences were found between cleared and non cleared areas). Further, we found multicollinearly in four pairs of variables: (1) *mean annual temperature* and *water deficit*; (2) *mean annual evapotranspiration* and *mean annual precipitation*; (3) *mean slope* and *standard deviation slope*, and 4) *distance to prior deforestation* and *land clearing density*. We only retained the easiest to interpret variables and presenting the greater explanatory power: *mean annual temperature*, *mean annual precipitation, mean slope,* and *distance to prior deforestation*. Although *land clearing density* variable was highly correlated with the *distance to prior deforestation* variable, both were used to analyze the relationships between agriculture parcels proximity and contiguity. Keeping both variables would improve our understanding on how local landscape influences land clearing probability. To do so, we fitted models where *distance to prior deforestation* or *land clearing density* variables were alternatively included. The variables used to perform de logistic regression are indicated in Table 1 (in bold).

2.6. Statistical analysis

2.6.1. Sampling strategy

We built logistic regression models using a random sample dataset. Samples were drawn in equal proportion, both for cleared areas (category 1), and non-cleared areas (category 0). To avoid spatial autocorrelation in the dependent variable we performed a spatial autocorrelation analysis within the entire study area, calculating "Pearson r" correlation coefficient between the values of the dependent variable in each cell and the average value (of the same variable) in a radius r, for different distances or lags. Different Pearson r values were plotted for each lag distance (1 lag = 1 km). A Pearson $r < 0.4$ as threshold (Griffith, 1987) yields a 5 km lag (Appendix B, Fig. B10). Hence, sampling was performed with a 5 km spatial restriction between unit samples. We selected 87 cells for each category: 1 and 0. The sample size $n = 174$ is the maximum number of samples that could be extracted considering the 5 km spatial restriction in the smallest period studying cleared areas (2007–2011).

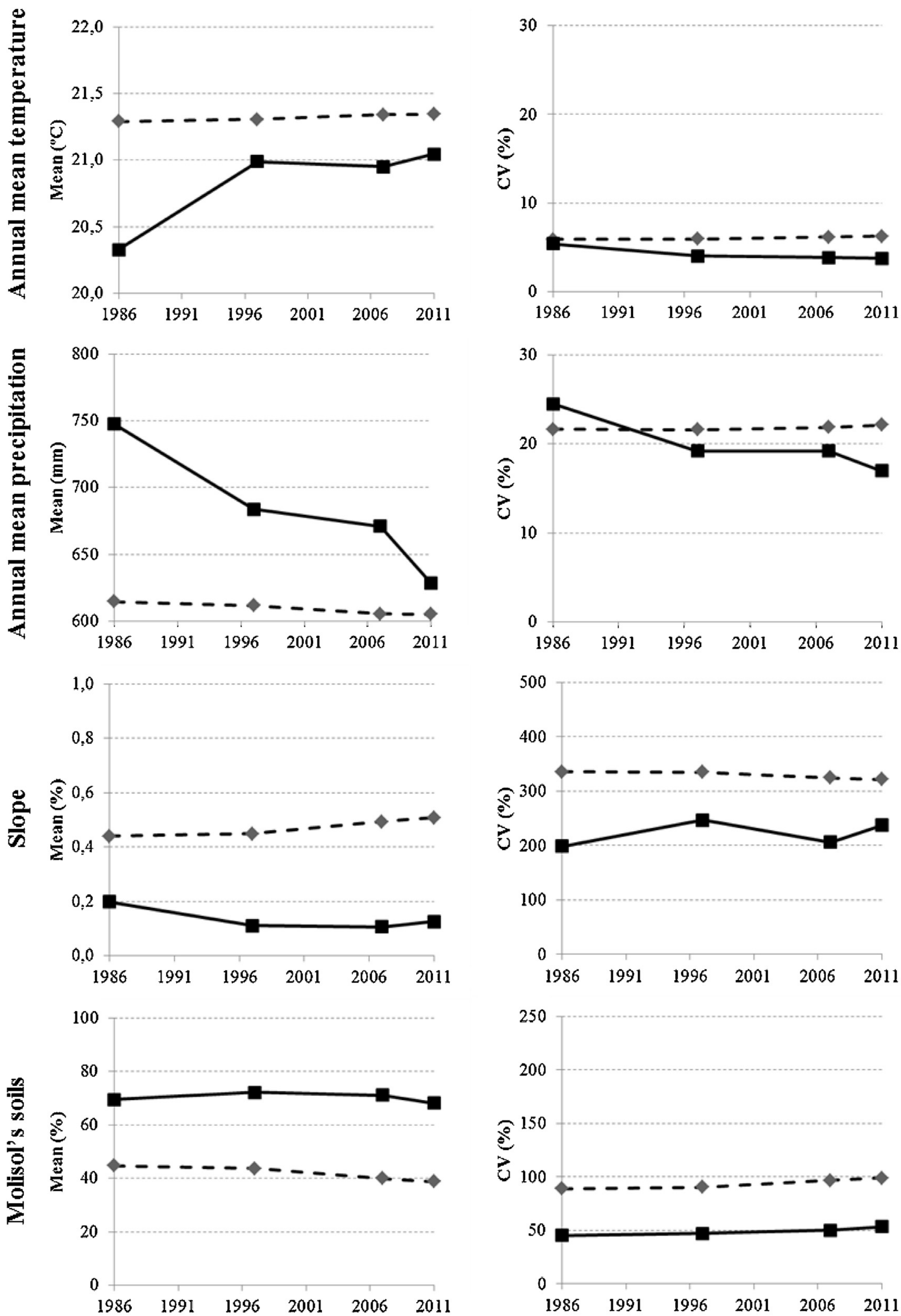

Fig. 2. Biophysical characterization of the study area by description of mean and variation coefficients of temperature, rainfall, slope and soil type in cleared (solid black line) and non-cleared areas (dashed gray line), at different periods of time.

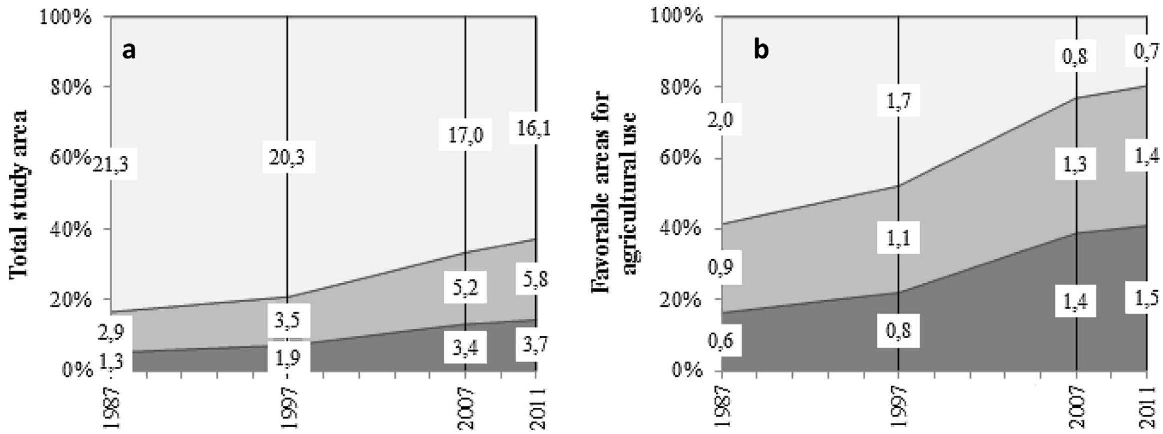

Fig. 3. Land-use changes for the 1987–2011 period. In dark gray, land with more than 90% of agricultural use; in light gray, land with less than 10% of agricultural use; and intermediate gray represents land with less than 90% and over 10% of agricultural use. Figure (a) presents the values for the entire study area; and (b) values for only the areas considered as favorable for agricultural use. The latter are sites presenting the best conditions for cropping (rainfall >615 mm, mean annual temperature <21 °C, slopes <0.43% and soils with more than 44% of mollisols). Labels expressing the area in million of hectares.

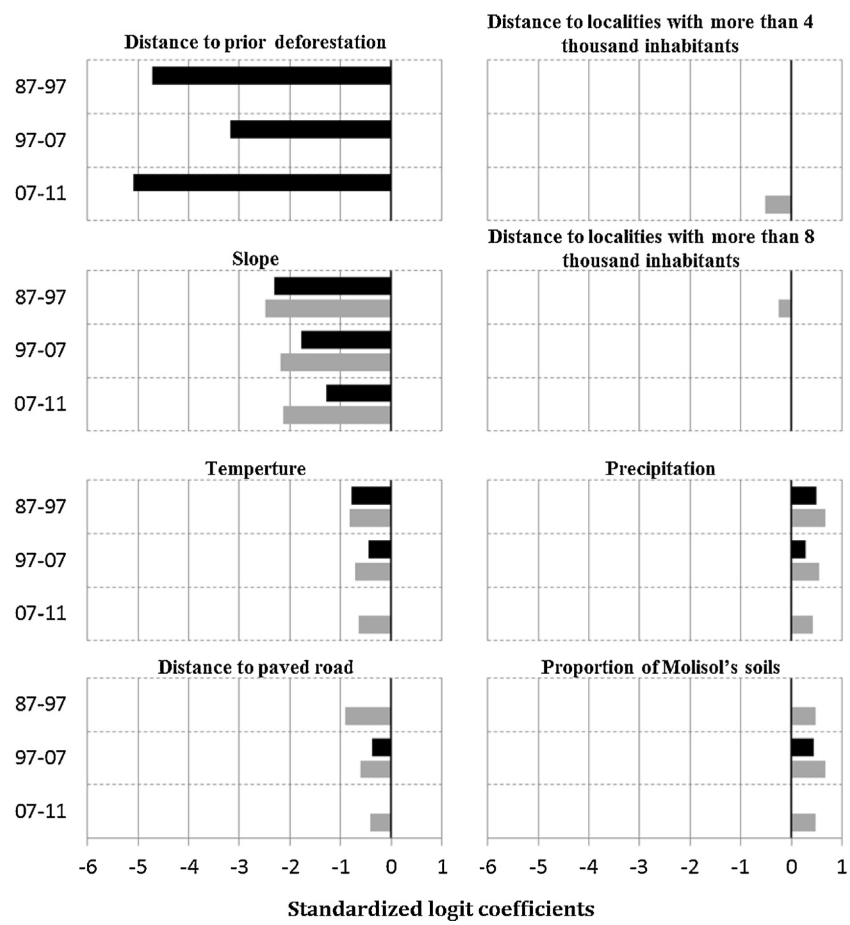

Fig. 4. Standardized logit coefficients of explanatory variables of agricultural expansion at different periods of time. In black DPD models (models including the variable distance to prior deforestation); in gray N-DPD models (models not including the distance to prior deforestation variable). The standardized logit coefficient symbol indicates the type of association (direct or inverse) between the independent variables and the dependent variable (deforestation).

2.6.2. Model fitting procedure

Three sets of logistic regression models were fitted, one for each time period (1987–1997; 1997–2007; 2007–2011). Due to the relative importance of the variable "distance to prior deforestation" in other South American regions (i.e., Kirby et al., 2006; Müller et al., 2010, 2012), we first evaluated two models for each period, one including this variable (DPD models with *distance to prior deforestation*) and another one not including it (N-DPD without *distance to prior deforestation*). Afterwards, we fitted logistic models with the *density of land clearing* variable to compare it with the results obtained including *distance to prior deforestation* variable so to understand the influence of surrounding landscape in the deforestation process. Finally, to evaluate the effect of the "Native Forest Law" implementation in the area, we compared two fitted models of the 2007–2011 period, one including the *Native Forest Law* inforcement, and the other one not including it.

To build the regression models we performed a backward selection approach starting with the entire model (including all variables) but gradually removing non-significant variables to select the best subset based on the Akaike information criterion (AIC) (Burnham and Anderson, 1998; Shtatland et al., 2001), which provides a measure of the modelís parsimony. The coefficients' significance was measured using the Wald's statistic (ratio logit coefficient by its standard error) with Z distribution. Results are presented as logit coefficients, standard logit and "odd ratios". Odd ratio is a measure of the effect of increasing a unit of the independent variable on the dependent variable. In order to compare variables measured in different units, logit coefficients were standardized by multiplying the logit coefficient of each independent variable by its own standard deviation (Menard, 2004). Additionally, we performed a Hierarchical Partition Analysis (Chevan and Sutherland, 1991) which provided information on the independent contribution of each variable to identify those factors with the highest degree of association (Mac Nally, 2002). When necessary we compared differences between models by inclusion or exclusion of variables, using Deviance Analysis, analogous to ANOVA (Rossiter and Loza, 2012). Logistic regression models were performed using the open source program R®, with statistical packages compiled for analysis of land-use changes and Hierarchical Analysis (Rossiter and Loza, 2012). To evaluate the logistic regressions fitting, we calculated a Pseudo R^2 value, also known as McFadden's R^2 (Pseudo $R^2 = 1 - [\text{residual deviance} \div \text{deviance null}]$) (Long and Freese, 2001; Williams, 2006). The accuracy of the probability maps was also evaluated calculating the Area Under the Curve (AUC) of Receiver Operating Characteristic (ROC) (Pontius and Schneider, 2001).

3. Results

3.1. Agricultural expansion and site quality

During the 1987–2011 period, 15.3% of the area was transformed into croplands and pastures, comprising 4.23 millions of hectares. The transformation process varied during the three periods analyzed; with 0.34% annual change rates to agriculture (83,000 ha year^{-1}), 1.16% (239,000 ha year^{-1}) and 0.92% (193,000 ha year^{-1}) for the 1987–1997, 1997–2007 and 2007–2011 periods, respectively. Agriculture clearings occurred mainly on wet, cool and climate homogeneous areas (CV lower values of *mean annual temperature* and *mean annual precipitation*) (Fig. 2). Flat areas with high Mollisol proportions were also associated to agricultural conversion (Fig. 2).There is a temporal trend of the clearings advance on less suitable areas (drier and hotter) (Fig. 2).

Only 13.6% (3.5 million ha) of the area had a "favorable" combination of environmental conditions for farming, defined (according to the fitted models) as mean annual precipitation ≥615 mm, mean annual temperature ≤21 °C, mean slopes ≤0.43% and more than 44% of Mollisol type soil. These zones were located in transitional areas between the sub-humid and semi-arid portion of the study region. In 1987, at the beginning of the study period, less than 20% (600,000 ha) of the "favorable" areas were used as agricultural land (land with over 90% of agricultural use), and there was a 40% (2 million ha) of slightly modified areas (land with less than 10% of agricultural use). By 2011, these proportions reversed (Fig. 3), with a reduction of the most suitable lands for agriculture.

Table 2
Summary of the main performance indices for the adjusted models in the three periods analyzed, considering with and without *distance to prior deforestation* variable (DPD and N-DPD models) (detailed data in Appendix A Tables A2 and A3).

	DPD modelsnewline (With distance to prior deforestation)			N-DPD models (Without distance to prior deforestation)		
	1987–97	1997–07	2007–11	1987–97	1997–07	2007–11
Null deviance	1070	1067	1070	1070	1067	1070
AIC	440	616	478	734	817	884
Pseudo R^2	0.61	0.44	0.57	0.33	0.25	0.19
ROC	0.95	0.90	0.94	0.86	0.82	0.78

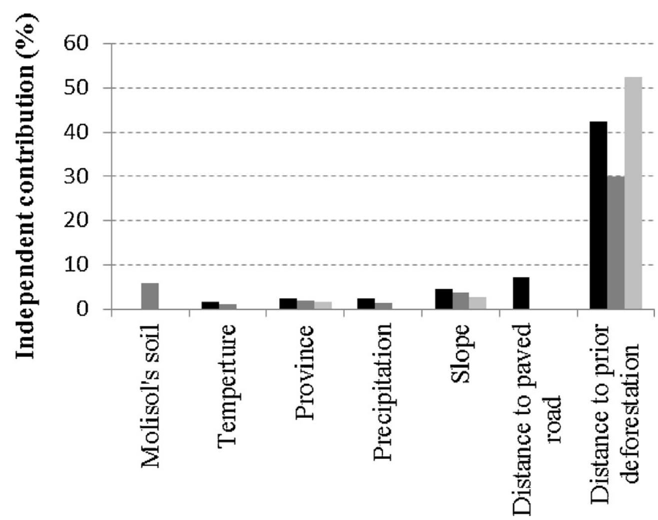

Fig. 5. Independent contribution to the total variability of models including the distance to prior deforestation variable (as a percentage of the Null Deviance). Comparison between logistic regression models for the 1987–1997 (black), 1997–2007 (dark gray) and 2007–2011 (light gray) periods.

3.2. Dynamics of the influence of deforestation factors during space and time

After performing the regression analysis taking into consideration all the variables, we found out that only a small set was significantly associated to agricultural expansion (six variables in the 1987–1997 period, six from 1997 to 2007; and three from 2007 to 2011). We found out that eight of the considered variables were significantly associated to agricultural expansion (Table 2, Fig. 4, Appendix A Table A2). Except for the "distance to prior deforestation" variable, there is a decreasing trend over time of variables and models explanatory power. Distance to prior deforestation had a larger relative significance exceeding eight to ten times the importance of the other aspects (Fig. 4, Table 2, and Appendix B Fig. B2). This information explains 30–52% of the overall variability (Fig. 5). Other factors showed stability and consistency over time, in terms of direction and magnitude. A decreasing influence of most factors was observed over time (Fig. 4).

We observed significant differences between *Distance to Prior Deforestation*—DPD and N-DPD models (P-value <0.0001, Deviance Analysis). Compared with DPD, N-DPD model had lower explanatory power (measured as Pseudo R^2), it was less parsimonious (AIC between 32 and 84% higher) and also presented a predictive power more than 10% lower (in terms of ROC) (Table 2). In the DPD model the *distance to prior deforestation* variable captured some of the variability explained by other factors, downplaying the influence of the remaining variables by 30% on average. DPD model did not include the *distances to location* and *distance to paved roads* variables (Fig. 4; and Appendix A Tables A3 and A4).

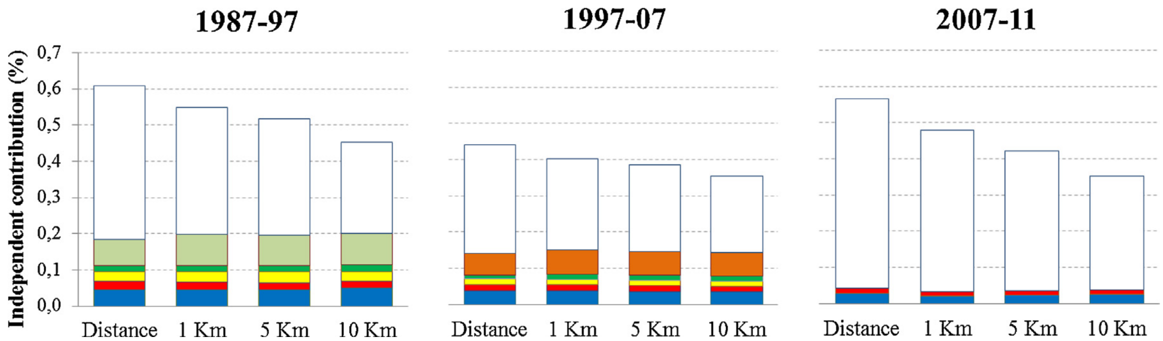

Fig. 6. Independent contribution of the explanatory variables as deviance percentage explained by the complete model. Comparison of logistic regression models for the periods 1987–1997, 1997–2007 and 2007–2011, taking into account the distance to prior deforestation and density of land clearing variables in radius of 1, 5 and 10 km.

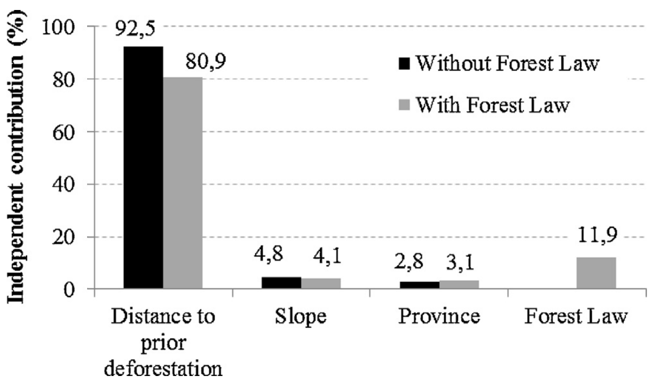

Fig. 7. Independent contribution variables as deviance percentage explained by the model; logistic regression models' comparison for the period 2007–2011, including the Native Forest Law's variable (gray) and not including it (black).

Distance to prior deforestation had more explanatory power than *land clearing density* variable, and the models including it had higher predictive power (higher ROC rates) (Appendix A, Tables A5–7). When the *distance to prior deforestation* variable was replaced by *land clearing density*, the model's explanatory power declined. The reduction in the explanatory power was greater as the radius of observation to calculate the density grew up. In other words, the larger the observation resolution, the larger the explanatory power of the variable (Fig. 6; and Appendix A Table A5–7).

3.3. *The influence of the Forest Law implementation on clearing patterns*

The comparison of models fitting, including or not the *Native Forest Law* variable, showed no significant differences (95% confidence level, P = 0.07). The model not including the *Native Forest Law* variable was the most parsimonious, in which the *distance to prior deforestation* variable captured all the variability explained by the *Native Forests Law* (12%). However, the *Native Forests Law* variable had a significant effect on the model (Fig. 7). Natural areas located in protected zones (red zones) and areas to be managed (yellow zones) had a lower probability of being deforested (2.8 and 1.5 times less) than those located in the green zones (odds ratio 0, 35 and 0.68, respectively).

3.4. *Future deforestation spatial pattern*

The risk of deforestation after 2011 was highly dependent on the *distance to prior deforestation* (see Appendix A, Table A7) (Fig. 8). Due to the importance of the *distance to prior deforestation* variable, the spatial distribution of clearing risks showed a concentric pattern that diminishes with distance. The result was a spatially advance pattern from the W and E borders towards the central driest portion of the Semiarid Chaco (See Appendix B Figure B2). The agricultural advance was contagious, but however not necessarily contiguous. Furthermore, there is a "leap frogging" expansion pattern, wherein land clearings may occur at some distance from prior agricultural areas. Locally, this phenomenon included a high frequency of small "jumps" advances (like leapfrog) and a low frequency of larger "jumps" (Figs. 1 and 8). According to the 2007–2011 model, more than 2,785,000 ha presented more than 85% of clearing chances.

4. Discussion

During the last 25 years agricultural expansion in NW Argentina transformed an area as large as Switzerland. The larger clearing area was observed during the 1997–2007 period, coincident with the release of transgenic soybean. During this period the transformation exceeded by 42% the average rate informed by FAO (2011) for Argentina (−0.82%) and by 127% for South America (−0.51%). Large transformation rate differences throughout the three periods might indicate a complex regional and global interplay between market (increases in commodities prices) (Zoomers and Goldfarb, 2013), technological (RR soybean) (Grau et al., 2005b; Gasparri and Grau, 2009) and environmental conditions (an increase in the mean annual precipitation) (Zak et al., 2004; Grau et al., 2005a), with a trend of the first two factors to outweigh the last one over time. These factors operated throughout the whole region without a particular spatial pattern.

The legal instrument devised by the Argentinean federal government to control the clearing process was insufficient to restrict both the annually transformed areas and the clearing locations. After the Native Forest Law implementation (2007) a slight decrease of the land clearings rate was observed. Although significant differences were observed between the three zones (green, yellow and red), areas corresponding to conservation categories (yellow and red) exhibit an important transformation.

Agriculture in NW Argentina is starting to expand over marginal areas. In the last 25 years deforestation occurred in areas with the highest suitability conditions for agricultural production (high mean annual precipitation, low mean slopes and high Mollisols type soils proportion), located in two longitudinal stripes on the western and eastern regions. Due to this site's depletion, agriculture expanded to the central, drier, area of the Chaco region. In fact, the influence of environmental variables on the location of new agricultural areas became less important through time. The expansion of subtropical livestock production on C4 showed exotic pastures (*Panicum maximum* and *Cenchrus ciliaris*) and some technological changes for crops (i.e., drought resistant soybean cultivars) reduced the importance of the new clearings environmental controls.

Land clearing dynamics has been increasingly controlled by proximity to already cleared areas. This fact resulted in a pattern of

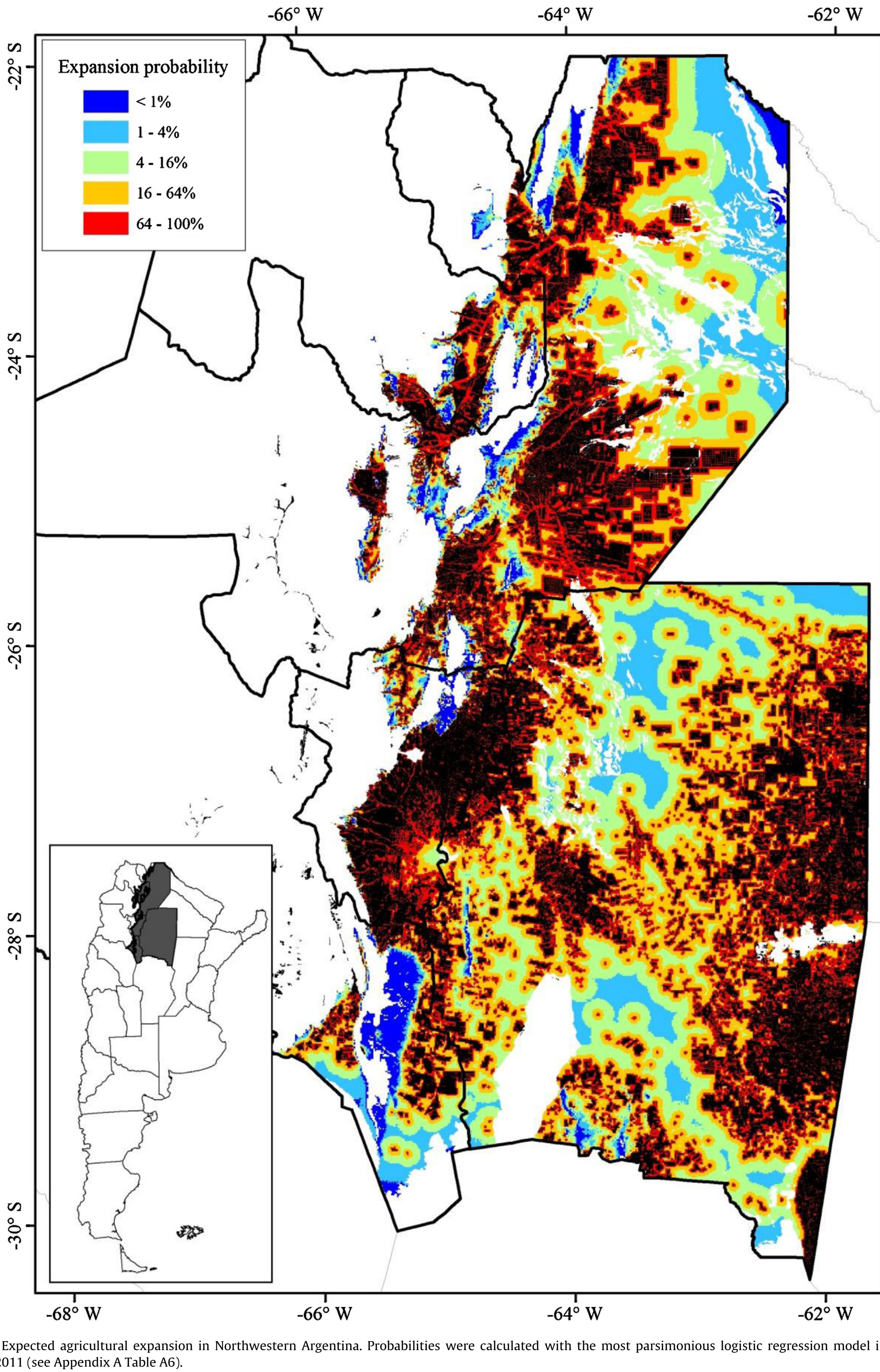

Fig. 8. Expected agricultural expansion in Northwestern Argentina. Probabilities were calculated with the most parsimonious logistic regression model in the period 2007–2011 (see Appendix A Table A6).

"advancement of frontier" (i.e., contiguous growth through contagion), probably determined by a series of human location controls (land tenure, proximity to services, infrastructure, etc.). This contagious effect of agricultural expansion was reported in other areas (Kaimowitz et al., 2002; Mertens et al., 2004; Müller et al., 2010). In the study region, the clearance probability is 10 to 25 times larger in areas less than 1 km away from agricultural areas. It is interesting to note that in the period with the highest clearing rates (1997–2007), the model including the *distance to prior deforestation* variable had less explanatory power than DPD models of the other periods (1987–1997 and 2007–2011).

Results indicate that at the local level the probability of deforestation is mostly controlled by factors related to proximity (distance) rather than density (quantity). This highlights the importance that local conditions such as access to services, land tenure, or "land control" processes probably have. "Land control" processes are associated with the industrial agriculture expansion in the semi-arid Chaco (Leake and Ecónomo, 2008; Paruelo et al., 2011; Seghezzo et al., 2011; Venencia et al., 2012). Land control constitutes a set of processes or strategies to gain access to land, and to keep other people away from it, including practices such as occupation, legalization, territorial isolation and violence (coercion) (Peluso and Lund, 2011). These factors are the basis of land grabbing processes (Borras et al., 2011) and form part of the "accumulation by dispossession" dynamics (Harvey, 2004). Due to this set of human controls, systems oriented to the production of international commodities are increasingly self-sufficient in terms of infrastructure and services, which in turn attract investment to places near to already developed areas (Müller et al., 2010).

The contagious expansion model is controlled by the supply of external (imported) commodities (seeds, agrochemicals, fuel, harvesting services, etc.) (Grau et al., 2005b; Oesterheld, 2008; Gasparri et al., 2008; Aizen et al., 2009; Viglizzo et al., 2012). In this context, local communities have little intervention as service or supplies providers. Moreover, the advent of four-wheel traction vehicles and large motorized agricultural machinery has allowed using previously inaccessible areas, which could in turn explain the lower influence of paved roads and the human settlements proximity on the allocation of new clearings.

The observed and expected changes in the Semi-arid Chaco could have enormous ecological and social consequences, compromising the production sustainability and the provision of ecosystem services. Land-cover change is a major control of changes in C gains (Volante et al., 2012), biodiversity (Torres et al., 2014), water dynamics (Amdan et al., 2013) and climate in the Chaco. The high levels of habitat fragmentation presented in the Chaco (Gasparri and Grau, 2009) could increase if the clearing process continues as expected, increasing the deforestation negative effects regarding the provision of intermediate ecosystem services (sensu Fisher et al., 2009) such as biodiversity, water regulation (Amdan et al., 2013) and carbon gains (Volante et al., 2012).

Our results have important management implications. We found out that the classic interplay of underlying factors of agriculture-mediated deforestation in the Chaco, including environment limitations to agriculture, technological development and socioeconomic factors (Zak et al., 2008) changed in importance through time. The temporal trend of a prevalence of human-mediated factors implies that human decisions (governmental policies, landowner's behavior, public pressure, investment decisions, etc.) would likely shape the future social and environmental conditions in the Chaco. In this scenario, the implementation of regulations and controls will be a key point to manage the conflict between production and ecosystem services provision.

Although the Native Forest Law had a measurable effect upon deforestation rate, as implemented nowadays it does not ensure the conservation and stability of the Chaco forests in Argentina. Soybean expansion in the Chaco has been dissociated from high deforestation rates during periods of poor economic incentives (for example from 1997 to 2002), but after 2002 it is strongly coupled with deforestation due to strong favorable market conditions (Gasparri et al., 2013). The favorable conditions for agricultural expansion will be likely to continue outweighing the regulatory power of the Native Forest Law unless enforcement strategies change or alternative conservation incentive are tried (for example meeting the European Union biofuel import standards).

Even small new clearings will have a strong impact in future deforestation patterns. The fast contagion agricultural expansion pattern indicates that in the near future a large area of land around cultivated zones will be transformed. This fact magnifies the potential "leap frogging" effect (new small clearings isolated in a matrix of natural habitats away from the expansion centers) (Liu et al., 2005). If no major environmental restrictions are implemented, any isolated agriculture foci would fracture the natural landscape matrix (Forman, 1995; Jaeger, 2000) which would in turn generate favorable conditions to provoque new land clearings (deforestation by contagion).

Finding alternatives for the Chaco development will have to include not only the analysis of the importance of land-use change factors based on land-use history, but also the influence of new arising factors or land-use types. New potential crops for biofuel, a changing international political scenario and climate change poses important uncertainty for the future of this area. The construction of possible future scenarios would be an important step to developing alternatives aimed to increase the equal provision and distribution of multiple ecosystem services. In our study area, we speculate that unless management and law enforcement is revised, land grabbing phenomena would have an increasing influence controlling the land-use and land-cover dynamics in the Chaco. The land grabbing scenario could pose important potentially negative impacts on the production sustainability, the ecosystems conditions and the provision of ecosystem services.

Acknowledgements

This research was supported by INTA (Proyecto PNNAT-1128032), CONICET, UBACyT, FONCyT and CONAE (Argentinean National Commission on Space Activities). This work was carried out with the aid of a grant from the Inter-American Institute for Global Change Research (IAI) CRN3095, which is supported by the US National Science Foundation (Grant GEO-1128040).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2016.03.025.

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