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Deforestation and precipitation patterns in the arid Chaco forests of central Argentina

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Abstract

Aims: (1) to compare two series of precipitation data from different periods (1930–1950 and 1950–2000) in three sectors of the southern dry Chaco in the arid and semi-arid sub-regions; (2) construct maps showing the distribution of land-cover units for 1979, 1999, 2004 and 2010 for the same three sectors; and (3) assess the changes in land-cover units occurred between 1979 and 2010 in the three sectors.

Location: Southern extreme of the dry Chaco in NE and NW Córdoba Province, central Argentina.

Methods: We compared annual and growth period (November–March) precipitation among the three sectors and between two series of data corresponding to different periods (1930–1950 and 1950–2000) using repeated measures ANOVA, with the station as the subject variable, period as the within-factor and sector as the between factor. Using three Landsat MSS (1979) and nine Landsat TM (1999, 2004 and 2010) images we mapped the distribution of eight land-cover units for the whole study area. For each sector (NE, NW and W), we performed a change detection analysis between 1979 and 2010.

Results: The classification of Landsat MSS and TM images resulted in reliable land-cover maps (overall accuracy 80%). Our results showed that vegetation cover in the area is highly disturbed and that the present status of vegetation cover differs among the three sectors. In the more humid sector, the land-cover changes have been dominated by replacement of closed forests by crops, while in the driest portion of the study area forest loss was not related to agriculture. Additionally, we found that significant increases in precipitation have occurred in all three sectors, but the increase was highest in the humid sector.

Conclusions: The differences observed among the three sectors suggest that precipitation may have effectively played a dominant role in the process of forest conversion to agriculture.

Introduction

Worldwide land-use and land-cover changes, primarily for agricultural expansion and timber extraction, have caused a net loss of 7–11 million km^2 of forest in the past 300 yr (Foley et al. 2005). Nearly 40% of the planet's ice-free land surface is now being used for agriculture, and much of this land cover has replaced forests, savannas and grasslands (Turner et al. 2007; Ramankutty et al. 2008). While the cultivated area in developed countries decreased nearly 1.3% from 1961 to 1999 (FAO 2001), it has increased by about 19% in the developing world, mainly in Asia and South America (Ramankutty et al. 2008). According to most projections, land-use and land-cover changes are likely to continue rapidly in the next decades (Tilman et al. 2001).

In South America, a continuous advance of the agricultural frontier into forest areas has been reported in the last few years (Eva et al. 2004). Although important tracts of forest are still intact, the extent and rates of deforestation in the Brazilian Amazon have led to a dramatic and well-documented forest retraction during the last decades (Fearnside 2001; Kaimowitz & Smith 2001; Laurance et al. 2001; Carreiras et al. 2006). Meanwhile, the loss and

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fragmentation of subtropical, seasonally dry forests and savannas has not received similar attention to tropical forests until recently (Zak et al. 2004, 2008; Grau et al. 2005a,b). In their land-cover map of South America, Eva et al. (2004) highlighted the increasing isolation and fragmentation of the Brazilian *cerrado* and *caatinga*, and of the *chaco* in southern Bolivia and northern Argentina.

The Great Chaco is a large region comprising more than 1 200 000 km^2 in Paraguay, Bolivia and Argentina. According to precipitation patterns, an eastern humid to sub-humid Chaco and a western dry semi-arid to arid Chaco may be differentiated in Argentina (Fig. 1). While the humid Chaco showed earlier expansion of both cattle grazing and agriculture since the beginning of the 20th century (Adámoli et al. 2004; Ginzburg & Adámoli 2006; Morello et al. 2006), it was not until the last decades that the dry Chaco forests were partially converted to agriculture, mainly due to the expansion of soybean cultivation (Grau et al. 2005a,b; Zak et al. 2008). Deforestation of seasonally dry Chaco forests has now been reported for almost all the provinces in northern Argentina: Tucumán and Salta (Grau et al. 2005a,b; Paruelo et al. 2005), Chaco and Formosa (Torrella & Adámoli 2006), Santiago del Estero (Boletta et al. 2006) and Córdoba (Zak et al. 2004, 2008). Only in the province of Córdoba, central Argentina, more than 1 000 000 ha of seasonally dry forests of the semi-arid Chaco were lost from 1970 to 2000, with deforestation rates similar to or even higher than those recorded for tropical forests (Zak et al. 2004).

Following the same trend reported for some other Latin American regions, the main driver of deforestation in the dry Chaco is the expansion of agriculture (Grau et al. 2005a,b; Zak et al. 2008). Technological factors such as the introduction of transgenic cultivars (Round-up ready technology), and the rise of international prices have been suggested as factors driving to recent soybean expansion into the Chaco forests (Grau et al. 2005a,b; Zak et al. 2008). On the other hand, Purcell et al. (2003) indicated that soybean yields vary considerably among locations and seasons. Much of this variation appears to be related to rainfall amounts during the growing season, indicating that this crop is strongly sensitive to precipitation in the study area. Supporting this, Grau et al. (2005a,b) and Zak et al. (2008) reported more intense deforestation in areas with higher precipitation, suggesting that soybean expansion may be more concentrated in areas without severe rainfall limitation. Additionally, for the southern extreme of the Chaco region, in Córdoba Province (Fig. 1), Zak et al. (2004, 2008) compared the 1950–1999 precipitation trends for data obtained from two meteorological stations located in the semi-arid and in arid dry Chaco. They found a significant increase in precipitation in the last three decades of this period only at the semi-arid (eastern) meteorological station, but not at the arid (western) one. Although the eastern sector has always been more humid, such an increase could have triggered the changes in land use, especially considering that precipitation of 500–600 mm during the growth period (November–March) is the minimum necessary to obtain profitable soybean crops (Dardanelli 1998; Andriani 2000, 2002). These results suggest that the increase in precipitation may play an important role, together with technological and socioeconomic factors, in the expansion of agriculture in the dry Chaco. Nevertheless, and since access to technology and

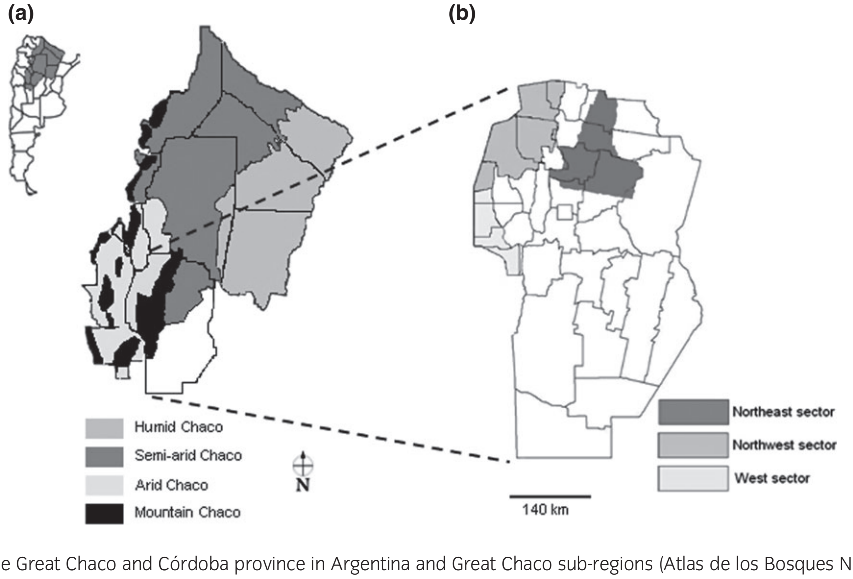

Fig. 1. (**a**) Location of the Great Chaco and Córdoba province in Argentina and Great Chaco sub-regions (Atlas de los Bosques Nativos Argentinos 2003). (**b**) Location of the three study sectors (northeast, northwest and west) in the Córdoba province.

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the influence of economic factors do not vary substantially between the arid and semi-arid portions of the southern Chaco, it is worth exploring how changes in precipitation patterns may differentially affect land-cover changes in the two sectors.

If the differential trends in precipitation between two meteorological stations in the semi-arid and arid Chaco plains are confirmed for larger areas, they could contribute to explain the differences in development of agricultural activity between the semi-arid and arid sectors of the whole dry Chaco. In this study, we expanded previous analyses of precipitation patterns and land-cover changes to the whole lowland Chaco of Córdoba Province. In this context, we aimed to: (1) compare two series of precipitation data from different periods (1930–1950 and 1950–2000) in three sectors of the southern dry Chaco involving the arid and semi-arid sub-regions; (2) construct maps showing the distribution of land-cover units for 1979, 1999, 2004 and 2010 for the same three sectors; and (3) assess the changes in land-cover units that occurred between 1979 and 2010 in the three sectors.

Methods

Study area

The study area is located at the southern extreme of the dry Chaco, to the northeast and northwest of Córdoba Province (Argentina) (Fig. 1a). The area was divided into three sectors, designated 'northeast', 'northwest' and 'west' (Fig. 1b). The first sector is located east of a mountain range (eastern semi-arid plain), while the other two occupy the western arid plain, west of the same range (Fig. 1b). The area belongs to the Chaco Phytogeographical Province (Cabrera 1976): its lowlands were formerly dominated by *Aspidosperma quebracho-blanco* (white quebracho) and *Schinopsis lorentzii* (red quebracho) subtropical seasonal forests. At present, the non-cultivated area is covered mostly with secondary semi-deciduous forests and shrublands, alternating with patches of old-growth forests and open shrublands. To both the northwest and northeast of the area saline depressions occur, where succulent shrublands dominate. The plant communities in the arid and semi-arid Chaco of Córdoba are known in detail from the works of Sayago (1969), Cabido et al. (1992, 1993) and Zak & Cabido (2002). In this area, water shortages were formerly a major constraint to agricultural development (Sayago 1969; Steininger et al. 2001). Precipitation in the study area mainly occurs in the summer, between November and March. Previous studies of Zak et al. (2004, 2008) based in only one meteorological station located in the northeast part of the area, showed that precipitation increased from 650 to 750 $\mathrm{mm \cdot yr^{-1}}$ between 1970 and 1999. However, data from another meteorological station located in the drier northwest area (440 $\mathrm{mm \cdot yr^{-1}}$), showed no significant increase in precipitation during the last decades.

Precipitation data

To compare precipitation patterns between periods for the three sectors, we used two series of data. First, we used unpublished data from 31 meteorological stations provided by the Córdoba Department of Hydrology (Dirección Provincial de Hidráulica) and the National Railway Administration (Ferrocarriles Argentinos): 15 corresponded to stations located in the northeastern area, 14 to the northwestern area and two to the western area. Each station provided monthly and annual averages for 2–20 yr (average 12) within the 1930–1950 period. Second, we used a series of data from Worldclim (http://www.worldclim.org) for the period 1950–2000. Worldclim information provides average data for a 50-yr period (1950–2000) of monthly precipitation, with a resolution of 1 $\mathrm{km^2}$, which was obtained by interpolation from weather stations with sufficient available data (Hijmans et al. 2005). In this case, we used data from the same geographic locations corresponding to the 31 meteorological stations. Most meteorological stations in the area were deactivated after 1970, and the Worldclim data became the only source of precipitation data available. Unfortunately, precipitation records are not available for the study area after 2000.

We compared annual and growth period (November–March) precipitation among the three sectors and between the two series of data (1930–1950 and 1950–2000) using repeated measures ANOVA, with station as the subject variable, series (period) as the within-factor, and sector as the between factor. When necessary to meet statistical assumptions of normality and homoscedasticity, we performed power transformations (order 2 or 3). Additionally, and in order to further explore whether the expansion of soybean cultivation is related to the increase in precipitation, we calculated the percentage of years that had precipitation below 500 mm during the growth period for the series of data from 1930 to 1950, and for the three sectors.

Satellite imagery selection and processing

To identify the land-cover units in the three sectors of the study area we used three Landsat 3 Multispectral Scanner (hereafter 'Landsat MSS') and nine Landsat 5 Thematic Mapper (hereafter 'Landsat TM') images. We used three scenes from February 1979 (Landsat MSS, Path/Row: 246/81, 247/81 and 247/82, 79 × 79 m resolution), three from November 1999, three from December 2004 and three from March 2010 (Landsat TM, Path/Row: 229/81, 230/81 and 230/82, 30 × 30 m resolution). All scenes

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were provided by the National Commission for Spatial Activities (CONAE). The scenes were geo-referenced on the basis of 1:50 000 topographic maps (Military Geographic Institute 1963–1997) to the Gauss-Krüger projection, with Campo Inchauspe datum and the International 1909 ellipsoid.

Before classifying the images, all areas that differed from lowland Chaco were eliminated from the images (e.g. mountains and water bodies), with a resulting total working area of 2 713 508 ha, distributed over the three selected sectors. Then, the 2004 scenes were analysed through a cluster technique (unsupervised classification). On the basis of this unsupervised classification and the units considered in Cabido & Zak (1999) and Zak et al. (2008), we defined eight land-cover units for the whole area: closed forest, open forest, closed shrubland, open shrubland, grassland with scattered shrubs, halophytic vegetation, salt, and cultural vegetation (croplands plus urban areas). Subsequently, field sampling was performed in 60 areas corresponding to the different clusters defined by the unsupervised classification. During fieldwork (between 2005 and 2006), we described vegetation structure and recorded dominant species, and on this basis we assigned each area to one of the eight previously defined units. The sampling areas served as a basis to select training sites to generate spectral signatures for the supervised classification. This classification, based on training sites whose ground characteristics were known with certainty, was performed independently for each 2004 scene through a maximum likelihood routine using the six non-thermal bands of the Landsat TM images. When necessary, several training sites and signatures were used for each class, with their outputs merged after the classification.

For each 1979 Landsat MSS scene and for each 1999 and 2010 Landsat TM scene, a radiometric co-registration to the corresponding 2004 scene was performed through selection of invariant targets and regression analysis on a band-by-band basis (Jensen 1996). Bands 1 and 2 (green and red) of the Landsat MSS scenes correspond to bands 2 and 3 of the Landsat TM scenes, respectively. Because both bands 3 and 4 (near-infrared) of Landsat MSS correspond to band 4 of the Landsat TM scenes, we only chose and transformed band 4 of Landsat MSS. To allow a more objective comparison between dates, the 2004 scene was re-classified from the same spectral signatures but using only bands 2, 3 and 4. As the output was very similar to the classification using all six bands, in this paper we report the results using only three bands. Following this spectral co-registration, the 1979, 1999 and 2010 scenes were classified using the same spectral signatures and bands used for the 2004 scenes. However, in some cases, to improve the classification of the 1979, 1999 and 2010 scenes, it was necessary to add some spectral signatures in areas where the cover type in these years was known with certainty. The final products of the whole process were 12 classified scenes (three by each one of the analysed years, 1979, 1999, 2004 and 2010) in which a total of eight land-cover units were discriminated. However, for further analyses, both shrubland types and the grasslands with scattered shrubs classes were merged into a unique type (hereafter 'shrublands'), because they were not present in the three scenes.

For field validation of the classifications obtained using the 2004 and 2010 scenes, we used 145 and 125 sites selected from the images, respectively. For 2004 scenes, 22 sites were located within the study area and their cover was defined through fieldwork, while the 123 remaining sites were located in the study area using 'QuickBird' images (Google Earth 2008) and their cover defined by visual interpretation. For 2010 scenes, 31 sites were defined through fieldwork and 94 using 'QuickBird' images. All sites corresponded to homogeneous areas of at least 3 × 3 pixels (as in Cingolani et al. 2004). A confusion matrix was constructed for the whole study area and the Kappa statistic calculated for each date (2004, 2010). The matrix was constructed using five vegetation classes: closed forest, open forest, shrublands, halophytic vegetation and cultural vegetation (salt was not included so as to avoid an artificial increase of accuracy).

Before comparing the classified images among dates, and to allow a more accurate comparison, we discarded pixels that were classified as salt or halophytic vegetation in at least one of the dates. On the basis of these images a table was constructed where the proportion of each land-cover unit present in the whole study area was compared throughout the four dates.

Finally, and in order to obtain a better insight into the dynamics of the land-cover change, we performed a change detection analysis for each sector (northeast, northwest and west) between the two extreme dates: 1979 and 2010 (Singh 1989). Additionally, we calculated the number and mean size of non-cultural patches (closed forest, open forest and shrubland) for the three sectors in 1979 and 2010.

Results

Precipitation patterns

Annual precipitation was significantly different between the two series of data corresponding to different periods ($F_{1,28}$: 114.08; $P < 0.001$) and among the three sectors ($F_{1,28}$: 45.80; $P < 0.001$). The series of data–sector interactions was also significant ($F_{2,28}$: 4.77; $P < 0.05$; Fig. 2a). Similarly, growth period precipitation was significantly different between the two series of data ($F_{1,28}$: 117.02;

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$P < 0.001$) and among the sectors ($F_{2,28}$: 37.97; $P < 0.001$), with the series of data–sector interactions also being significant ($F_{2,28}$: 16.12; $P < 0.001$; Fig. 2b). For the series of data from 1930 to 1950, the northeast sector had an average mean annual precipitation of 529 mm, whereas for the northwestern and western sectors annual precipitation averaged 386 and 423 mm, respectively. For the series of data from 1950 to 2000, the pattern was similar, but average values were higher for the three sectors: the northeast sector had an average of 748 mm, while the northwestern and western sectors averaged 553 and 543 mm, respectively (Fig. 2a).

The average mean precipitation of the growth period (November–March) also showed similar trends. In the series of data from 1930 to 1950 the mean precipitation values were 387 mm (northeast), 323 mm (northwest) and 329 mm (west). For the series of data from 1950 to 2000, we found the same pattern but, as for the annual precipitation, all values were higher: 175 mm higher in the northeast (with mean precipitation of 562 mm) and 93 and 83 mm higher in the northwest and west sectors, respectively. In both series of data, the northeast sector differed significantly from the northwestern and western sectors (Fig. 2b). Differences in precipitation patterns between sectors were less marked for the growth period than for annual precipitation, since in the northeast sector seasonality is less marked (73% of precipitation occurs during the growth period in the northeast, while 76% and 77% of all precipitation is concentrated during the growth season in the west and northwest sites).

Precipitation data of the growth season for the series of data from 1930 to 1950 showed that 83% of the years had precipitation values below 500 mm, ranging from 56% to 100%, in the northeast sector. This result means that in most of the stations of the wettest sector, precipitation was low enough so as to inhibit profitable and continued crop production. In the northwest and west sectors, 98% and 92% of the years had <500 mm of rainfall during the growth period, respectively.

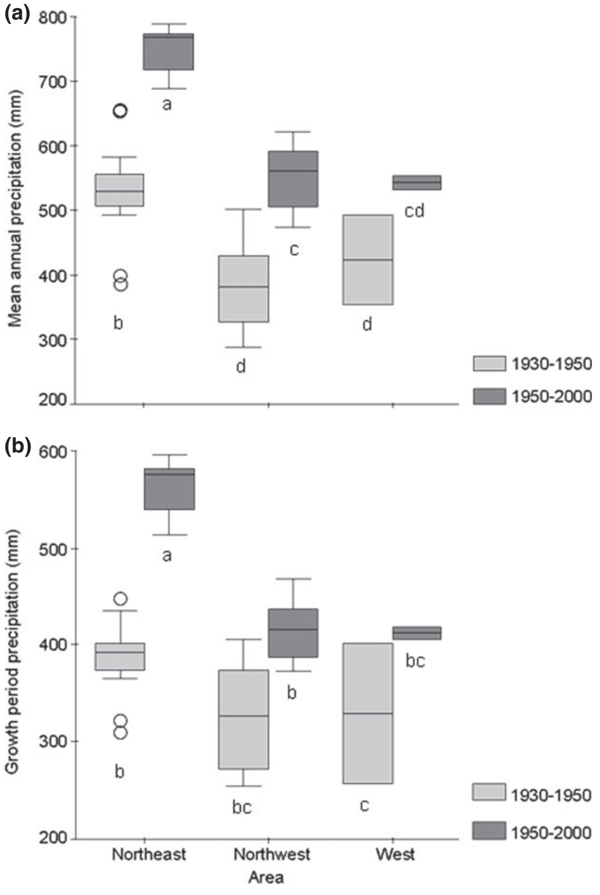

Fig. 2. Box plots of (**a**) mean annual precipitation (mm) and (**b**) growth period precipitation (November–March) (mm) for the three sectors of the study area in 1930–1950 and 1950–2000. Letters under the boxes indicate significant differences ($P < 0.01$) outlier.

Land-cover patterns

The 2004 classification had an accuracy of 80% (κ = 0.72); 115 out of the 145 validation sites selected were confirmed as precisely classified, while the 2010 classification had an accuracy of 89% (κ = 0.87); 111 out of the 121 validation sites selected were confirmed as precisely classified (Table 1). From the initial 2 713 508 ha that the whole area occupied, we discarded 466 748 ha classified as halophytic vegetation or salt for at least one of the dates. The

Table 1. Confusion matrix for the classification of different land covers units in 2004 (a) and in 2010 (b). Land cover units 1–5 refer to stands of ground truth according to field information, while map units 1–5 refer to the classification of those stands according to spectral information.

Map units	Land cover units					
	1	2	3	4	5	Percentage
(a)						
1	20	3	6	0	2	64.52
2	2	21	5	0	0	75.00
3	3	4	47	0	0	87.04
4	0	0	0	4	0	100.00
5	1	0	4	0	23	82.14
Percentage	76.92	75.00	75.81	100.00	92	79.31
(b)						
1	2	1	0	0	0	66.67
2	2	24	2	0	0	85.71
3	2	0	44	0	2	91.67
4	0	0	0	6	0	100.00
5	0	1	0	0	35	97.22
Percentage	33.33	92.31	95.65	100.00	94.59	92.74

1: Closed forest, 2: Open forest, 3: Shrubland, 4: Halophytic vegetation, 5: Cultural vegetation.

Table 2. Proportion covered by the different land cover in the north, the northwest and the west sector of the province of Córdoba in 1979, 1999, 2004 and 2010.

Proportion (%)	1979	1999	2004	2010
Closed forest	29	25	15	5
Open forest	10	16	15	13
Shrubland*	33	26	27	34
Cultural vegetation	27	33	43	48
Total	100	100	100	100

*Both shrubland types and the grasslands with scattered shrubs classes were merged into a unique one, because they were not present in the three scene.

remaining surface (2 246 761 ha) corresponded to closed forest, open forest, shrubland or cultural vegetation for all four dates. When comparing the proportion of each land cover unit through the four dates, we detected an important reduction of closed forest and an increase in cultural vegetation, whereas the open forest and the shrublands maintained a similar surface throughout the years (Table 2).

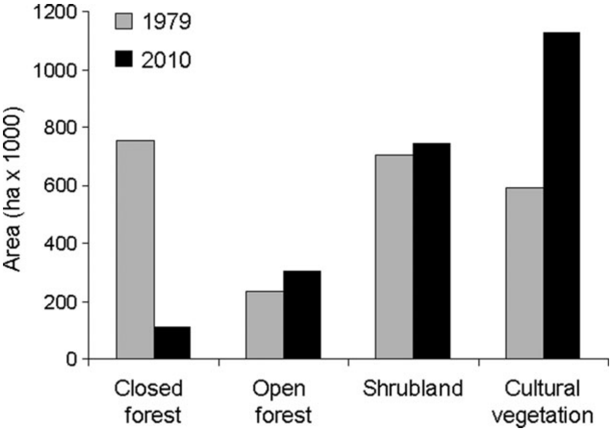

Fig. 3. Land cover changes in the whole study area between 1979 and 2010.

Land-cover changes

Even though all the vegetation units from the 1979 map (original cover for the purposes of this paper) were still present in the 2010 map, their spatial patterns have markedly changed. In 1979, closed forests occupied a considerable proportion of the study area and had a rather continuous distribution, with few deforested areas. Cultural vegetation was less extensively distributed at that time, especially in the northwestern and western sectors (Figs 3 and 4). Two land-cover units, closed forests and shrublands, have reduced their extension, the former being the most adversely affected. Meanwhile, cultural vegetation and open forests have expanded (Figs 3 and 4). Patch number and mean patch size of non-cultural cover units changed accordingly, with the northeast sector showing the highest patch number and the smaller patch size (Table 3).

Although important land-cover changes occurred in the three sectors, these changes have not been homogenous. The expansion of cultural vegetation was larger in the northeastern sector: from 41% of the area in 1979 to 81% in 2010 (Table 4). In the northwestern sector, the area covered by cultural vegetation has increased from 16% to 30% (Table 5). The western sector showed the smallest increase in cultural vegetation, from 12% to 17% of the area (Table 6).

Closed forests have been strongly affected in all three sectors, although the largest changes occurred in the northeast and northwest. In the northeast, the area covered by closed forest in 1979 represented 16% of the sector, but in 2010 this unit occupied only 2% of the area (Table 4). In the northwest, the closed forest occupied almost 50% of the area in 1979, but only 7% in 2010 (Table 4). This means that the annual rate of loss of closed forest was 4473 ha for the northeast sector and 10 113 ha for the northwest sector. Meanwhile, in the western sector the annual rate of loss of closed forest was 5646 ha, a change from 41% of the area in 1979 to 6% in 2010 (Table 6). These figures indicate that in the three sectors, closed forests were reduced to 15% of their original cover.

When the gross rate of change was analysed, in the northeast sector 163 304 ha occupied by closed forest in 1979 were transformed in cultural vegetation (77%) in 2010, whereas 5% of the area was transformed into open forest and almost 16% into shrubland (Table 4). Meanwhile, 86% of the closed forest present in 2010 had been other units in 1979 (Table 4). In the northwest sector, 369 347 ha occupied by closed forest in 1979 had been transformed into shrublands (51%), cultural vegetation (28%) and open forest (14%) (Table 5), while 54% closed forests present in 2010 had been other cover units in 1979. In the western sector, closed forests have also undergone an important reduction, with 175 015 ha lost between 1979 and 2010 (Table 6). Thirty-eight per cent of the closed forests had been converted into open forest, which increased their surface from 18% of the area in 1979 to 33% in 2010. Meanwhile, 11% of the closed forests became cultural vegetation; 59% of the closed forests present in 2010 had been other cover units in 1979 (Table 6).

Discussion

This study traces the recent history of forest cover change in the southern extreme of the Great Chaco, and provides an initial assessment of why it might have occurred. It also

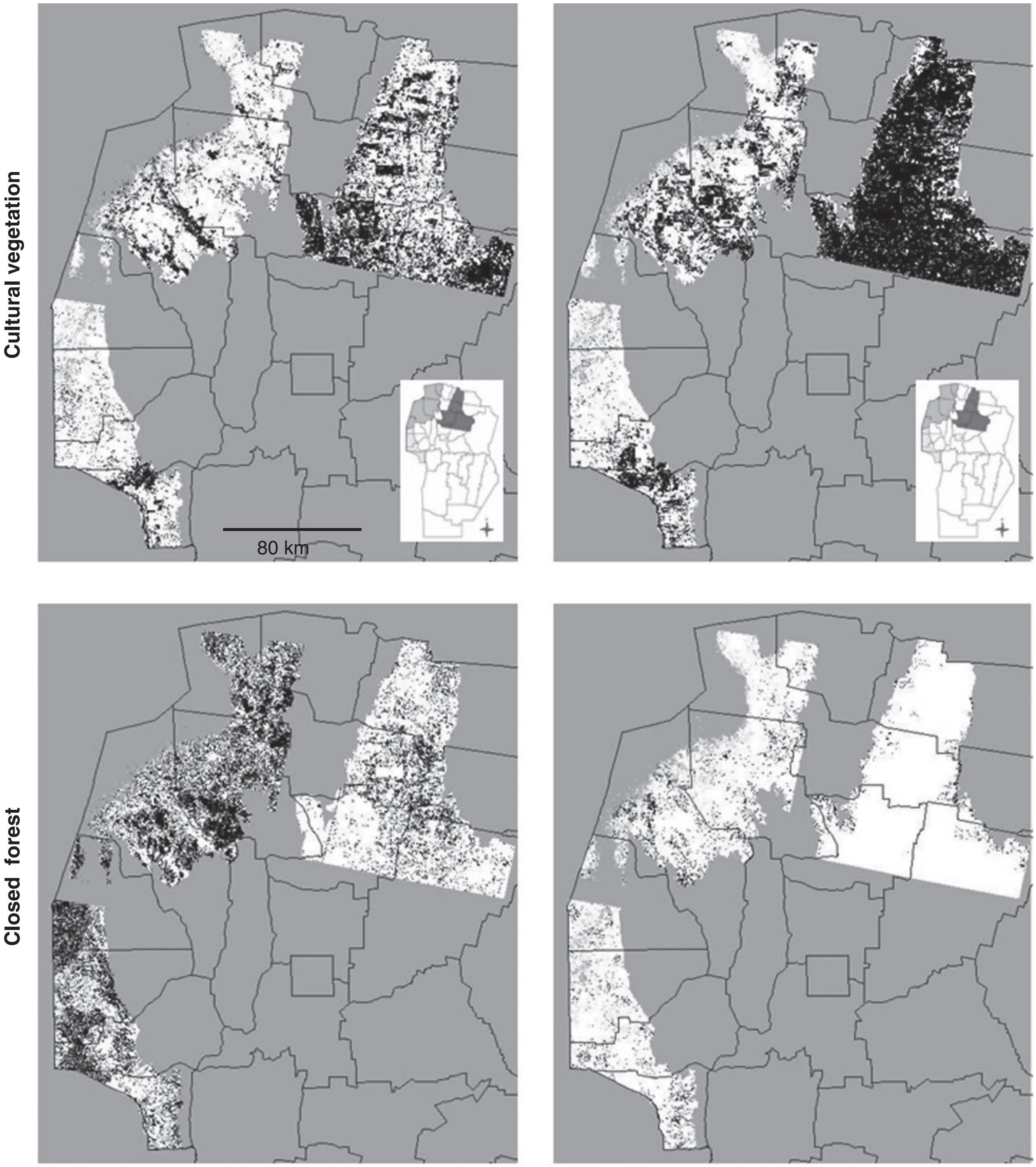

Fig. 4. Land cover changes in the three sectors of the study area (northeast, northwest and west) between 1979 (left) and 2010 (right). In each figure, the referred land cover type is represented in black.

provides a baseline description of present land cover in northeast and northwest Córdoba Province, so that patterns and trends can be followed into the future regarding subtropical forest loss in central Argentina. We identified eight land-cover units and described their spatial patterns. Our map showed that the dry Chaco vegetation in the study area is highly disturbed. Similar trends of devastation have already been reported for the Argentinean Chaco

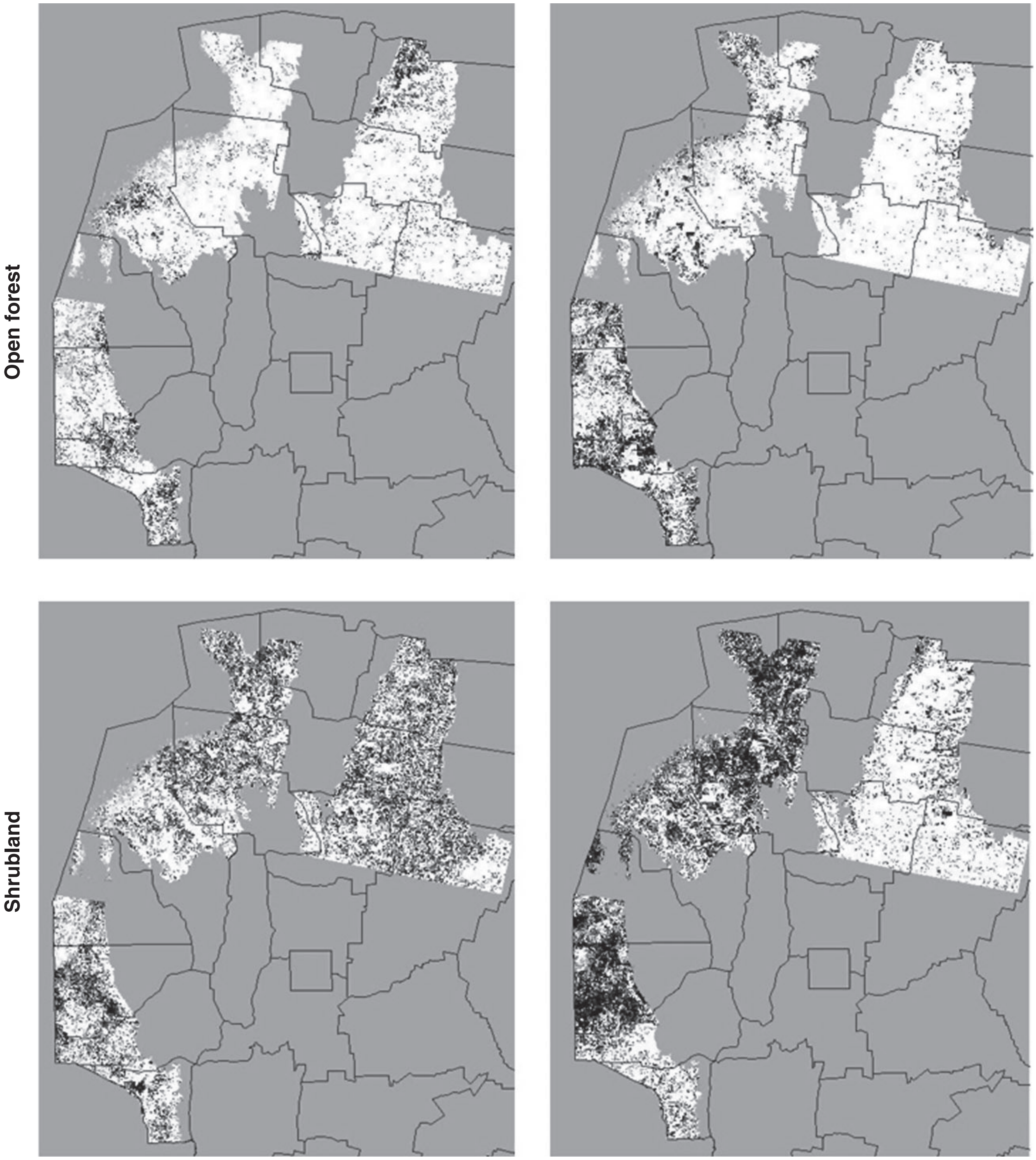

Fig. 4. Continued.

(Schofield & Bucher 1986; Grau et al. 2005a,b; Paruelo et al. 2005; Boletta et al. 2006; Torrella & Adámoli 2006; Zak et al. 2008).

Although the whole study area may be considered as dry (semi-arid). and water availability has always been a major constraint to agricultural development (Sayago 1969; Steininger et al. 2001), our results revealed that the present status of vegetation cover differs among the three sectors considered. The northeast sector had higher precipitation records for the two series of data, 1930–1950 and 1950–2000 (this is true for both the year-long and growth period precipitation). While the mean precipitation for the

Table 3. Number and mean patch size of non-cultural vegetation (closed forest, open forest and shrubland), for the three sectors in 1979 and 2010.

Sectors	1979		2010	
	No. of patches	Mean patch size (ha)	No. of patches	Mean patch size (ha)
Northeast	9327	63.41	119 775	1.58
Northwest	10 603	62.71	75 459	7.33
West	2202	179.47	39 643	7.59

growth season during the first period was below 500 mm, this record was soon surpassed in the series of data for 1950–2000 (reaching a mean precipitation of 563 mm). These records are in agreement with those of Minetti & Vargas (1997) and Zak et al. (2004, 2008) and indicate that mean annual precipitation showed a greater increase since 1960–1970, at least for the period under study. Considering that a precipitation of 500–600 mm during the growth period is needed to obtain profitable crops (Dardanelli 1998; Andriani 2000), this could explain why the conversion of forests in the northeast sector was higher than in the western plain, where precipitation increased only slightly during the studied period. In the case of the northwestern sector (where precipitation falls into the lower threshold for soybean and other crop production), an increase of annual precipitation over 500 mm made crop production possible. In contrast, in the western sector profitable crop production is not possible without irrigation. Our results incorporate more arguments and data to our assertion that before 1970, in most of the years during the period under study, precipitation was too low to support profitable crop production, even in the northeast (wettest) sector.

The northeast sector, which appears to be the most humid, is located in an area of recent agricultural development. The land-cover changes in northern Córdoba have been dominated by a replacement of closed forest by crops. This area has been extensively cleared for conversion to agricultural land, but the effects of deforestation for wood extraction and grazing activities have also been important

Table 4. Land cover types transitions for the Northern sector between 1979 and 2010. Numbers correspond to hectares (ha) while percentages (%) are shown between brackets. Totals represent values for each land cover class in both 1979 and 2010.

Northeastern sector	2010				
1979	Closed forest	Open forest	Shrubland	Cultural vegetation	Total
Closed forest	3048 (2)	8106 (5)	26198 (16)	125952 (77)	163304 (16)
Open forest	2259 (2)	6178 (6)	17178 (18)	70835 (73)	96450 (10)
Shrubland	8431 (3)	14225 (4)	48301 (15)	259372 (79)	330329 (33)
Cultural vegetation	10902 (3)	8970 (2)	35377 (9)	350796 (86)	406045 (41)
Total	24641 (2)	37479 (4)	127054 (13)	806955 (81)	996128 (100)

Table 5. Land cover types transitions for the Northwestern sector between 1979 and 2010. Numbers correspond to hectares (ha) while percentages (%) are shown between brackets. Totals represent values for each land cover class in both 1979 and 2010.

Northwestern sector	2010				
1979	Closed forest	Open forest	Shrubland	Cultural vegetation	Total
Closed forest	25674 (7)	50550 (14)	188386 (51)	104738 (28)	369347 (49)
Open forest	7415 (16)	5820 (12)	21485 (46)	12379 (26)	47099 (6)
Shrubland	10655 (5)	29708 (14)	122799 (56)	56830 (26)	219992 (29)
Cultural vegetation	12094 (10)	7797 (7)	48175 (41)	49240 (42)	117306 (16)
Total	55838 (7)	93874 (12)	380845 (51)	223186 (30)	753744 (100)

Table 6. Land cover types transitions for the Western sector between 1979 and 2010. Numbers correspond to hectares (ha) while percentages (%) are shown between brackets. Totals represent values for each land cover class in both 1979 and 2010.

Western sector	2010				
1979	Closed forest	Open forest	Shrubland	Cultural vegetation	Total
Closed forest	12228 (6)	77192 (38)	94137 (46)	21552 (11)	205109 (41)
Open forest	6275 (7)	39325 (45)	28760 (33)	13431 (15)	87791 (18)
Shrubland	9119 (6)	38289 (27)	74096 (52)	21078 (15)	142582 (29)
Cultural vegetation	2472 (4)	8423 (14)	19914 (32)	30597 (50)	61406 (12)
Total	30094 (6)	163229 (33)	216907 (44)	86658 (17)	496889 (100)

(Zak & Cabido 2002). Therefore, the area appears at present as a large matrix of agriculture, mainly soybean, with small patches of woody vegetation (open forests and shrublands).

The landscape of the northwestern sector changed significantly between 1979 and 2010, and some trends suggest that an increase in deforestation activity may continue to occur in the future. In 1979, forests occupied a considerable extent of the total area and had a continuous distribution, with large fragments and few deforested areas, whereas the cultural vegetation was still hardly developed. Similar results have been reported in Zak et al. (2004, 2008), comparing cover unit patterns in this area with those reported in a map of the area published in 1969 (Sayago 1969). At present, cultural vegetation occupies a larger surface than any other cover type in the sector, indicating that conversion (even when at a lower rate than in the northeast sector) is still continuing.

In the western sector, forest cover has also undergone an important reduction. Unlike events in the other sectors, not all deforestation was due to the introduction of cultural vegetation: most forests were converted into open forests and shrubland (both closde and open) due primarily to a reduction in the dominant tree species, e.g. *Aspidosperma quebracho-blanco* (Bonino & Araujo 2005). This suggests that the conversion of forests could be due, among other factors, to the production of two forest products of low commercial value: charcoal and fuelwood (Natenzon & Olivera 1994; Bonino & Araujo 2005; Morello et al. 2006), as well as to the occurrence of fires (Bono et al. 2004). The three sectors underwent an important fragmentation, with a corresponding increase in number and decrease in size of the non-cultural patches between 1979 and 2010. Similar results have been reported in Steininger et al. (2001), Barbosa de Oliveira-Filho & Metzger (2006) and Gasparri & Grau (2009) for other areas within the Great Chaco.

Although the change in land cover could be due to a series of factors that act synergistically (technological, climatic and socioeconomic factors; Geist & Lambin 2002; Zak et al. 2008), the differences observed in land cover between the three sectors of the study area suggest that increasing precipitation has effectively played a dominant role in the process of forest conversion to agriculture. The conversion of forests into croplands in the northeast has been higher, despite the fact that availability of new technology and accessibility to markets does not differ markedly among sectors. The most likely factor behind these differences in deforestation therefore appears to be climatic (Zak et al. 2008). This study confirms those results, showing that before 1970, precipitation during the growth period in the three sectors was, for most of the years, below 500 mm, the minimum necessary for profitable crop production. Although it was not possible to discriminate annual data after 1970, we show that even when precipitation increased in the three sectors, only in the wettest area did precipitation reach the levels needed (at least 500 mm during the growth period) for soybean, among other crops, cultivation. Taking into account future global demands for food and energy, it is likely that the rate of deforestation in the great Chaco and other subtropical forests throughout the world may further increase. This increase may affect not only areas with higher precipitation, as reported in this study, but also the other sectors examined in this research, in which biomass production for biofuels is likely to expand.

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References

Adámoli, J., Torrella, S. & Herrera, P. 2004. La expansión de la frontera agrícola y la conservación de la biodiversidad en el Chaco argentino. In: Castroviejo, S. (ed.) *Por la Biodiversidad en Latinoamérica*. Fundación Amigos de Doñana y Fundación Félix de Alzara, Buenos Aires, AR.

Andriani, J. 2000. *Consumo de agua de los cultivos. Para Mejorar la Producción Nº13*, pp. 27–30. EEA INTA Oliveros, Santa Fe, AR.

Andriani, J. 2002. *Estrés hídrico en soja*, pp. 48–51. IDIA XXI 3, Santa Fe, AR.

Atlas de los Bosques Nativos Argentinos. 2003. Proyecto Bosques Nativos y Áreas Protegidas BIRF 4085-AR. Dirección de Bosques, Secretaría de Ambiente y Desarrollo Sustentable, Buenos Aires, AR.

Barbosa de Oliveira-Filho, F.J. & Metzger, J.P. 2006. Thresholds in landscape structure for three common deforestation patterns in the Brazilian Amazon. *Landscape Ecology* 21: 1061–1073.

Boletta, P.E., Ravelo, A.C., Planchuelo, A.M. & Grilli, M. 2006. Assessing deforestation in the Argentine Chaco. *Forest Ecology and Management* 228: 108–114.

Bonino, E.E. & Araujo, P. 2005. Structural differences between a primary and a secondary forest in the Argentine Dry Chaco and management implications. *Forest Ecology and Management* 206: 407–412.

Bono, J., Parmuchi, M.G., Strada, M., Montenegro, C., Manghi, E. & Gasparri, I. 2004. *Mapa Forestal de la Provincia de Córdoba. Secretaría de Ambiente y Desarrollo Sustentable*. Dirección de Bosques, Buenos Aires, AR.

Cabido, M.R. & Zak, M. 1999. *Vegetación del Norte de Córdoba. Instituto Multidisciplinario de Biología Vegetal*. Universidad Nacional de Córdoba y CONICET, Córdoba, AR.

Cabido, M.R., Acosta, M., Carranza, M.L. & Diaz, S. 1992. La vegetación del Chaco Árido en el W de la provincia de Córdoba, Argentina. Documents Phytosociologiques. 14: 447–459.

Cabido, M.R., González, C. & Díaz, S. 1993. Vegetation changes along a precipitation gradient in Central Argentina. *Vegetatio* 109: 5–14.

Cabrera, A.L. 1976. *Regiones Fitogeográficas de Argentina. Enciclopedia Argentina de Agricultura y Jardinería*. ACME, Buenos Aires, AR.

Carreiras, J.M.B., Pereira, J.M.C., Campagnolo, M.L. & Shimabukuro, Y.E. 2006. Assessing the extent of agriculture/pasture and secondary succession forest in the Brazilian Legal Amazon using SPOT VEGETATION data. *Remote Sensing of Environment* 101: 283–298.

Cingolani, A.M., Renison, D., Zak, M.R. & Cabido, M.R. 2004. Mapping vegetation in a heterogeneous mountain rangeland using Landsat data: an alternative method to define and classify land-cover units. *Remote Sensing of Environment* 92: 84–97.

Dardanelli, J.1998. Efficiency in the use of water by different tillage systems. In: Panigatti, J.L., Marelli, H., Buschiazzo, D. & Gil, R. (eds.) *Zero tillage*, pp. 107–115. Hemisferio Sur, Buenos Aires, AR.

Eva, H.D., Belward, A.S., De Miranda, E.E., Di Bella, C.M., Gond, V., Huber, O., Jones, S., Sgrenzaroli, M. & Fritz, S. 2004. A land cover map of South America. *Global Change Biology* 10: 731–744.

FAO. 2001. *State of the world's forests 2001*. Food and Agriculture Organization of the United Nations, Rome, IT

Fearnside, P.M. 2001. Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation* 28: 23–38.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S. III, Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. & Snyder, P.K. 2005. Global consequences of land use. *Science* 309: 570–574.

Gasparri, N.I. & Grau, H.R. 2009. Deforestation and fragmentation of Chaco dry forest in NW Argentina (1972–2007). *Forest Ecology and Management* 258: 913–921.

Geist, J. & Lambin, E.F. 2002. Proximate causes and underlying driving forces of tropical deforestation. *BioScience* 52: 143–150.

Ginzburg, R. & Adámoli, J. 2006. Situación ambiental en el Chaco Húmedo. In: Brown, A., Martinez Ortiz, U., Acerbi, M. & Corchera, J. (eds.) *La Situación Ambiental Argentina 2005*. pp 103–113. Fundación Vida Silvestre Argentina, Buenos Aires, AR.

Grau, H.R., Aide, T.M. & Gasparri, N.I. 2005a. Globalization and soybean expansion into semiarid ecosystems of Argentina. *Ambio* 34: 265–266.

Grau, H.R., Gasparri, N.I. & Aide, T.M. 2005b. Agriculture expansion and deforestation in seasonally dry forest of north-west Argentina. *Environmental Conservation* 32: 140–148.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. & Jarvis, A. 2005. Very high resolution interpolated climate surface for global land areas. *International Journal of Climatology* 25: 1965–1978.

Jensen, J. 1996. *Introductory digital image processing*, 2nd edn. Prentice Hall, NJ, USA.

Kaimowitz, D. & Smith, J. 2001. Soybean technology and the loss of natural vegetation in Brazil and Bolivia. In: Angelsen, A. & Kaimowitz, D. (eds.) *Agricultural technologies and tropical deforestation*. pp 195–211. CAB International, Wallingford, UK.

Laurance, W.F., Albernaz, A.K.M. & Da Costa, C. 2001. Is deforestation accelerating in the Brazilian Amazon? *Environmental Conservation* 28: 305–311.

Minetti, J.L. & Vargas, W.M. 1997. Trends and jumps in the annual precipitation in South America, south of the 15°S. *Atmósfera* 11: 205–221.

Morello, J., Pengue, W. & Rodríguez, A. 2006. Etapas del uso de los recursos y desmantelamiento de la biota del Chaco. In: Brown, A., Martínez Ortiz, U., Acerbi, M. & Corcuera, J. (eds.) *La Situación Ambiental Argentina 2005*, pp. 83–90. Fundación Vida Silvestre Argentina, Buenos Aires, AR.

Natenzon, C.E. & Olivera, C. 1994. La tala del bosque en los llanos de La Rioja (1900–1960). *Desarrollo Económico* 34: 263–284.

Paruelo, J.M., Guerschman, J.P. & Verón, S.R. 2005. Expansión agrícola y cambios en el uso del suelo. *Ciencia Hoy* 15: 14–23.

Purcell, L.C., Sinclair, T.R. & McNew, R.W. 2003. Drought avoidance assessment for summer annual crops using long-term weather data. *Agronomy Journal* 95: 1566–1576.

Ramankutty, N., Evan, A., Monfreda, C. & Foley, J.A. 2008. Farming the planet. Part 1: the geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* 22: GB1003, doi: 10.1029/2007GB002952.

Sayago, M. 1969. Estudio fitogeográfico del norte de Córdoba. *Boletín Academia Nacional de Ciencias Córdoba* 46: 123–427.

Schofield, C.J. & Bucher, E.H. 1986. Industrial contributions to desertification in South America. *Trends in Ecology and Evolution* 1: 78–80.

Singh, A. 1989. Digital change detection techniques using remotely-sensed data. *International Journal of Remote Sensing* 6: 989–1003.

Steininger, M.K., Tucker, C.J., Ersts, P., Killen, T.J., Villegas, Z. & Hecht, S.B. 2001. Clearance and fragmentation of tropical deciduous forest in de Tierras bajas, Santa Cruz, Bolivia. *Conservation Biology* 15: 856–866.

Tilman, D., Fargione, J., Wolff, B., C'Antonio, D., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D. & Swackhamer, D. 2001. Forecasting agriculturally driven global environmental change. *Science* 292: 281–284.

Torrella, S. & Adámoli, J. 2006. Situación ambiental de la ecorregión del Chaco Seco. In: Brown, A., Martinez Ortiz, U., Acerbi, M. & Corchera, J. (eds.) *La Situación Ambiental Argentina 2005*, pp 75–82. Fundación Vida Silvestre Argentina, Buenos Aires, AR.

Turner, B.L., Lambin, E.F. & Reenberg, A. 2007. The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America* 104: 20666–20671.

WorldClim – Global Climate Data. Available at: http://www.worldclim.org/tiles.php.

Zak, M.R. & Cabido, M.R. 2002. Spatial patterns of the Chaco vegetation of central Argentina: integration of remote sensing and phytosociology. *Applied Vegetation Science* 5: 213–226.

Zak, M.R., Cabido, M.R. & Hodgson, J.G. 2004. Do subtropical seasonal forests in the Gran Chaco, Argentina, have a future? *Biological Conservation* 120: 589–598.

Zak, M.R., Cabido, M.R., Cáceres, D. & Diaz, S. 2008. What drives accelerated land cover change in central Argentina? Synergistic consequences of climatic, socioeconomic, and technological factors. *Environmental Management* 42: 181–189.

Zuloaga, F.O., Morrone, O. & Belgrano, M.J. 2008. Catálogo de las plantas vasculares del Cono Sur. (Argentina, Sur de Brasil, Chile, Paraguay y Uruguay). *Missouri Botanical Garden* 107: 1905–1908.