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PROFILE

What Drives Accelerated Land Cover Change in Central Argentina? Synergistic Consequences of Climatic, Socioeconomic, and Technological Factors

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Abstract Synergistic combinations of climatic and land use changes have the potential to produce the most dramatic impacts on land cover. Although this is widely accepted, empirical examples, particularly involving deforestation in Latin America, are still very few. The geographic extent and causes of deforestation in subtropical seasonally dry forests of the world have received very little attention. This is especially true for the Chaco forests in South America, which are being lost at an alarming rate, sometimes higher than those reported for tropical forests. On this basis, the aims of this study were to analyze the changes in land cover that have occurred during the last three decades of the 20th century in the Chaco forests of central Argentina, and to explain the factors that have driven those changes. Results show major land cover changes. Approximately 80% of the area that was originally undisturbed forest is now occupied by crops, pastures, and secondary scrub. The main proximate cause of deforestation has been agricultural expansion, soybean cultivation in particular. This appears as the result of the synergistic convergence of climatic, technological, and socioeconomic factors, supporting the hypothesis of a multiple-factor explanation for forest loss, while providing one of the very few existing analyses of changes in subtropical forests of the world.

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There is increasing recognition that land use change, through its impacts on land cover, is one of the global change drivers expected to have the largest impact on biodiversity by the end of the 21st century (Sala and others 2000; Foley and others 2005; Millennium Ecosystem Assessment 2005). Land use practices such as deforestation, grazing, and agriculture affect ecosystem structure and functioning and regional climate (Vitousek and others 1997; Baron and others 2000; Chapin and others 2000). There is also increasing acceptance that changes in land use and climate interact in complex ways, producing negative and positive feedbacks, so that their ecosystem consequences are not always easily predictable (McCarthy and others 2001; Peters and others 2004; Millennium Ecosystem Assessment 2005; Rudel and others 2005). For all these reasons, understanding land cover change and accounting for land use practices with greater geographic precision, especially in some understudied regions of the world, is highly desirable (Turner and Meyer 1994; Geist and Lambin 2002; Ramankutty and others 2002; Zak and others 2004).

One of the primary causes of change in land cover is deforestation and agricultural expansion, but the factors (both proximate—human activities that directly affect the environment, so constituting proximate sources of change—

and underlying driving forces—fundamental social processes that underpin the proximate causes and either operate at the local level or have an impact from the regional or global level) driving forest decline are still under debate (Angelsen and Kaimowitz 1999; Geist and Lambin 2002; Lambin and others 2003). Population growth is considered a major driving force, mainly in tropical underdeveloped countries (Allen and Barnes 1985; Southworth and Tucker 2001; Laurance and others 2002), but Angelsen and Kaimowitz (1999) suggest that population growth is not the only (not even the major) cause of forest cover decline. Cattle ranching through pasture creation (Fearnside 1993), cropland expansion (Noble and Dirzo 1997; Fearnside 2001; Zak and Cabido 2002), socioeconomic factors (Mertens and others 2000; Sunderlin and others 2000), technological factors such as agrotechnological changes (Kasperson and others 1995), urbanization (Morello and others 2000; Marzluff and Hamel 2001; McKinney 2002), pests, fires, atmospheric pollution, and extreme events such as storms (Fearnside 1995; Cochrane and Schulze 1999; FAO 2001) have alternatively been mentioned as causes of forest decline. Geist and Lambin (2002) concluded that deforestation, at least in the tropics, is determined by different combinations of proximate causes (direct drivers such as agricultural expansion and wood extraction) and underlying driving forces (indirect drivers, for example, demographic factors such as population growth and economic factors such as increased local or international demand for commodities) in different geographical and historical contexts.

In recent years, climatic change has been recognized as a major driver of land use and land cover change. In particular, synergistic combinations of climatic change, including shift in average values and extreme events, and land use changes have the potential to produce the most dramatic impacts on land cover (McCarthy and others 2001; Fischlin and Midgley 2007; Magrin and Gay García 2007; Sivakumar 2007). Although this is widely accepted, the empirical examples, particularly involving deforestation in Latin America, are still very few.

While considerable effort has been focused on the study of deforestation in the tropics (Rudel and Roper 1996; Laurance and others 2001; Achard and others 2002; Geist and Lambin 2002; Benhin 2005), the magnitude, geographic extent, and causes of deforestation in subtropical seasonally-dry forests of the world have received much less attention. This is especially true for the Chaco subtropical forests in South America (Janzen 1988; Redford and others 1990; Mooney and others 1995; Pennington and others 2000), formerly representing the most extensive seasonally-dry forest in the continent and one of the least disturbed worldwide (Hannah and others 1994; Moglia and Giménez 1998; Tálamo and Caziani 2003). However, Chaco forests are at present being lost at an alarming rate (Steininger and others 2001; Zak and others 2004), sometimes higher than those reported for some tropical forests (Steininger and others 2001; Achard and others 2002).

Before the Spanish occupation, the Chaco region was covered by primary forests and woodlands, alternating with patches of grasslands maintained through traditional management by Amerindians, who used fire in their hunting practices (Bucher 1982). This balance between woody and herbaceous vegetation was disrupted when Europeans occupied the region and selectively cleared the forest for extensive livestock raising, a practice that has continued for more than four centuries (Morello and Saravia Toledo 1959; Schofield and Bucher 1986; Díaz and others 1994). The construction of the railway toward the interior of the Chaco region during the early 20th century was accompanied by intense logging (Sayago 1969; Díaz and others 1987; Natenzon and Olivera 1994). More recently, agricultural expansion, including intensified cattle raising and annual crops, has further accelerated deforestation.

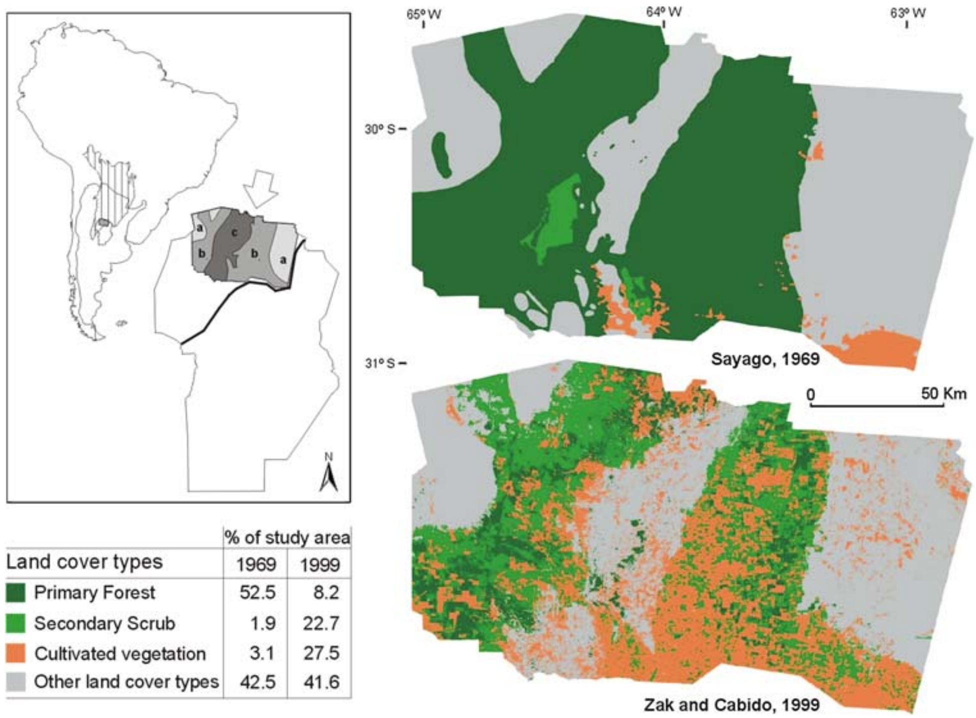
The aims of this article are to analyze the changes in land cover that occurred during the last three decades of the 20th century in the Chaco subtropical xerophytic forests of central Argentina, and to explain the factors (both proximate causes and underlying driving forces) that have driven those changes. In order to assess land cover change, we compared an old paper map with a recent satellite-derived map, while to understand the factors that have driven such change we used climatic and socioeconomic data.

Methods

Study Area

The study area comprises about 27,000 km^2 in the northern portion of Córdoba Province in central Argentina (Fig. 1). It is part of the Great Chaco, one of the largest ecosystems in South America and one of the most extended seasonally-dry forests in the world. The climate in the study area is warm temperate to subtropical, with a mean annual temperature increasing from 18.6°C in the east to 19.9°C in the west. Rainfall is mainly concentrated in the warm season and decreases from east to west from >700 to <500 mm·yr^{-1} (Zak and Cabido 2002).

A north-to-south mountain range (700 to 1800 m a.s.l.) divides the study area into two portions, both occupied by plains filled by deep Quaternary sediments. The northwestern and eastern parts of the area are occupied by saline depressions where edaphic conditions preclude agriculture. The potential vegetation is a seasonally dry forest with a tree canopy dominated by *Aspidosperma quebracho-blanco* Schlecht. (*quebracho blanco*; Apocinaceae) and *Schinopsis lorentzii* (Cris.) Engl. *(quebracho colorado*;



Land cover types	% of study area 1969	1999
Primary Forest	52.5	8.2
Secondary Scrub	1.9	22.7
Cultivated vegetation	3.1	27.5
Other land cover types	42.5	41.6

Fig. 1 Upper left: location of the study area (indicated by an arrow) in the northern territory of the Córdoba Province, central Argentina, within the Great Chaco. Letters identify three distinct environments: a, saline depressions; b1/b2, western and eastern lowlands; c, mountains. Lower left: keys to land cover types and their percentage cover in 1969 and 1999. Right: land cover changes in the study area between 1969 and 1999

Anacardiaceae). Vegetation cover in the mountain range varies with altitude, with a zonation from mountain woodlands on lower slopes to mountain scrubs and mountain grasslands on the highest slopes and plateaus. Further descriptions of the vegetation in the study area are given by Sayago (1969) and Zak and Cabido (2002).

Analysis of Land Cover Changes

The changes in land cover that occurred during the last three decades of the 20th century were estimated by comparing a digitally scanned 1969 paper map based on two decades of intensive field work (Sayago 1969) and a 1999 digital map based on Landsat TM data and fieldwork (Zak and Cabido 2002) as described by Zak and others (2004). The map by Sayago (1969) provides a unique and reliable record of the vegetation cover of the study area in the 1950s and 1960s with an outstanding level of detail. The 1999 map was obtained through the classification of two Landsat 5 TM images (Path/Row: 229/081 and 230/081) and showed an overall accuracy of about 83% and an accuracy of >90% for all nonmountainous classes (see Zak and Cabido [2002] for further details on the construction of the digital map and its accuracy assessment).

Analysis of Proximate Causes and Underlying Driving Forces

The analysis of factors causing land cover changes considered both proximate causes (agricultural expansion and logging) and underlying driving forces (changes in biophysical, socioeconomic, and demographic factors). Data on changes in cultivated area and livestock numbers were provided by the Córdoba Department of Agriculture (Secretaría de Agricultura, Ganadería y Alimentación; SAGyA); records of wood extraction were obtained from the National Department of Sustainable Development (Secretaría de Desarrollo Sustentable y Política Ambiental) and records kept by the Córdoba Environmental Agency (Agencia Córdoba Ambiente) and completed on the basis of Sayago (1969) and Natenzon and Olivera (1994). Climatic data were extracted from long-term records gathered by the Córdoba Department of Hydrology (Dirección Provincial de Hidraúlica) and the National Railway Administration (Ferrocarriles Argentinos). Demographic data were obtained from the National Census Bureau (Instituto Nacional de Estadísticas y Censos; INDEC), while the size and number of farms were provided by the INDEC and the SAGyA. For all factors all available data for the area from all sources were used.

Results

Land Cover Changes

Strong land cover changes took place during the period 1969–1999, with a dramatic spread of croplands at the expense of the eastern and western Chaco forests and mountain woodlands (Table 1, Fig. 1). However, the

Table 1 Total cover changes of Chaco subtropical xerophytic forests, cultivated vegetation, and other land cover types[a] in the study area between 1969 and 1999

Land cover units	Total cover (ha)	
	1969 map	1999 map
Eastern Chaco Forest	554,800	57,900
Western Chaco Forest	638,600	150,800
Mountain Chaco Forest	228,800	13,700
Secondary scrub	50,600	614,200
Cultivated vegetation	83,600	746,000
Other land cover types	1,155,200	1,129,000

[a] Other land cover types include mountain shrublands, palm savannas, halophytic shrublands and grasslands, bare soils, and water

composition of forest relicts did not show noticeable differences from the composition of forest communities as described by Sayago (1969), with the only exception the almost-complete disappearance of the tannin-rich *Schinopsis lorentzii* as a consequence of selective logging. Other land cover types, such as halophytic vegetation, have also undergone changes of different magnitude (see Zak and others [2004] for a detailed description) but their analysis exceeds the purpose of this study.

A considerable proportion of the forests and woodlands has been converted to secondary forests and scrubs, which are the product of both selective logging of primary forests and the regrowth of impoverished forests after fire, pasture, or agricultural abandonment. The most dramatic pattern arising from the comparison of the 1969 and 1999 maps is the steep increase in cultivated lands, occurring almost entirely within the lowlands, from just above 3% to almost 30% of the study area, so representing an increase of more than 790%. During the 30-year period analyzed, the total forest cover decreased from 52.5% to 8.2% of the study area. This means a deforestation rate of about 2.8% per year, with a total of ca. 1.2 million hectares of lowland forest and mountain woodlands eliminated. The observed land cover changes were different in the eastern and western sides of the mountains. The eastern plains showed a larger forest reduction (with 21,495 patches to the western side of the mountain range and 5852 to the eastern side) and a higher degree of fragmentation (with 18,100 ha for the largest western patch and 4500 ha for the eastern one).

Causal Factors of Deforestation

Proximate Causes

Logging for nonagricultural purposes, such as the extraction of firewood and timber and clearing for natural pastures, has occurred throughout the period studied. For example, the National Department of Sustainable Development (unpublished data) recorded an extraction of 1,092,038 tons of firewood and timber between 1991 and 1999. However, agricultural expansion has been the most important proximate cause of deforestation in the study area between 1969 and 1999. This agricultural expansion has been accounted for mostly by conversion of forest into annual crops, especially during the last decade of the 20th century (Fig. 2). This agricultural expansion contributed to the national total exports of grains, which increased from 7,153,113 tons in 1960 to 49,002,715 tons in 2002, while soy exports increased from 76,913 to 6,170,630 tons during the same period (Bolsa de Cereales 2003). The study area provided 2.3% of the national production during the period, with an average yield of 2 939 kg $\cdot$ ha^{-1}$\cdot$ year^{-1}, compared to 2630 kg $\cdot$ ha^{-1} $\cdot$ year^{-1} at the national level (SAGyA, unpublished data).

Conversion to pasture played an important role until the 1980s but then decreased sharply (Fig. 2). During the period analyzed, cattle raising increased, but all other livestock items decreased markedly (Fig. 3).

Underlying Driving Forces

Which have been the driving forces underlying the agricultural expansion that caused the land use changes documented above? We analyzed changes in climate, local and regional human population, markets, and technology.

Climate changes: There has been a continuous increase in annual rainfall in the eastern plains during the second half of the 20th century (with an average increase of

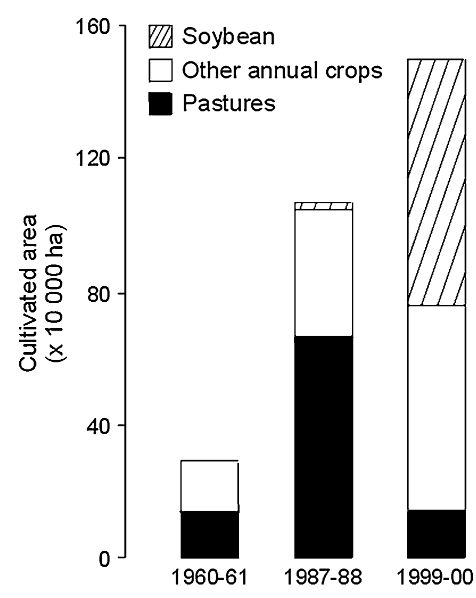


Fig. 2 Changes in cultivated area for three periods between 1960 and 2000. Please note that these data (the only available) correspond to an area slightly larger than the study area. Data provided by the Córdoba Department of Agriculture

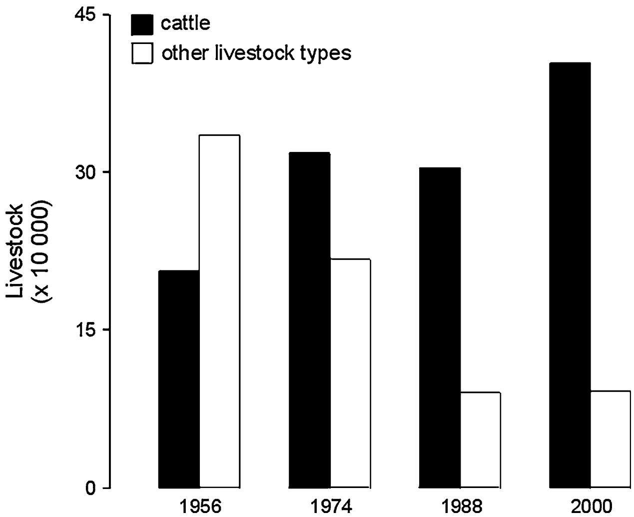


Fig. 3 Livestock in the study area between 1956 and 2000. Black bars represent cattle, while white bars represent all other livestock types (goats, sheep, horses, mules, pigs). Data provided by the Córdoba Department of Agriculture

126 mm in annual rainfall during the period). In contrast, no significant change was detected in the western plains (Figs. 4 and 5).

Demographic changes: The human population of the study area remained relatively constant during the study period (Fig. 6; left *y*-axis), representing an increasingly lower proportion of the population of Córdoba Province (Fig. 6; right *y*-axis). This was accompanied by a depopulation of rural areas. This rural depopulation of the study

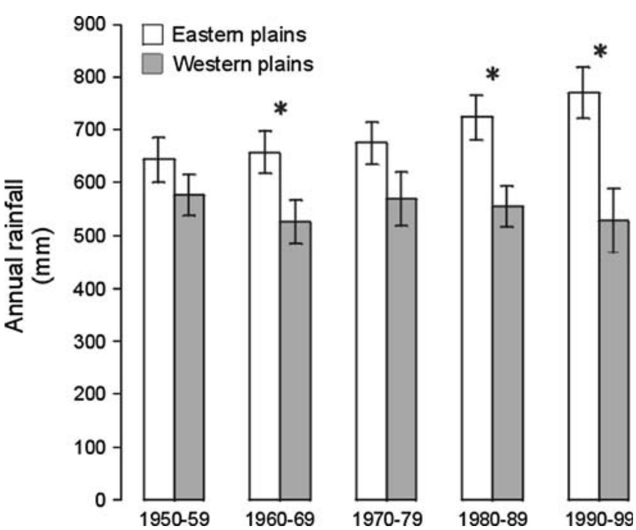


Fig. 4 Rainfall dynamics in the lowlands of the study area between 1950 and 1999. Values represent average rainfall (mm) for each decade. Standard error from the mean is also shown. Asterisks indicate significant differences ($P < 0.05$; Student's *t*-test) between annual rainfall in the eastern and western meteorological stations during the same decade. Data provided by the Córdoba Department of Hydrology and the National Railway Administration

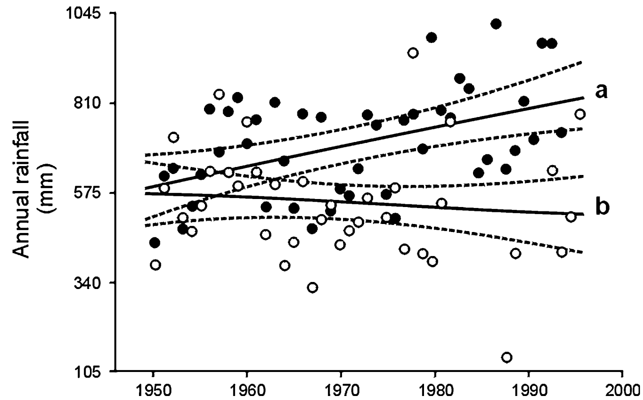


Fig. 5 Linear regression analysis of annual rainfall in two meteorological stations during the second half of the 20th century. Filled symbols, eastern plains; open symbols, western plains. Solid lines indicate linear fit, and dashed lines indicate 95% confidence intervals. (a) Eastern plains: slope = 5.04 mm · year^{-1}; $P = 0.0084$. (b) Western plains: slope = −1.33 mm · year^{-1}; $P = 0.4431$

area was associated with the concentration of the land in fewer hands. Data adapted from INDEC (1988) and SAGyA (1999) show a 32% reduction of small farms (properties of <200 ha).

National and international market changes: The sharp increase in the proportion of land devoted to crops in Northern Córdoba has been accounted for mainly by the increase in soybean cultivation since the 1990s (Fig. 2) that transformed Argentina to the third largest soybean producer in the world (2001). The growth of international soybean markets brought about an increased interest in soybean cultivation in the region. This caused a sharp increase in the price of land in the Pampas region, historically preferred for annual crops. As a consequence, it is

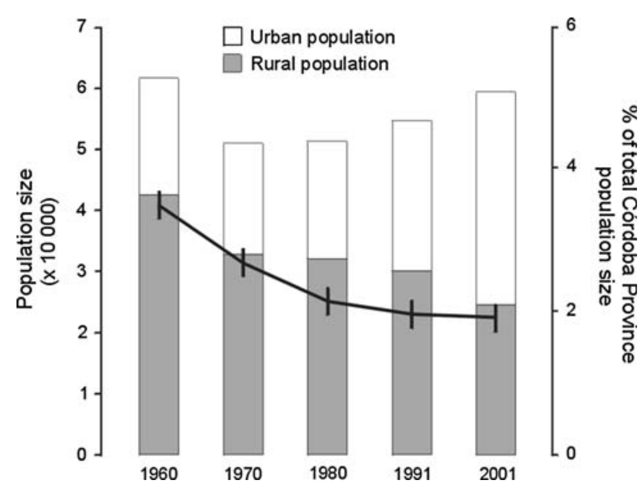


Fig. 6 Population dynamics of Córdoba Province and of the study area between 1960 and 2001. Both rural and urban populations are shown (bars), as well as the percentage of the total province's population represented by that of the study area (curve). Data provided by the National Census Bureau

likely that farmers expanded to more marginal areas, such as northern Córdoba, where land was less expensive (US $270 ha^{-1} in the study area, compared to US $2058 ha^{-1} in the Pampas region in 1990) (Sociedad Rural Argentina 1992; Bertolasi 2004).

Technological changes: Another important factor leading to the expansion of soybean cultivation in the study area, as well as in other formerly marginal agricultural areas, has been the development and wide implementation of zero-tillage (ZT) technology—virtually all soybean cultivation in the study area is under ZT. This technology opened areas previously closed to annual crops because of water restrictions. Soils under ZT have a higher infiltration rate and water storage capacity and lower runoff losses than tilled soils (Dardanelli 1998; Pengue 2000). The area under ZT in Argentina has increased from 5000 ha in 1977/1978 to 7,269,500 ha in 1998/1999 and 15,100,000 ha in 2001/2002 (Craviotti 2002; AAPRESID 2004).

In addition, the development of short-cycle varieties of transgenic soybean that can take maximum advantage of the wettest months, and of Roundup Ready (RR) technology, has also allowed the conversion to agriculture of otherwise unsuitable areas for agriculture.

Discussion

Changes in Land Cover

During the last three decades of the 20th century, the land cover changes in northern Córdoba, representing the southern extreme of the Great Chaco region, have been dominated by a replacement of forests by crops. Approximately 80% of the area that was originally undisturbed Chaco forest is now occupied by annual crops and improved pastures in the lowlands and by secondary scrub in both lowlands and mountains.

About 1.2 million ha of Chaco forest has been cleared since 1969, which implies a deforestation rate of about 2.75% · year^{-1} in the lowlands and 3.13% · year^{-1} in the mountains. To our knowledge, this is among the first estimates of deforestation rates for a subtropical seasonally-dry forest in South America. This loss rate is similar to those reported for many tropical sites. Achard and others (2002) have determined average annual rates of 0.52% for the period 1990–1997, with extreme records as high as 2.5%; rates within that range have been reported for other humid (Sunderlin and others 2000) and dry (Trejo and Dirzo 2000) tropical forests as well. Our findings, then, are in agreement with FAO (2001) estimates, which rank Argentina among the countries with the largest losses of forest cover during the 1990–2000 period, and the only nontropical country within the list.

Proximate Causes of Deforestation

Our findings show that the main proximate cause of deforestation in the study area in the last three decades of the 20th century has been agricultural expansion, soybean cultivation in particular. Logging for nonagricultural purposes appears as a secondary cause. This has been a constant throughout the 20th century (Díaz and others 1987), but its relative importance has decreased since the second half of the 20th century. Human-caused fires have also played a role in the reduction of forest land cover, but in the lowlands its importance has been secondary compared to that of agricultural expansion (according to unpublished data from the Córdoba Environmental Agency).

Underlying Factors

The agricultural expansion in the study area appears as the result of the synergistic convergence of climatic, technological, and socioeconomic factors. Worldwide, the expansion of agriculture has been related to these factors, acting alone or, more commonly, in combination. Among the socioeconomic factors, the most frequently mentioned are changes in human population density, land tenure structure, and land prices. In a review of 152 cases in tropical ecosystems of Asia, Africa, and South America, Geist and Lambin (2002) concluded that in 96% of the cases deforestation is associated with agricultural expansion, which in turn occurs as a consequence of economic, institutional, technological, sociopolitical, and demographic factors. However, in one-third of all cases, predisposing environmental causes such as land characteristics (soil quality, topography) or trigger events (droughts, floods) have played an important role. Our results in a nontropical ecosystem are in accordance with these global trends. Changes in the national and, especially, international markets and technological factors have played a strong role in determining the expansion of soybean cultivation in northern Córdoba. These alone would have possibly led to a considerable amount of deforestation. In 1969, Sayago mentioned that the extremely small area occupied by agriculture in the study area was due to the fact that it was too dry for viable crops. However, the development of ZT technology, and of RR soybeans, has allowed cultivation with acceptable yields on areas that would be too dry for more conventional agriculture, including the one under study (Dardanelli 1998). Still, our study indicates that changes in climate in the last decades of the 20th century have accelerated this expansion of soybean cultivation. As shown in Fig. 1 and Table 1, the conversion of forests into croplands has been more marked in the eastern plains, despite the fact that the accessibility to new technology and to markets has been similar in the eastern and western plains. The most likely factor behind these differences in deforestation therefore appears to be climatic. In the eastern plains there has been a significant increase in rainfall in the last decades of the 20th century, while no increase has occurred in the western plains (Figs. 4 and 5). Whether climate change has been a triggering agent or simply a concurrent factor in determining land cover change in the area cannot be established with certainty, but these differences between the two sides of the mountains are suggestive of an important role, most likely acting in synergy with technological and socioeconomic factors.

Among socioeconomic factors, the most important appear to be changes in the soybean and land markets and the resulting concentration of the land in fewer hands (Steininger and others 2001).

Local and regional population growth, often involved in deforestation processes in some other areas of the world (Geist and Lambin 2002; Laurance and others 2002; Vasconcelos and others 2002), have not played a relevant role in the deforestation of the study area, since the trend has been toward stabilization in general and depopulation of rural areas in particular. The increase in cattle raising within the study area, at the expense of other livestock types, is another indicator of the switch from a subsistence economy to a commercial one. This is part of the rural emigration process that has been occurring in northern Córdoba (Díaz and others 1987; Silvetti and Cáceres 1998) and in the Great Chaco in general (Morello 1983) since the 19th century, and has recently accelerated. In the past few years, large numbers of local inhabitants lost their land at low prices to sowing pools—agricultural mutual funds (Bertolasi 2004). As in many other forests in southern South America (Canziani and Díaz 1998), the socioeconomic factors driving land cover changes in central Argentina appear not to be internal population growth or higher level of consumption but, rather, external demands. For example, a similar expulsion of population to marginal areas as a consequence of soybean expansion has also been reported by Fearnside (2001) for Brazil.

Concluding Remarks

Evidence presented in this study suggests that no single factor can account for the changes in Chaco subtropical xerophytic forest cover in central Argentina. On the contrary, its dramatic deforestation is best explained by the synergistic effect of climatic, socioeconomic, and technological changes. These underlying factors have triggered agricultural expansion, which in turn appears to be the main proximate cause of forest loss.

Our analysis thus challenges single-factor explanations that put most of the blame for deforestation on human population growth and its ecological consequences, and highlights the importance of considering the nonlinear effects of the combination of climatic change and variability and land use change. As soybean expansion is approaching its limits in developed regions (Fearnside 2001), positive trends in annual rainfall such as that observed in the eastern plains of our study area may promote the expansion of croplands into otherwise inappropriate areas for agriculture. If the trend toward higher rainfall shifts, these marginal areas may undergo accelerated erosion processes, such as the “dust bowls” in America (Peters and others 2004) or similar processes experienced in the dry Argentine pampas in the first half of the 20th century (Suriano and others 1992). On the other hand, if climatic and economic trends reported in this paper remain unchanged, the next 50 years could bring a dramatic reduction of the remaining subtropical forests of the Great Chaco, as previously suggested by different authors for tropical areas of the world (Fearnside 2001; Tilman and others 2001; Defries and others 2002).

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