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Deforestation and fragmentation of Chaco dry forest in NW Argentina (1972–2007)

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ABSTRACT

The sustained increase in the global food demand has favoured the recent expansion of industrial agriculture into neotropical dry forest ecosystems, with resulting changes in their extent and spatial configuration. Based on Landsat satellite images, we analyzed changes in forest cover and landscape configuration over an area of 600 by 100 km located in NW Argentina (Tucumán and Salta provinces) in four periods between 1972 and 2007. The study area, one of the most active deforestation frontiers of South American dry forest, was divided into six relatively homogeneous sectors in terms of land property structure and biophysical characteristics. During the study period 1.4 millions hectares of dry forest were cleared. Deforestation started in the 1970s as a result of technological changes and increasing rainfall; continued (with spatial and temporal fluctuations) during the 1980s and 1990s in association to the sustained global demand of soybean, and was accelerated (to ca. 100,000 ha year^{-1}) between 2001 and 2007 following the global increase in commodity prices, and the national peso devaluation. We described the landscape structure using eight landscape indices, summarized as one synthesis value: the Euclidian distance across the seven dimensions from a theoretical non-fragmented situation. In areas with soil limitations deforestation resulted in relatively stable, highly fragmented landscapes. In contrast, the sites with regional coarser-scale limitations (rainfall), deforestation produced a less fragmented landscape where agriculture concentrates in sites with high rainfall. Sites with no limitations for agriculture tend to a largely deforested landscape with few small and poorly connected forest patches. The land properties size seems to influence some indices of fragmentation, but the synthetic index of fragmentation suggests an overall convergence of fragmentation patterns towards a similar configuration across different biophysical and land tenure conditions.

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1. Introduction

Deforestation is a main driver of species extinctions (Sala et al., 2000; Foley et al., 2005), carbon emissions (Houghton, 2003) and climate change at regional and global scale (Pielke et al., 2002). Deforestation not only produces a reduction in forest area, but also changes the landscape configuration (Skole and Tucker, 1993), which further contributes to habitat degradation, affecting the ecological conditions of the remaining forests with consequences over the fluxes of species, energy and matter.

Tropical dry forests are one of the most threatened ecosystems worldwide (Hoekstra et al., 2005). Major dry forest areas have been cleared for agriculture and today show a highly fragmented landscape with a mosaic of crops, secondary forests and remnants forests. This is a common situation in Mesoamerica, the Caribbean, and northern South America. In contrast, dry forests of Bolivia, Paraguay and Argentina, still have large continuous areas with natural or semi-natural vegetation (Eva et al., 2004), where land use is mostly limited to extensive cattle ranching, charcoal extraction, and selective logging. This pattern, however, has been changing during the last three decades as a result of expanding modern agriculture over dry forests ecosystems of the southern hemisphere. Recent processes of rapid deforestation have been described in the Cerrado of Brazil (Morton et al., 2006), the Chiquitano forest of Bolivia (Steininger et al., 2001a,b) and Chaco forest in Bolivia, Paraguay and Argentina (Zak et al., 2004; Grau et al., 2005; Boletta et al., 2006). Recent agricultural expansion is largely driven by modern agribusiness companies oriented to the global market of grains (mainly soybean); which follow different decision rules of investment to clearing new land in comparison to more traditional agents of tropical deforestation (e.g. shifting cultivators, cattle ranchers, and illegal crop farmers). Agribusiness companies work as scale economies, administrate very large properties, and aim to put into production all land with positive

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rent in order to maximize revenues. In consequence, in southern South America, deforestation of dry forests has strong links with trends of national and international economies, which need attention and still remain poorly described (Grau and Aide, 2008).

Studies on fragmentation are common in Amazonian rain forests (e.g. Skole and Tucker, 1993; Frosini de Barros-Ferraz et al., 2005; Barbosa de Oliveira-Filho and Metzger, 2006) but in the case of dry forests, they are limited to highly fragmented landscapes in Mesoamerica and the Caribbean (Arroyo-Mora et al., 2005) and the Bolivian Chiquitano forests (Steininger et al., 2001b). The Chaco forests of northwest Argentina are a clear example of deforestation driven by agribusiness expansion, with particularities resulting from the local environment and driving forces (global market, technology development and climatic change; Grau et al., 2005). In subtropical Argentina, the Chaco region has the highest absolute deforestation rates (Gasparri and Grau, 2006; Gasparri et al., 2008) for the country, and at the same time, is the least represented ecoregion in the national protected areas system (Izquierdo and Grau, 2008). The most recent report indicates a current deforestation rate for the Chaco region of 200,000 ha year^{-1} (UMSEF, 2008).

Local patterns of deforestation of Chaco ecosystems have been recently described in different sectors (Zak et al., 2004; Grau et al., 2005; Boletta et al., 2006) but these studies neither analyze fragmentation nor they include the most recent period (i.e. post, 2001), characterized by important changes in the local and global economies. These previous studies identified the soybean global market, technology changes (transgenic cultivars, and non-till practice) and the rainfall increase in subtropical Argentina as key drivers for deforestation in the Chaco region (Grau et al., 2005; Zak et al., in press) but relations with national economy were not clear, partly because the periods of analyses were too long to capture the effects of shorter term political changes. In this work, we describe the deforestation and forest fragmentation dynamic due to the agribusiness expansion in NW Argentina, we explore the relations between the deforestation rates and the country economy related to the agriculture sector, and we analyze patterns of fragmentation in relation to land property structure and ecological restrictions for agriculture.

2. Materials and methods

2.1. Study area

Our study area (ca. 90,000 km^2) is located in the provinces of Salta and Tucumán, in NW Argentina, between 22° and 27.5° S (600 km of latitudinal range). The western limit of the study followed the limit adopted by the National Forest Inventory to define Chaco forest and Yungas forest (UMSEF, 2008) except for the most northern site (SAMA) where we also included the last remains of Yungas piedmont forests (*Selva pedemontana*). The eastern limit was defined by the boundary of the administrative units (*departamentos*) with significant deforestation processes. The study area includes a strong rainfall gradient, from 400 mm year^{-1} in the eastern border to 1000 mm year^{-1} in the transition of Chaco forest with the Yungas forest, near the foothills (Fig. 1). Vegetation reflects the rainfall gradient. Below 700 or 800 mm year^{-1} (most of the area) vegetation is representative of Chaco forests, dominated by *Quebrachos* (*Schinopsisi lorentzeii* and *Aspidosperma quebracho-blanco*), and accompanied by *Bulnesia sarmientoi*; *Prosopis alba*; *Prosopis nigra* and *Ziziphus mistol*. In areas above 800 mm year^{-1}, forests are more diverse, corresponding to the piedmont forest types, dominated by species such as *Anadenanthera macrocarpa*; *Phyllostyllum rhamnoides* and *Callicophyllum multiflorum* (Cabrera, 1976). Hypothetically, pre-European landscape was a mosaic of dense forest and pirogenic grassland, but the cattle introduction promoted woodland encroachment into most grassland areas (Morello and Saravia-Toledo, 1959a,b). In consequence, the landscape is currently dominated by continuous woody vegetation strongly degraded by extensive grazing and wood extraction; and grasslands are largely restricted to comparatively small areas with sandy soils. At the beginning of our study period (1972) agriculture was restricted to the southern sector of the study area in the Tucumán province and next to rivers and main roads in Salta. Currently the area is one of the most active deforestation fronts in the Argentine Chaco (Grau et al., 2005, 2008), and in consequence it has been the focus of active political debate centred in the conflict between modern agriculture production and nature conservation (e.g. Greenpeace, 2008; Huffy, 2008).

Most of the recently deforested plots in the study area are used for soybean cultivation (Volante et al., 2006) under non-tillage practices based on gliphosate-resistant transgenic cultivars. Production is capital intensive, scale-economy dependent and driven by decisions of companies and owners of medium (between 1000 and 10,000 ha) or large (between 10,000 and 100,000 ha) properties. Areas with rainfall below 600 mm year^{-1} have major limitations for soybean production (Grau et al., 2005). Heavy machinery is used for forest clearing; aerial biomass and large roots are burnt on site in order to facilitate subsequent machinery operations.

2.2. Sites characterization

For the purpose of our analysis we defined six sites of similar area (0.5–1.5 millions hectares), based on a combination of administrative boundaries, vegetation units and environmental characteristics (Fig. 1). Each site represents particular conditions of land ownership structure, stages in the deforestation process, and environmental constraints for agriculture. SAMA and ANTA sites include the Yungas piedmont (*Selva pedemontana*) and Chaco forests of the departments San Martín and Anta, in the Salta province; ORAN includes the Chaco forest of the department Orán; ROME includes piedmont and Chaco forests of the departments Rosario de la Frontera and Metan in Salta province. TUNO includes the Chaco forests of the departments Burruyacú and Cruz Alta, in the northern sector of the Tucumán province; and TUSU includes the departments Leales, Simoca, Graneros and La Cocha in eastern and south-eastern Tucumán province (Fig. 1A).

ORAN and ANTA are dominated by large properties, with more than 40% of their area included in properties larger than 10,000 ha; SAMA and ROME have a more equilibrated distribution with medium-size properties, and TUSU and TUNO have the major part of the area (82% and 66%, respectively) in small properties (less than 1000 ha) (INDEC, 2002; Fig. 1B). In terms of environmental limitations for agriculture, shallow water table and salinity are significant in TUSU (Zuccardi and Fadda, 1992); hills with calcium-rich soils and rocks in surface are a limitation in ROME, whereas the other four sites have no main soil limitations for agriculture. In five sites (except for TUNO and TUSU), there are large sectors with rainfall below 600 mm year^{-1} (Fig. 1A).

2.3. Deforestation mapping

We mapped forests by screen-digitizing Landsat images of six dates: 1972, 1984 (only for sites ORAN, ANTA and SAMA), 1989/1992, 1997/1998, 2002 and 2007 (for all sites). The periods analyzed are representative of different national government policies.

The coordinated system employed was the Argentinean official system Gauss-Krügger using Zone 4 to SAMA, ORAN, ANTA and ROME and Zone 3 to TUNO and TUSU. A list of images used in our study and the correspondence to each site are showed in Table 1. Images of 1997/1998 and 2002 are the same used for the National Forest Monitoring program (UMSEF, 2008) and were used as

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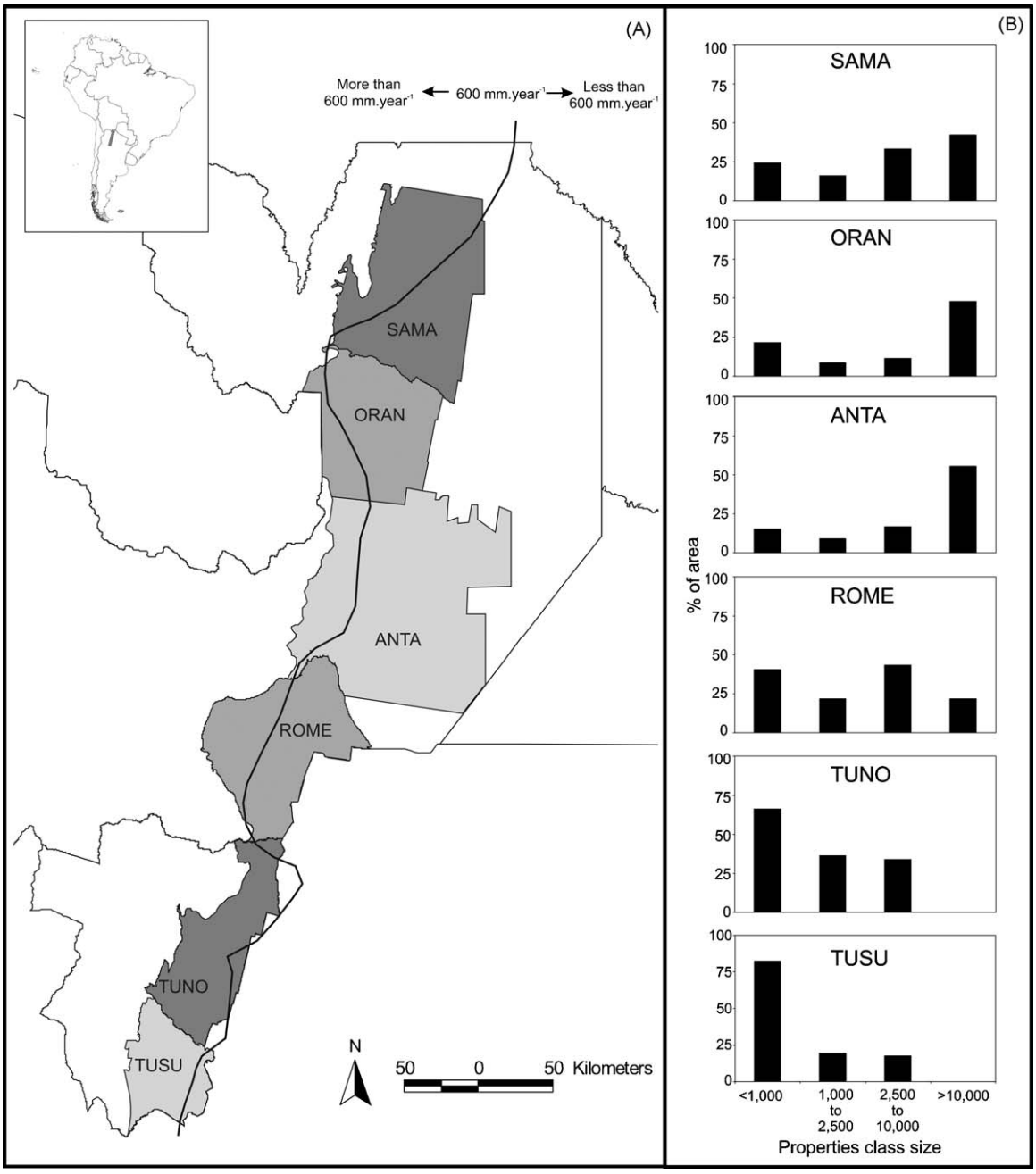

Fig. 1. Study area. (A) Location in South America; distribution of focal sites indicating the isoline of 600 mm of annual rainfall. (B) Property size structure of the six sites.

reference for images of other years. All images were co-registered with error less than 30 m and at least ten ground control points. We used the standard forest definition from the National Forests Resource Assessment program (UMSEF, 2008). To generate binary maps of forest/no forest, we merged the categories Forest Land, Rural Forest and Others Forest Land from the national forest inventory into the forest category. The national forest category "other lands" was considered as No-Forest. We applied the same procedure of the national forest monitoring program to map forest in each date: we screen-digitized forest clearing areas, editing the cover of the forward or backward date of each image used as reference. This method makes our results comparable with the national forests maps and was previously used in Grau et al. (2005) with an overall exactitude of 92%.

Table 1
Landsat images used in this work.

	Sites			
	SAMA	ORAN, ANTA	ROME, TUNO	TUSU
Landsat scene	230/76	230/77	230/78	230/79
Date 1	11/08/1975	09/02/1972	09/02/1972	09/02/1972
Date 2	09/30/1984	09/30/1984	–	–
Date 3	03/20/1989	02/29/1992	08/11/1989	03/20/1989
Date 4	04/27/1997	04/27/1997	04/27/1997	04/27/1997
Date 5	08/04/2001	08/04/2001	06/20/2002	08/04/2001
Date 6	08/29/2007	07/12/2007	07/12/2007	07/12/2007

2.4. Landscape index and forest fragmentation

We used eight indices to characterize the forest landscape structure. Seven of them are well known and are intuitively easy to interpret: (i) proportion of land with forest (PLAND); (ii) average

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patch area (APA); (iii) number of patches (NP); (iv) average patch shape index (APSI): the mean of the shape index calculated for each patch as the ratio between the perimeter of a given patch and the perimeter of one circle with the same area of a given patch (McGarigal and Marks, 1995); (v) Landscape shape index (LSI), the ratio of the forest perimeter over the perimeter of a circle with the same area of the total forest area of each site (McGarigal and Marks, 1995); (vi) Large patch index (LPI); and (vii) Average nearest neighbour distance (ANND). In addition, we included the (viii) Landscape division index (LDI) which shows low sensitivity to the inclusion of very small patches (Jaeger, 2000), and is computed as the probability that two randomly chosen places in the landscape are not in the same connected land cover category (forest patch in our case). The LDI is 0 for the no-fragmented situation and 1 for maximum fragmentation. To describe the forest landscape structure evolution, we plotted each landscape index in relation to the percent deforested which is the inverse of PLAND. We used the V-LATE 1.1 module for ArcGis 9 (Lang and Tiede, 2003) to calculate indices from the polygon layers.

PLAND was computed assuming the complete area of each site was forested prior to human intervention. Additionally, to describe overall trends in fragmentation we computed a synthesis fragmentation index (SFI). To do so, we first computed the individual landscape indices for a theoretical situation consisting of a single circular patch with the total area of the site, which we defined as the reference of non-fragmentation situation. We used a ranging procedure (Legendre and Legendre, 1998) to re-scale the seven landscape indices used (with the exception of PLAND) between 0 (non-fragmentation) and 1 (highest fragmentation value found in the entire study area and study period) by simple linear interpolation between these extreme values, thus eliminating differences related to units of measurement of each individual index. The SFI was computed as the Euclidian distance of each site at each date from this theoretical reference of non-fragmented landscape, and could show values ranging between 0 and 2.654 (i.e. $7^{1/2}$).

3. Results

In the entire study area 1,451,959 ha were deforested during the last 35 years. ANTA contributed with 42% of this area, SAMA ca. 16% ORAN 6% and the other three sites with ca. 10% (Table 2). At the beginning of the study period, deforestation was highest in the southern sites (especially in TUNO) and increased sharply during the 1990s in the northern sites, particularly in ANTA. In 1972 all sites of Salta province showed more than 75% of the land covered by forest, but by 2007 only ORAN was above this value (Fig. 2A). Prior to 2001, trends in deforestation varied, including periods with increases and decreases differing among sites and dates. But, after 2002 deforestation accelerated in all sites, with a more than four-fold increase in the annual rate in ANTA (Fig. 2B). As a consequence, the deforestation rate (slope in Fig. 2C) shows a reduction between 1998 and 2002 and an increase between 2002 and 2007.

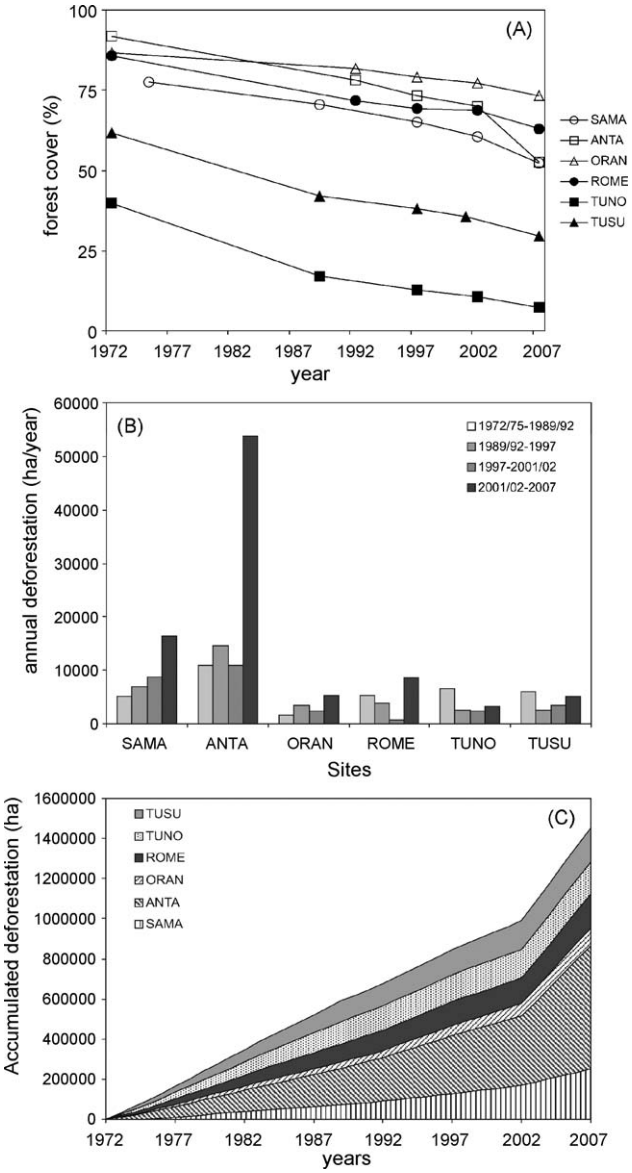

Fig. 2. (A) Evolution of percent of forest cover in the different focal sites, (B) annual absolute deforestation rate in different time periods and different focal sites and (C) accumulated deforestation in the region discriminated by focal sites.

Deforestation in general shows an aggregated pattern, in particular for the northern sites with big properties (Supplementary Material S1). Despite the varying behaviour of the different indices, the synthesis fragmentation index showed a convergent and relative uniform linear increase between 0% and 60% of deforestation, and a trend towards stabilization between 1.5 and

Table 2
Forest area and deforestation by sites.

	Site						
	SAMA	ANTA	ORAN	ROME	TUNO	TUSU	Total
Total area	990,360	1,564,926	669,643	730,331	491,233	524,266	4,970,759
Forest area in 1972/1975 (ha)	769,058	1,438,129	580,162	626,187	196,180	323,553	3,933,269
Forest area in 1984 (ha)	720,160	1,311,134	554,363	–	–	–	–
Forest area in 1989/1992 (ha)	698,346	1,220,889	546,604	535,230	83,909	220,113	3,305,091
Forest area in 1997 (ha)	642,787	1,147,495	529,382	505,184	63,422	199,582	3,087,852
Forest area in 2002 (ha)	599,440	1,092,552	517,250	501,292	51,617	185,898	2,948,048
Forest area in 2007 (ha)	517,708	823,547	490,889	458,400	35,576	155,189	2,481,309
Deforested area (1972/1975–2007) (ha)	251,350	614,582	89,273	167,787	160,604	168,364	1,451,959

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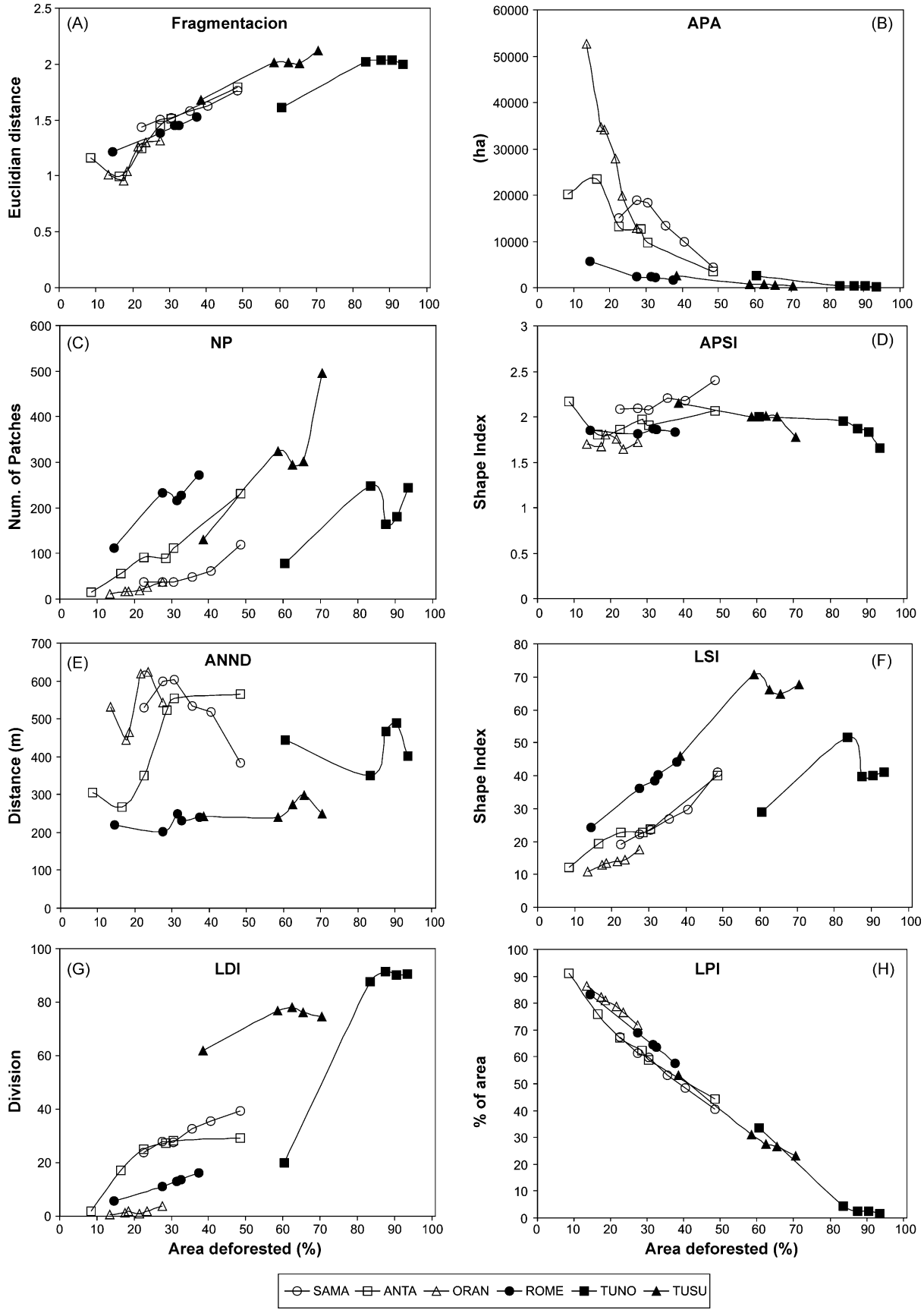

Fig. 3. Descriptors of fragmentation across a gradient of increasing deforestation in the six focal sites. (A) Synthesis fragmentation index; (B) average patch area; (C) number of patches; (D) average patch shape index; (E) average nearest neighbour distance; (F) landscape shape index; (G) land division index; (H) large patch index. Lines represent the trajectory of each site through time. Data for this graph are included in Supplementary Material S2.

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2.0 of Euclidean distance as deforestation keeps increasing (Fig. 3A).

Landscape indices showed different behaviour in relation to the proportion of land deforested. The average patch area decreased steeply in the early transformation stage because is very sensible to the emergence of small patches (Fig. 3B). The average patch shape index stays relatively stable across the entire deforestation gradient (Fig. 3D). Average nearest neighbour distance is erratic (Fig. 3E). Land shape index showed high values for intermediate levels of deforestation (Fig. 3F). The landscape division index increased steadily until 50–60% deforested (Fig. 3G). TUNO shows a rise of LDI in the first period when deforestation moved from 60% to 70%, and the LDI increase from 20% to more than 80% (Fig. 3G). Only the large patch index shows a linear relation with the proportion of deforested area (Fig. 3H).

Individual indices show patterns differing among sites. TUSU, TUNO and ROME have the smallest average shape area (less than 5000 ha) but sites that reached 50% of deforestation (SAMA, ANTA) reach similar values despite large average patch area in 1972 (15,000–25,000 ha) and ORAN showed an abrupt declination of the average patch area (Fig. 3B). Number of patches shows a similar increasing trend across sites, in which southern sites have higher values. ROME has 200–300 patches from 1990 and stayed later in this range; that is the highest for sites with less than 50% deforested (Fig. 3C). NP showed two distinct periods of sharp increase, in TUSU, TUNO, ROME and ANTA following the trend in deforestation (Fig. 3C). Landscape shape index showed peaks at intermediate values of deforestation in ROME and TUSU (the maximum values, Fig. 3F).

4. Discussion

4.1. Deforestation and national economy

Prior to 2001, deforestation in the area was associated to increasing rainfall, technological improvement and a sustained international demand for soybean (Grau et al., 2005). At the end of 2001, Argentina experienced a profound economic crisis that derived in a strong devaluation of the Argentine peso, and a movement away from policies characteristic of the previous (i.e. privatization and economic deregulation). Here, we analyzed a larger study area than in Grau et al. (2005) in order to capture differences in land property size and, most significantly, to included the 2001-2007 period, covering the post crisis recovery of the Argentina economy under different conditions of both the national administration and the global economic conditions. Our results show that the highly favourable exchange ratio for exports, simultaneous to growing commodity prices worldwide, greatly stimulated soybean production (and deforestation) in Argentina.

By the end of the 1980s approximately 600,000 ha were deforested in the area (43% of deforestation from 1972 to 2007). During the first periods (1972/1975–1989/1992) the economy of Argentina was strongly affected by political and economic instability, reflected in a very high inflation (Rapoport, 2006). From 1978 to 1983 during the military government, the agriculture sector was favoured by policies to promote exportation and by the elimination of export taxes, but was also negatively affected by high interest rates and unfavourable currency exchange rate (Rapoport, 2006). From 1984 to 1990 the agriculture sector was seriously affected by low international prices, re-implementation of export taxes since 1983 and domestic hyperinflation (Barsky and Gelman, 2001; Rapoport, 2006). The decreasing deforestation rates in SAMA, ORAN and ANTA during the 1972–1984 and 1984–1990 periods (the annual deforestation rate reduction in the second period was −8.5%, Table 2), probably reflect these contrasting situations in the 1970s and 1980s, but the overall sustained deforestation despite dramatic changes in the national economy suggests that less volatile factors were the major drivers. In our opinion, agronomic and technological developments played this role; particularly in the case of soybean. During this period, major technological and agronomic changes included the strong adoption of up to date use of herbicides and fertilizers, genetic research and development, and the machinery incorporation (Obschatko, 1992). Tucumán province was one of the first regions in the country to start agronomic research on the cultivation of soybean. By the early 1970s, one decade of research has identified the best agriculture practices and the varietals to be cultivated in sites with less than 800 mm of annual rainfall (Hemsy, 1970; Remussi, 1970); providing the potential for agriculture expansion into an area previously considered unsuitable for rain fed agriculture.

Between 1989/1992 and 1997 the government again removed the export taxes and favoured economic stability, sustained growth and a fixed currency exchange ratio that derived in an overvaluation of the Argentine peso. While this overvaluation did not contribute directly to large profits, it facilitated the acquisition of technology (machinery, agrochemicals) at comparatively low prices, which resulted in increasing yields and a stronger participation in the international market. Fuelled by growing international prices (that reached a decadal peak in 1997), Argentina soybean production increased significantly, but more based on increasing yields than in expanding area, which explains that during this period, deforestation rates decreased (−4.7% in relation to the annual deforestation rate of the previous period) in the study area. This reduced deforestation was the result of the trends in the south of the study area (ROME, TUNO and TUSO) whereas the three northern sites showed a moderate increase, likely reflecting a delayed agriculture development.

The third period (1997-2001/2002) corresponds to the continuity of the economic policies but with a national economy in recession that ended in the 2001 crisis. Soybean price also decreased but the introduction of the transgenic cultivar of the soybean improved the profitability of this crop. The combination of favourable and unfavourable factors resulted in small increases in deforestation in some sites (SAMA and TUSU), but a net decrease in the regional deforestation rate (−15% in relation to the annual deforestation rate of the previous period) driven by low deforestation in ANTA, ORAN and ROME.

The post 2001 period (2002-2007) was characterized by a shift in the Argentine economy, away from the economic policies of the 1990s. After the 2001 crisis, the Argentinean peso was strongly devaluated (to ca. 30%), export taxes were again implemented and repeatedly increased following increased international commodity prices. National GDP showed a strong and sustained recovery. Despite increasing export taxes, soybean profitability was high, due to growing global prices (Rapoport, 2006). These conditions seemingly promoted deforestation in all sites but particularly in ANTA (Fig. 2). High deforestation may have been further promoted in 2007 by the prospect of a new National Forest Law aimed to restrict deforestation in the long term. In response, agribusiness companies appear to have invested more in deforestation prior to the implementation of the law, in order to be less affected by future prohibitions (Leake and De Ecónomo, 2008).

In summary, our results indicate a generalized process of deforestation that started in the early 1970s in the South of the study area (Tucumán province) and had a strong acceleration in the post 2001 period mostly in the Salta province (North of the study area). In Bolivia, deforestation in dry forest was postulated as consequence of structural adjustment and economic deregulation politics of the 1990s (Kaimowitz et al., 1999). In contrast, our data show that in NW Argentina, deforestation started early in the

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1970s, especially in sites ANTA, TUNO and TUSU, and accelerated during the post 2001 years. Both periods were characterized by policies oriented to promoting and protect local industry and regional production. These policies included a competitive money exchange (i.e. peso devaluation) and a state intervention to promote economic development through subsidies and infrastructure improvement. Macroeconomic policies oriented to promote national industry (especially peso devaluation) at the same time impulse agriculture sector oriented to exportations (mainly grains) and these incentives are not compensated with the implementation of the rising exportation taxes. The overall result was a strong deforestation increase.

A comparative analysis of the different sites shows that sites dominated by large properties tend to have faster deforestation (high annual deforestation rates). Additionally, large properties commonly imply large economic agents well integrated with the financial system and with more options of investments. In consequence, sites dominated by large properties could more sensible to macroeconomic signals and deforestation process could be more volatile as in ANTA.

In addition to economy there are other aspects related to the social dynamics that have consequences for deforestation. In our study we found that political uncertainty related with the promotion of a new forest protection law, in combination with the change of provincial authorities in December 2007, favoured deforestation in Salta. Provincial authorities finishing their mandates in the last months of 2007 in agreement with the agriculture sector, significantly increase the approved plans for forest clearing before leaving the government (Leake and De Ecónomo, 2008). Infrastructure development has been repeatedly reported as a socioeconomic factor promoting deforestation. In our study area, we found no clear relationship between roads density and deforestation or fragmentation, and new paved roads may be more a consequence than a cause of deforestation. Future studies using a more extensive region, covering more situations and finer temporal resolutions are needed to explore the role of road expansion in the deforestation dynamic and landscape structure.

4.2. Forest fragmentation

It has been argued that industrial agriculture expansion leads to lesser fragmentation than deforestation by small land holders (Steininger et al., 2001a; Alves, 2002). Agribusiness deforestation is characterized by large clearing events (Geist and Lambin, 2002) and by retaining large forest patches that result in relative simple landscapes. Our results do show some differences in the magnitude of fragmentation measured with SFI, but follows a similar general pattern in the other indices despite differences in the size of management units and environmental conditions, reaching a plateau of persistent fragmentation when approximately 50% of the area is deforested (Fig. 3). The different specific indices show a more complex picture indicating different kinds of fragmentation. In general, sites with high proportion of small properties present forest landscape with more patches and smaller fragments because each property represents a decision unit of clearing or preserving forest. Soil limitation also favours fragmentation, increasing the number of patches and the complexity of the landscape shape (i.e. high values of LSI) because places with soil limitation retain forest cover locally. The site TUSU represents an example of high fragmentation due to a combination of both soil limitation (high salinity and water table) and small properties, which is reflected in the highest values of fragmentation in all the indices (Table 3, Fig. 3 and Supplementary Materials S2).

Based on our results, we can identify three general patterns of fragmentation; reflected in four indices (APA, NP, LSI, and LDI). Using these landscape indices we suggest the general tendency for values of each index under different situations and propose a coarse classification (low, middle, high; Table 3):

(i) Fragmented forest by soil limitation. Under this condition (TUSU and ROME in our study), transformation tends to occupy all lands suitable for modern agriculture, producing a landscape with a high proportion of perimeter (high LSI) and number of small fragments. Soil limitations are difficult to avoid by agriculture practices or technology and this kind of landscape probably remains stable.

(ii) Fragmented forest in agriculture matrix. Represented by TUNO in 2007, this landscape is the results of few limitations for agriculture; leading to a landscape with small and isolated remnants in riparian zones (high values of LDI). The transition towards this situation can be more or less fragmented depending on the property structure.

(iii) Aggregated forest by rainfall limitation. Examples for this situation include TUNO in 1972, and SAMA, ANTA and ORAN. Crop yield decreases with annual rainfall and produces a limit for a profitable agriculture. Agriculture tends to be aggregated in large patches with comparatively low fragmentation levels in the more humid sectors. In this situation the land property structure could represent different degrees of fragmentation since areas with small properties tend to be more fragmented (Table 3).

The three patterns suggested can be modified according to particular situations of local management or environmental situation, which is reflected in the behaviour of four landscape indices: APA, NP, LSI, and LDI (Table 3). For example, the landscapes with aggregated forest by rainfall limitation (type (iii)) are not stable, since technological changes, climatic oscillations or economic conditions (taxes policies and crop prices) may change rainfall limit for a profitable agriculture. TUNO is an example of this

Table 3
Characterization of general situations of dry forest fragmentation.

General situation	Environmental limitation for agriculture	Property size structure (example)	Tendency for landscape index values			
			APA	NP	LSI	LDI
(i) Fragmented forest by soil limitation	Local (soil)	Small (TUSU-2007) Middle (ROME-2007)	Low (314) Low (1685)	High (495) Middle (272)	High (67) Middle (44)	High (74) Low (16)
(ii) Fragmented forest in agriculture matrix	No limitation	Small (TUNO-2007)	Low (154)	Middle (245)	Middle (40)	High (90)
(iii) Aggregated forest by rainfall limitation	Regional (rainfall)	Small (TUNO-1972) Middle (SAMA-2007) Large (ORAN-2007) (ANTA-1997)	Low (2515) Middle (4350) High (12918) (12750)	Low (78) Middle (119) Low (38) (90)	Low (29) Middle (41) Low (17) (22)	Low (20) Middle (40) Low (3) (27)

Values of each landscape index, corresponding to the specific site and date used as example, are included between brackets. ANTA 2007 is not used as example because it changed its fragmentation patterns in the last period (see text).

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instability. Having been more than half deforested by 1972, TUNO was already a site in an advanced stage of deforestation. However, it continued to experience significant deforestation during the study period promoted by technological and climatic change. Historical statistics indicate that during the 1960s agriculture area increased to 20,000 ha, but this figure climbs to more than 100,000 ha during the 1970s (INDEC, 1988, 1969). In 1972, agriculture was concentrated in the western portion without rainfall limitation (above 800 mm year^{-1}) and large fragments of forest remained in the drier eastern side of this study site (Supplementary Material S1), resulting in an overall low level of fragmentation (low values of NP, DI, LSI) (Supplementary Material S2 and Table 3). Post 1972 deforestation driven by technological change (soybean varietals for sites with rainfall below 800 mm year^{-1}) and climatic change (rainfall increase), resulted in a new wave of agriculture expansion into the drier areas, showing a trend towards almost complete deforestation leading to an almost completely deforested landscape in the present (see Supplementary Material S2 and Table 3).

Other factors with effects over the fragmentation patterns are legal regulations. For example, between 2002 and 2007, the Salta province government promoted the conservation of forest strips between cleared patches aimed to prevent wind erosion (see the map for ANTA 2007 in S1), and this policy was highly influential in the resulting landscape configuration, since is was applied during a period of very high deforestation. In consequence, the site ANTA changed the tendency in its landscape indices, increasing the fragmentation of remnant forests and departing from the expected patterns for a site with large property and regional limitations.

5. Conclusions

In this paper we described the evolution of the landscape configuration of one of the most active deforestation areas in South American dry forests over the past 35 years, during which 1.4 millions hectares were cleared. Deforestation started in the 1970s as a result of technological changes and increasing rainfall; continued (with spatial and temporal fluctuations) during the 1980s and 1990s, responding to the sustain global demand of soybean, and was accelerated (to ca. 100,000 ha year^{-1}) during the last six years as a consequence of the combination of global (increasing commodity prices), and national (peso undervaluation) economic conditions; locally exacerbated by political uncertainty derived from discussions around conservation laws.

This paper is the first to describe large-scale patterns of fragmentation patterns related to agribusiness expansion in subtropical Argentina. Deforestation by industrial agriculture showed a variety of landscape patterns depending on the existence of limitations for the crops and the land properties structure. Our results suggest that under current condition, all areas profitable for agriculture will be deforested in the long term (as in our site TUNO) if no formal conservation and land planning are applied, independently of the property size. In sites with soil limitation the landscape evolves to a fragmented forest relatively stable through time, but with low levels of connection among remnants. In areas with rainfall limitation, the landscape evolves to landscape structure with large forest patches located in drier conditions, but the fluctuating economic conditions controlling the levels of yields at which the crop becomes profitable (e.g. subsidies, exchange rations, tax policies, international markets). Climatic change is also likely to make these landscapes less stable.

5.1. Implications for conservation of Chaco dry forests

Chaco forests are the largest continuum area of dry forest in South America and a main extra tropical habitat for many species with high conservation value. For example, the area is the largest remaining extratropical habitat for Jaguar (*Panther onca*), Tapir (*Tapirus terrestris*); Giant Anteater (*Myrmecophaga tridactyla*), Giant Armadillo (*Priodontes maximus*); and three species of peccaries including an endemic one (*Tayassu pecari*; *Tayassu tajacu*; *Catagonus wagneri*). Deforestation in the transition between Mountain forest (Yungas) and dry forest (Chaco), largely across our study area, has been considered a major regional conservation concern (Pacheco and Brown, 2006). Accelerated deforestation reported in our study could have consequences for conservation not only in the Chaco but also in the Yungas by affecting the connectivity between these two ecoregions. Our work indicates that it is very difficult to estimate a equilibrium point for the agriculture expansion in the area under which deforestation would stop. Therefore, unless specific conservation policies are adopted (e.g. including the protection of effective corridors), conservation of the connectivity between Chaco and Yungas will be severely affected in a few decades.

At a within-ecoregion scale, our work suggests that fragmentation in Chaco forest is comparatively less important than habitat transformation; but does represent an additional problem to take into account. Forest patch remnants in Chaco under current land use change patterns appear to be of limited value for the conservation of biodiversity due to the comparatively low area included in them, and the deleterious environmental effects of agrochemical spread, wood extraction and hunting. Legal requirements to retain forest patches do not follow any criteria based on population or community behaviour but on loose rules related to soil restrictions and properties sizes. Our study identified that some indices of fragmentation as particularly sensitive to current trends in land use change and are related to patch size and connectivity (indices APA and LDI). Field based research on the population and community responses to these indices would be highly valuable to understand the effects of forest fragmentation at local scales and to develop landscape regulations with relevant consequences for biodiversity conservation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2009.02.024.

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