Agriculture expansion and deforestation in seasonally dry forests of north-west Argentina

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SUMMARY

In Argentina, deforestation due to agriculture expansion is threatening the Semi-arid Chaco, one of the largest forested biomes of South America. This study focuses on the north-west boundary of the Argentine Semi-arid Chaco, where soybean is the most important crop. Deforestation was estimated for areas with different levels of soil and rainfall limitation for agriculture between 1972 and 2001, with a finer analysis in three periods starting in 1984, which are characterized by differences in rainfall, soybean price, production cost, technology-driven yield and national gross domestic product. Between 1972 and 2001, 588 900 ha (*c*. 20% of the forests) were deforested. Deforestation has been accelerating, reaching >28 000 ha yr^{-1} after 1997. The initial deforestation was associated with black bean cultivation following an increase in rainfall during the 1970s. In the 1980s, high soybean prices stimulated further deforestation. Finally, the introduction of soybean transgenic cultivars in 1997 reduced plantation costs and stimulated a further increase in deforestation. The domestic economy had little association with deforestation. Although deforestation was more intense in the moister (rainfall >600 mm yr^{-1}) areas, more than 300 000 ha have already been deforested in the drier areas, suggesting that climatic limitations are being overcome by technological and genetic improvement. Furthermore, more than 300 000 ha of forest occur in sectors without major soil and rainfall limitations. If global trends of technology, soybean markets and climate continue, and no active conservation policies are applied, vast areas of the Chaco will be deforested in the coming decades.

Keywords: agriculture expansion, Chaco, deforestation, globalization, soybean, subtropical dry forest

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INTRODUCTION

The main driver of deforestation in South America is agricultural expansion (Geist & Lambin 2002). At the global scale, soybean is one of the fastest expanding crops; in the last 30 years, the area planted with soybean in the world has more than doubled (Food and Agriculture Organization of the United Nations 2002). Globally there are approximately 80 million hectares planted with soybean, >70% of which are planted in the USA, Brazil and Argentina. While the area planted with soybean has remained relatively stable during the last decade in the USA, it has expanded rapidly in South America becoming the major cause of the high deforestation rates in tropical and subtropical seasonally-dry forests (Fearnside 2001; Kaimowitz & Smith 2001; Steininger *et al.* 2001; Paruelo *et al.* 2004).

Dry forests and savannahs are the second largest biome in South America after the Amazonian rainforest. The *Cerrado* in Brazil and Chaco in Argentina, Paraguay and Bolivia are the two largest continuous units of this biome. The Chaco covers a total area of *c*.1 200 000 km^2 (Dinerstein *et al.* 1995), in Argentina, Bolivia and Paraguay. In Argentina, the Chaco region is divided into two zones based on rainfall (Cabrera 1976; Prado 1993). The eastern 'Humid Chaco' has been intensively transformed into agriculture, while the western 'Semi-arid Chaco' has remained largely forested because, despite high soil fertility and flat terrain, rain fed agriculture was historically unprofitable (Bucher & Huszar 1999). Recent deforestation in the Semi-arid Chaco for soybean production suggests that the major drivers and limitations for deforestation in the region have changed.

Large-scale soybean production in Argentina began in the 1980s. Currently, Argentina is the third largest soybean producer with 15% of world production. Between 1993 and 2003 the annual increase in area planted with soybean was 12.3%, compared with a 3.3% annual increase globally. The area planted with soybean in Argentina increased from less than a million hectares in 1970 to more than 13 million hectares in 2003. In part, this increase has occurred in areas that were previously used for other agricultural or grazing activities, but extensive new areas also originated from the transformation of native vegetation. Deforestation due to agriculture expansion has been particularly intense in four provinces of northern

Argentina, namely Santiago del Estero, Chaco, Tucuman and Salta (Grau *et al.* 2005).

Soybean expansion into forest areas has been attributed, in part, to the increase in rainfall that has affected north-western Argentina during the last decades (Minetti & Lamelas 1997). Rainfall increased in subtropical Argentina during the 20th century (Minetti & Vargas 1997). Rainfall increase is associated with an intensification of the continental circulation (Rao *et al.* 1996), a process likely related to the global increase in CO_2 (Labraga 1997). Global circulation models predict that high precipitation in the region is likely to persist or even increase during the coming decades (Hulme *et al.* 1999).

In addition to climate, agriculture expansion can be influenced by socioeconomic changes of both global (for example international markets) and local origin (for example infrastructure development and availability of credit) (Fearnside 1993, 2001; Browder 1994; Coomes 1996), and by technological change. For example, new varieties of soybean, including glyphosate-resistant transgenic cultivars, are increasing yields and overriding the environmental constraints, making this a very profitable endeavour (Kaimowitz & Smith 2001).

Deforestation for soybean expansion has been identified as a major environmental threat in Brazil, Bolivia and Paraguay (Fearnside 2001; Kaimowitz & Smith 2001; Steininger *et al.* 2001). In Argentina, it has received less research attention and the extent of the deforestation caused by soybean expansion has not been quantified. We estimate deforestation rates between the early 1970s and 2001 in the north-western boundary of the Semi-arid Chaco. We explore the relative importance of different factors influencing deforestation due to soybean expansion by comparing deforestation patterns during three periods between 1984 and 2001 and relating them to climatic conditions and socioeconomic drivers. In addition, we investigate the potential for future soybean expansion in the study region by relating the geographic distribution of present agriculture fields with the distributions of the two main limiting factors for soybean cultivation, namely rainfall and soils.

Study area

Our study focused on the departments of San Martín, Anta, and the eastern sector of Oran, in the province of Salta, north-west Argentina (Fig. 1). This area extends between 22º S (Argentina-Bolivia boundary) and 26º S, and between 63º W and 65° W, and is included in two adjacent Landsat Thematic Mapper (TM) images (230/76 and 230/77). In these departments, more than 80% of the agriculture area is soybean (INTA [Instituto Nacional de Tecnología Agropecuria] 2003).

The western sector of the images (∼25% of the area), which corresponds to humid montane forests and grasslands, was excluded from the analysis because it is mostly mountains and unsuitable for agriculture. Our analysis focused on the remaining area (3 051 285 ha) on the eastern side of the images, which corresponds to seasonally deciduous forest vegetation extending mostly over flat topography. In some analyses, we separated the data into two geographical sectors, namely northern sector (departments of San Martin and Oran, Landsat TM image 230-76), and southern sector (department of Anta, Landsat TM image 230-77). The separated analysis of the two sectors allowed us to relate differences in rainfall and initial settlement time (which differed latitudinally) to the different patterns of deforestation.

There is little geographic variation in temperature within the study area; mean annual temperature varies between 20º and 22ºC, mean January (hottest month) temperature between 24° and 27°C, and mean July (coldest month) temperature between 14.5° and 15.5°C. Instead, annual rainfall decreases from 700–1000 mm in the northern sector to 500–800 mm in the southern sector, and there is a strong east-west gradient in rainfall, with higher levels in the west near the mountains (Fig. 1). Rainfall has a strong pattern of monsoonal seasonality with more than 80% of the precipitation occurring between November and March (Minetti 1999). Rainfall has increased in the region for at least the last 70 years. In Tartagal (northern sector) rainfall was always higher than in Las Lajitas (southern sector). During the study period, rainfall was higher than during previous decades; however, the increasing trend did not continue during the last 20 years. Since the mid-1980s there has been a decrease in rainfall in Tartagal, and no clear trend in Las Lajitas (Fig. 2*a*).

The natural vegetation of the area is seasonally dry forest. Most of the area has typical Semi-arid Chaco vegetation dominated by *Aspidosperma quebracho blanco*, *Schinopsis quebracho-colorado*, *Chorisia speciosa*, *Cesalpinea paraguariensis* and *Prosopis* spp. Towards the western side (i.e. close to the mountains) the forests include species typical of the Piedmont forest such as *Phyllostillon rhamnoides*, *Callicophyllum multiflorum*, *Astronium urundeva* and *Anandenathera colubrina* (Adamoli *et al.* 1972; Cabrera 1976; Prado 1993).

The soils of the region are formed by aeolian sediments characteristic of the Chaco plains, and fluvial sediments originating from the main rivers (Bermejo, Pilcomayo, Dorado, Del Valle and Juramento). The main limitations for agriculture include slope, salinity, soil texture and water table depth (Nadir & Chafatinos 1995.)

In the region, soybean is a summer crop planted between November and December and harvested between April and May (Devani *et al.* 2002). Other crops in the area include summer crops such as black beans and corn, and winter crops such as wheat and chickpea (INTA 2003).

METHODS

To explore the potential effects of global and local socio-economic factors on agriculture expansion and deforestation for the period post-1980 when soybean expansion occurred in the study area, we analysed the trends in (1) soybean prices

Figure 1 (*a*) Map of the study area indicating rainfall isoclines, areas with soil limitation for soybean cultivation, and land cover type: forest, agriculture and flood plains (also classified as 'soil–limited' in the analysis. (*b*) Relative location of the study area in South America. (*c*) 2001 Landsat TM satellite scene of the study area.
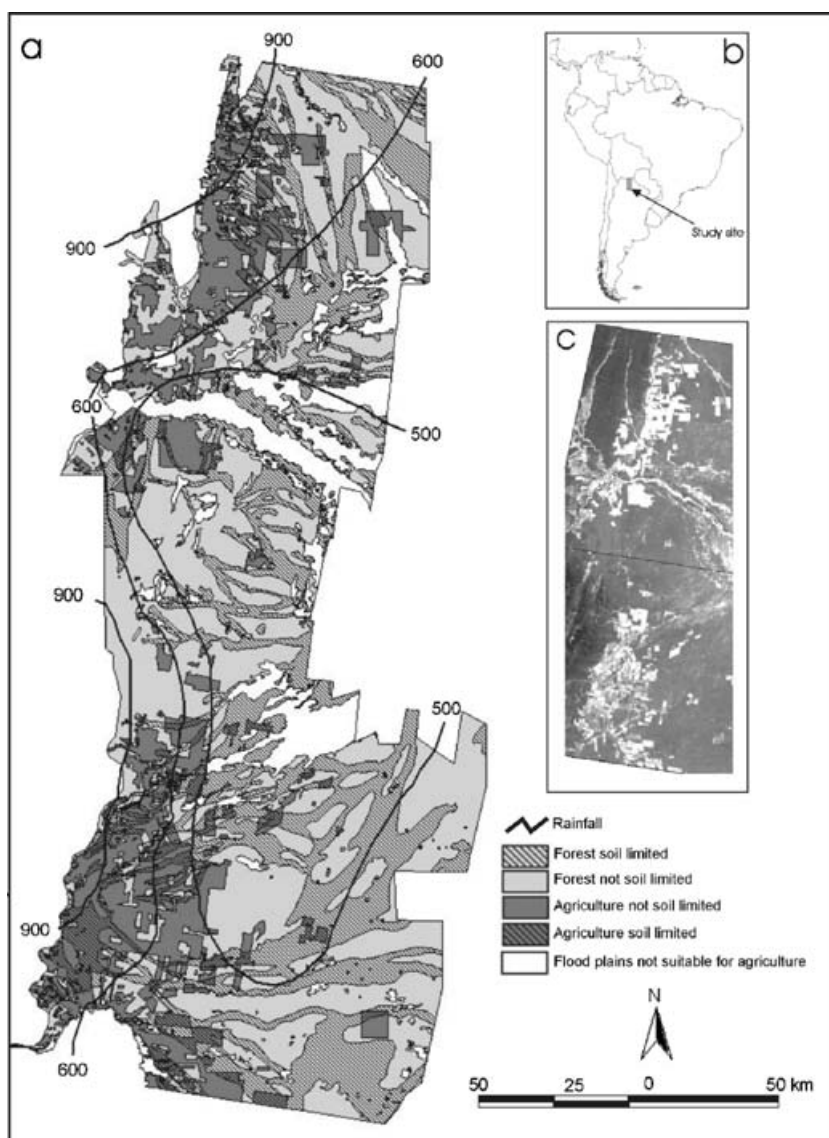

from national statistics, (2) per hectare yield and costs based on literature, and (3) gross domestic product as an index of domestic economic activity based on the literature.

We estimated deforestation rates during four periods: 1972/1975–1984, 1984–1989/92, 1989/92–1997 and 1997–2001. These periods include most of the agriculture expansion in the Salta province and differ in terms of socioeconomic and climatic factors potentially affecting soybean production. To quantify deforestation rates in the four periods we analysed images of five dates using Landsat MSS (multispectral scanner, 80×80 pixel resolution of 1972/1975) and TM images with a 30×30 m pixel resolution for the other four dates (Fig. 3). For three dates we used Landsat images 77 and 76 obtained on the same day: TM 30 September 1984; TM 27 April 1997; and ETM (enhanced thematic mapper) 4 August 2001. For the first and third date it was not possible to obtain cloud-free images in both sectors, so we used different scenes. The first date of analysis was based

on a 3 September 1972 (path 247, row 77) image for the southern sector and an 8 November 1975 (267, 76) image for the northern sector. For the third date, we used a TM image of 20 March 1989 for the northern sector, and a TM image of 29 February 1992 for the southern sector. The MSS image was resampled to a 30×30 m pixel, and the images of different dates were co-registered in the same map projection in order to standardize the computation of areas and conduct further analyses. Co-registration error was in all cases less than one 30×30 m pixel.

For each scene, land-cover types were screen-digitalized into two categories, namely forest and non-forest. Visual classification has shown some overestimation of deforestation in the Amazon rainforest because of positional inaccuracy and boundary generalization, but these types of errors are significant when deforestation occurs in patches <10 ha in areas with a high border-patch ratio. In our study area, deforestation has typically occurred in patches of 100–10 000 ha
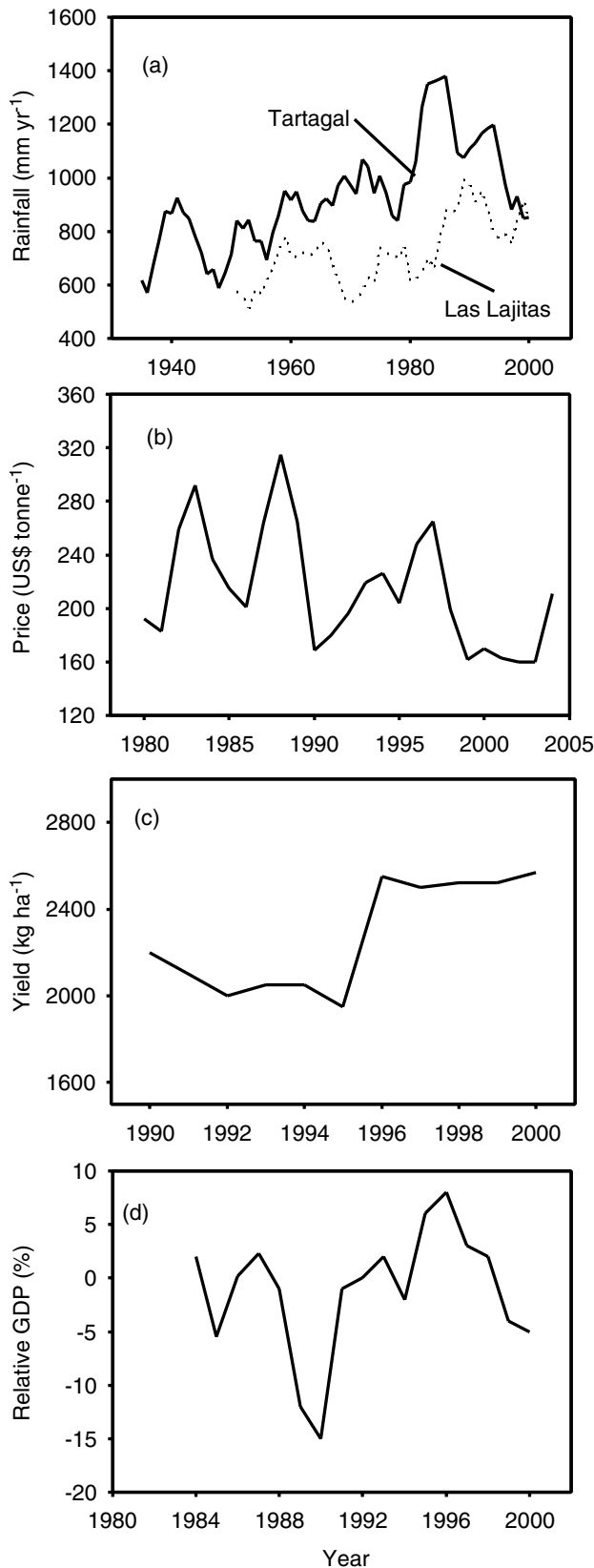
Figure 2 (*a*) Rainfall in Las Lajitas (southern sector) and Tartagal (northern sector) during the second half of the 20th century. (*b*) Average soybean price. (*c*) Soybean yield in Argentina. (*d*) Argentina's relative GDP annual growth.

and boundaries are clearly visible, therefore classification inaccuracies caused by border effects are likely to be negligible. Simple forest/non forest cover change has been estimated successfully, even in areas with more complex patterns of deforestation combining different images (see for example Skole & Tucker 1993; Alvarez & Naughton-Treves 2003.)

To assess classification accuracy, in August 2004 we conducted a ground survey of GPS (geographic positioning system)-located points. We classified 257 points along the complete latitudinal range of the study area, mostly in zones of agriculture expansion. Of the 117 points defined as forests in the field, 115 (98.3%) were correctly classified; and of the 140 agriculture sites, 121 (86.4%) were correctly classified. This yields an overall 92% accuracy. Most of the errors are likely a result of imperfections in the registration procedures (i.e. border errors), therefore our estimate of accuracy is probably conservative for the TM images because we sampled in areas where borders are more common, and errors are likely to decrease strongly into the continuous forest and continuous agriculture patches, which include most of the pixels in the images. We calculated relative deforestation rate (r = change in forest area in relation to remaining forest) following Puyravaud (2003).

To assess the spatial relationship between deforestation and environmental variables, and the potential for future soybean expansion in the region, we related the geographic distribution of present deforested areas with the distributions of the two main limiting factors for soybean cultivation, namely rainfall and soils. The study region was segregated into six rainfall sectors (<500, 500–600, 600–700, 700–800, 800–900 and >900 mm) based on the annual rainfall isoclines of Minetti (1999). Rainfall isoclines were incorporated into the GIS to calculate the percentage area of each rainfall sector that had been deforested by 2001. Based on the per cent of deforested area in each rainfall sector, we defined as 'rainfall-limited' those areas with less than 600 mm of annual rainfall. We used the digital soil map of Argentina to classify the region as limited or non-limited for agriculture use (INTA 1990). Finally, we calculated the total area and the deforested area in sectors with rainfall limitation, soil limitation, and without limitation.

RESULTS

The price of soybean (Bolsa de Comercio de Rosario 2004) in 1984 was higher than during the previous years, and it reached the maximum value in 1988. During the 1990s, the price was lower, with the steepest decrease occurring between 1997 and 1999 (Fig. 2*b*), coinciding with the transition between the third and fourth periods analysed in this study. Production costs prior to 1997 were approximately US$ 245 ha^{-1}, but in 1997 they dropped to US$ 220 ha^{-1} with the introduction of glyphosate-resistant transgenic cultivars that save expenditure in soil tillage (Perez *et al.* 2002; Perez & Gonzáles Lelong 2003). Since the 1970s, soybean yield has increased as a result of technological improvement. Between 1990 and 2001, the
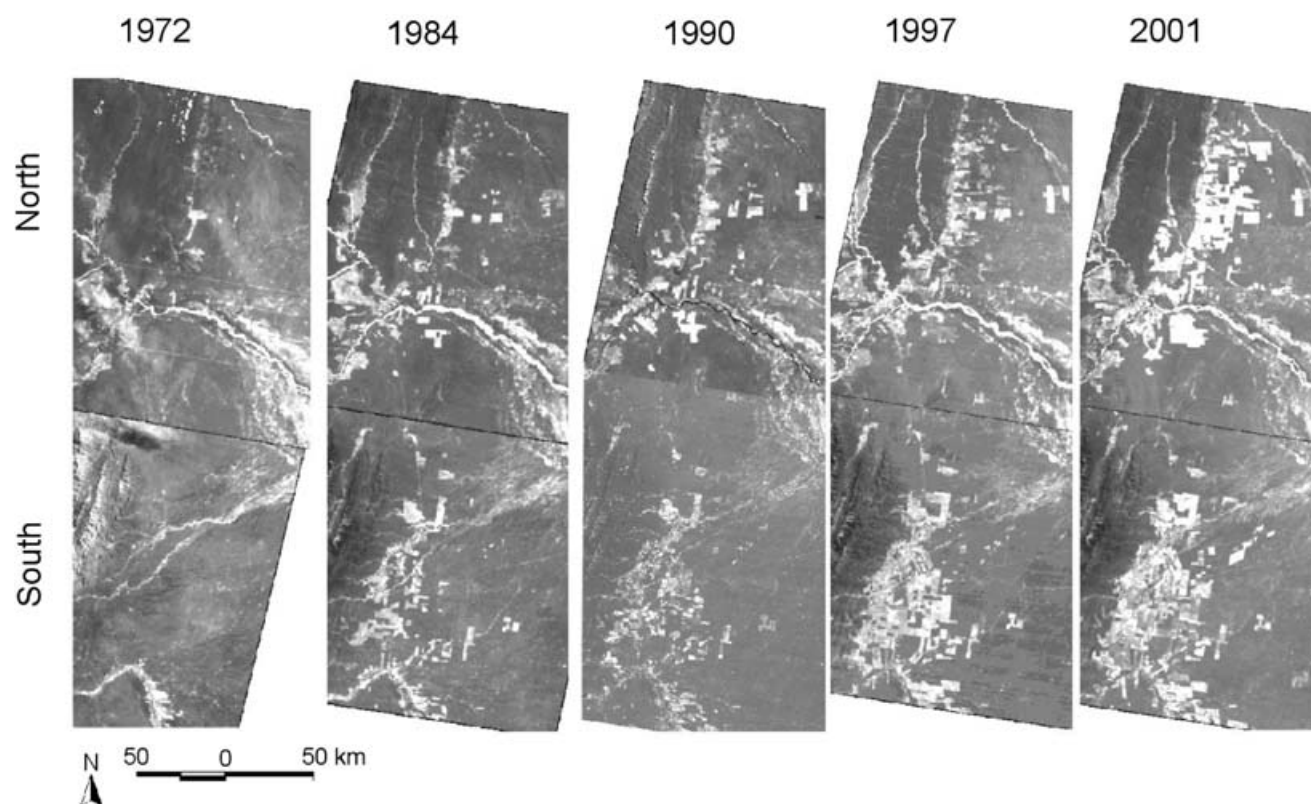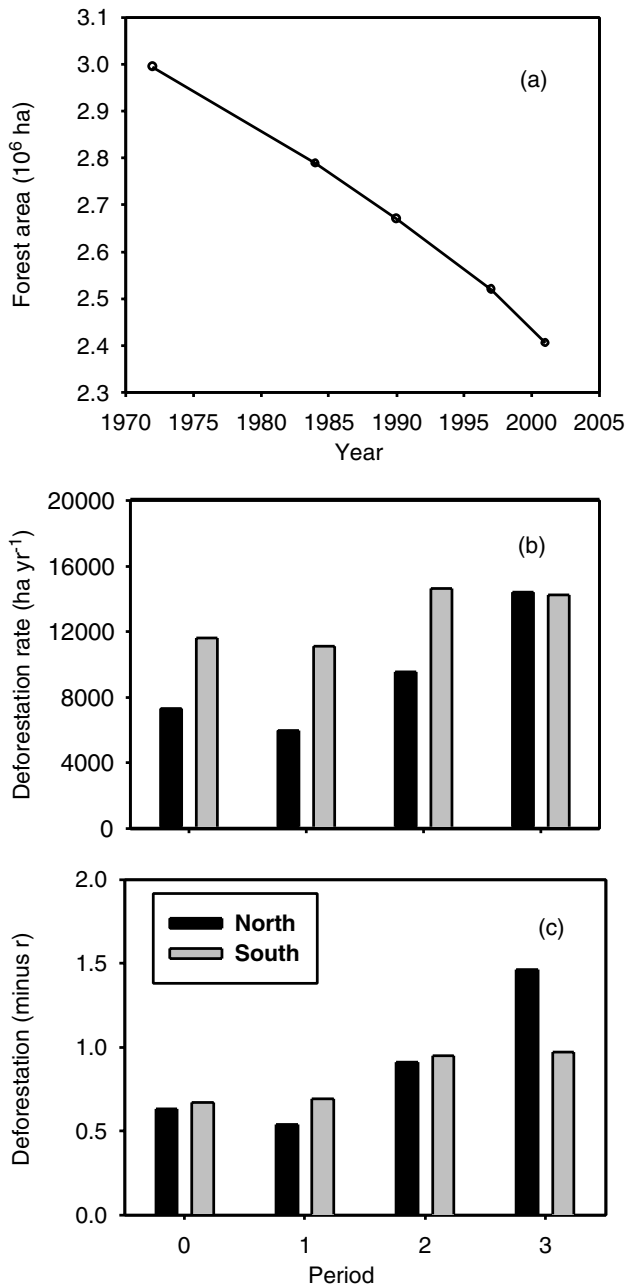
Figure 3 Landsat images showing the cover of forest (dark areas) and non forest (agriculture, light areas) for 1972–1975 (MSS), 1984, 1989–1992, 1997 and 2001 (TM).

main contribution to this trend was the >20% increase that occurred in 1996 (i.e. at the end of the third period analysed in this study), because of the incorporation of transgenic cultivars (Fig. 2c; Lebed 2002). The domestic economy varied widely during the study period during which soybean expanded. Between 1984 and 1990, gross domestic product (GDP) was low and decreasing. This trend reverted between 1990 and 1997, reaching one of the highest historical values. After 1998, it started decreasing again (Fig. 2d; Stutzeneger 2003).

At the beginning of the study period (1972/1975), only 57 000 ha were deforested (Fig. 3). By 1984, 262 450 ha were deforested, and between 1984 and 2001 an additional 383 450 ha were deforested (Fig. 4a). This adds up to 645 900 ha deforested at the end of the study, 588 900 ha during the study period (c. 20% of the study area). The deforestation rate (slope of the curve in Fig. 4a) has accelerated through time, reaching 28 600 ha yr^{-1} between 1997 and 2001. The northern and southern sectors differed both in the magnitude and the temporal pattern of deforestation (Figs 3 and 4). The southern sector experienced greater deforestation; it already had a relatively high rate in the 1970s, the deforestation rate increased between 1991 and 1997, and it remained relatively stable after 1997. The northern sector showed an accelerating deforestation rate (Fig. 4b). Deforestation rates relative to the remaining forest area showed the same pattern, but more marked in the northern sector, where the deforestation was larger in relation to the remaining forest (Fig. 4c).
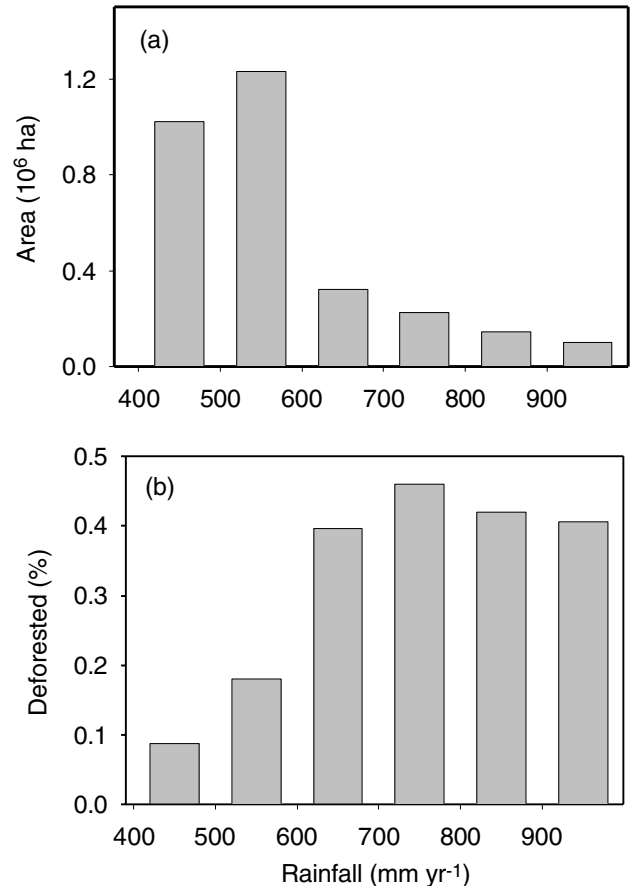
More than 70% of the study area falls below the isocline of 600 mm of mean annual rainfall (Fig. 5a), and deforestation was lower in these drier areas. Sectors with more than 600 mm annual rainfall have lost close to 40% of their forests, while sectors with less than 600 mm annually, have lost less than 20% (Fig. 5b). Deforestation was proportionally greater in areas without soil or rainfall limitation (Figs 1 and 6), but the differences in deforestation between areas classified as soil-limited and non-soil-limited were not dramatic. More than 50% of the total area without limitation is still covered by forest (Fig. 6c), particularly in the northernmost areas where the rainfall isoclines extend towards the east, indicating a larger area with rainfall above 600 mm per year in flat terrains that have not been deforested (Fig. 6a). The percentage of deforested area in the different limitation categories was higher in the southern than in the northern sector. Soil limitation showed a minor effect as a barrier for deforestation, and in the southern sector, almost all the area with soil limitation but not rain limitation was deforested (Fig. 6b). Areas with rainfall limitation had much lower deforestation, which is apparent in the large remaining forests in the eastern side of the study area (Figs 1 and 3). Most of the remaining forests (80.1% of the 2 405 400 ha) occurred in areas classified as rainfall-limited or rainfall-and-soil-limited, but these areas have not been immune to deforestation; 301 000 ha, 46% of the total agriculture area, occurs in sectors classified either as rainfall- or rainfall-and-soil-limited.

Figure 5 (*a*) Area, and (*b*) per cent of area that was deforested by 2001 in sectors with different mean annual rainfall.

Figure 4 (*a*) Area of remaining forest in the complete study region during the study period. (*b*) Annual deforestation rate in the two subsectors during the four periods analysed: (0) 1972/75–1984, (1) 1984–1989/92, (2) 1989/92–1997, and (3) 1997–2001. (*c*) Relative deforestation rate in relation to remaining forest in the four periods and the two subsectors.

DISCUSSION

Soybean expansion is a major cause of deforestation in tropical areas of Brazil, Paraguay and Bolivia (Fearnside 2001; Kaimowitz & Smith 2001). Following the continental trend, soybean is rapidly expanding in Argentina. Our study documents the magnitude and temporal dynamics of the defore-

station process in one sector of the agriculture frontier, namely the north-western boundary of the Semi-arid Chaco in the province of Salta. Deforestation is accelerating (Figs 3 and 4), reflecting a trend also occurring in other Argentine provinces such as Chaco and Santiago del Estero (Grau *et al.* 2005). Despite the comparatively small study area, our estimates of annual deforestation represent approximately 1.5% of the annual deforestation in the entire Amazon region (Laurance *et al.* 2001), an area 1200 times larger.

The initial agricultural expansion in the southern sector was first because of the cultivation of black beans during the 1970s and early 1980s. The high rate of agriculture expansion registered in our study in the second half of the 1980s can be attributed to the introduction of soybean in the region, and the increasing profitability of soybean during the 1980s as a result of three factors, namely high rainfall, high prices and gradually increasing yields (Fig. 2). Deforestation has been more extensive in areas with higher rainfall (Figs 1 and 6), suggesting that climate has partially limited agriculture expansion (Minetti & Lamelas 1997; Minetti & Vargas 1997). These patterns are consistent with previous studies in the
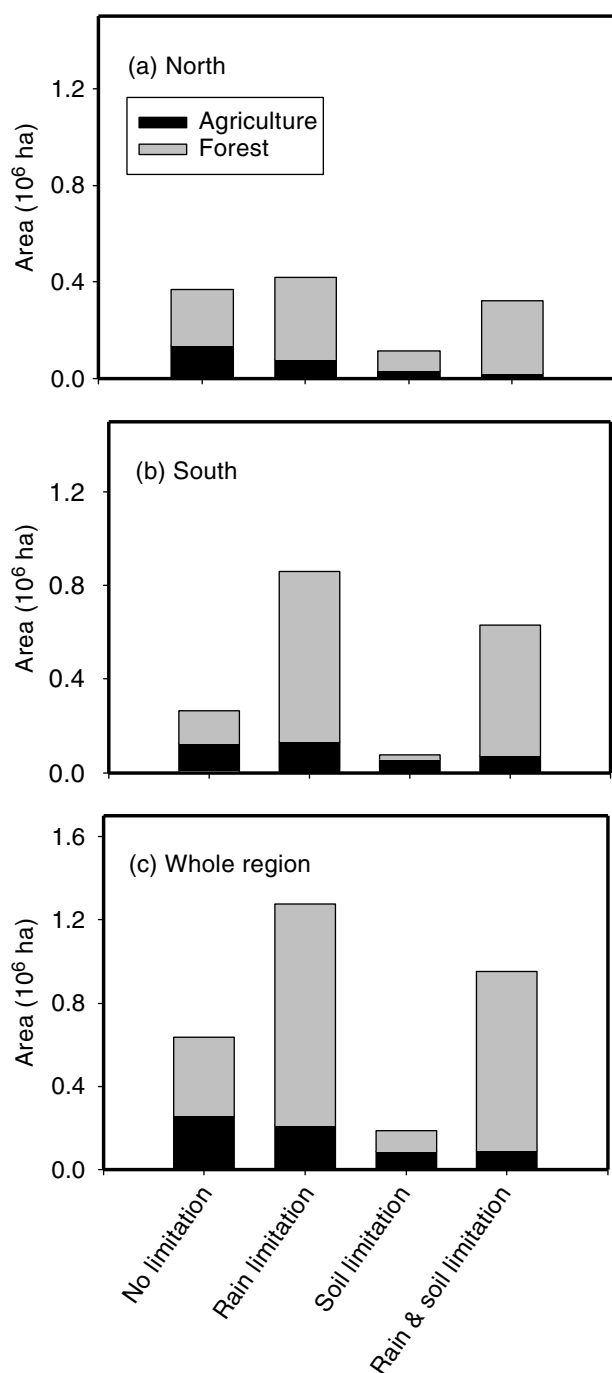
Figure 6 Area of forest and agriculture in 2001 in the different categories of limitation: no-limitation, rainfall limitation (<600 mm yr^{-1}), soil limitation, rainfall and soil limitation. (*a*) Northern sector, (*b*) southern sector, and (*c*) whole region.

province of Tucuman, where soybean expansion started during the 1970s (Minetti & Lamelas 1997), and suggest that the areas without rainfall limitation (approximately 300 000 ha, mostly located in the northern sector; Fig. 6) are likely to be deforested rapidly.

The environmental limitations to agricultural expansion are not strict, and a significant proportion of the recently defor-

ested areas occurs in sectors with some edaphic or climatic limitation (Figs 1 and 6). Deforestation accelerated later in the northern sector despite this sector being characterized by higher rainfall (Figs 3 and 4); this was probably caused by a later development of the local infrastructure or realization of the profitability of the crop by local land owners. Despite the decreasing prices and rainfall between 1990 and 1997, deforestation remained almost constant in the southern sector (Fig. 4*b*). Once a crop becomes a major economic activity, it generates conditions which favour its persistence. For example, Fearnside (2001) documented that soybean expansion in Brazil promoted more research on soybean agronomy, infrastructure development and economic-political power to promote risk-reducing policies such as inexpensive credits during years of low production or profitability. Similar factors may explain the relative constant deforestation rate in the southern sector during the 1990s, despite the deterioration in climatic and economic conditions. The huge current importance of soybean for the Argentine economy (Grau *et al.* 2005) is likely to be stimulating measures to ensure stability under unfavourable years. For example, by subsidizing a low peso: dollar ratio since 2002, the Argentine government is reducing the vulnerability of soybean companies to fluctuations in the exchange ratio. This pattern suggests that only conditions unfavourable in the long term for soybean production may stop or significantly reduce deforestation.

Despite the Argentina economic crisis reflected in the low relative GDP and the continuing low international prices (Fig. 2), deforestation accelerated after 1997 (Figs 3 and 4) because of the incorporation of transgenic cultivars which increased yields and reduced production costs (Lebed 2002; Perez *et al.* 2002; Perez & Gonzáles Lelong 2003). Our results in north-west Argentina support the model of Angelsen and Kaimowitz (2001) that relates technological changes to deforestation. Specifically, they predicted that yield-increasing and labour-saving technology would increase deforestation, especially if the crop was planted extensively (for example maize, wheat and soybean) rather than intensively (for example coffee and fruits). Another important factor promoting agriculture expansion is access to international markets, which often results in more stable demand and prices. In north-west Argentina, soybean cultivation has caused extensive deforestation by combining a yield-increasing trend, labour-saving technology and access to a large international market (for example China and the European Union).

Roads construction has been reported as a main factor favouring tropical deforestation (Fearnside 2001; Nepstad *et al.* 2001; Geist & Lambin 2002), but it does not seem to be very important in our study region. All national and provincial roads were already built at the beginning of our study period. Road paving was most active during the early 1990s when deforestation did not increase. Many local minor roads where built during the study period, but these were mainly a consequence of the agriculture expansion rather than an external cause.

CONCLUSIONS

Global factors (technological development and international prices) are the main drivers of soybean expansion (Fearnside 2001; Kaimowitz & Smith 2001; Grau *et al.* 2005). In climatically-marginal areas such as the semi-arid Chaco; increasing rainfall is an additional driver. Compared with such global factors, local economy plays a relatively irrelevant role, contrary to what has been suggested for other areas (see Fearnside 1993; Coomes 1996; Geist & Lambin 2002; Laurance *et al.* 2002; Alvarez & Naughton-Treves 2003). However, as the local importance of the crop increases, local institutions may develop ways to reduce the vulnerability of the economic activity to negative trends, stabilizing the deforestation trend that could only be balanced by conservation policies.

The Semi-arid Chaco is the largest continuous forest south of 15º S, and it may represent the largest extratropical carbon stock in the southern hemisphere. If the global effects (climate, markets and transgenic cultivars) continue the current trends, a large proportion of this biome is likely to be deforested in the coming decades unless strong conservation actions are taken.

ACKNOWLEDGEMENTS

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