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Biological Conservation 120 (2004) 589–598

BIOLOGICAL CONSERVATION

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Do subtropical seasonal forests in the Gran Chaco, Argentina, have a future?

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Received 20 August 2003; received in revised form 28 March 2004; accepted 31 March 2004

Abstract

While much information is available about tropical and temperate ecosystems, there is a remarkably little information as to land cover and land use changes in the subtropical biomes of the world. Here, we quantify changes in the spatial patterns of land cover types at the southern edge of the seasonally dry, subtropical Chaco forest of South America during the second half of the 20th century using a vegetation map printed in 1969 and a Landsat TM based digital map produced 30 years later. Results show a massive contraction of forest; ca. 1.2 million ha of original lowland and mountain subtropical dry forests and woodlands, 85% of the total, have been cleared in only 30 years. This loss of Chaco forests of 2.2% year^{-1} is consistent with or even exceeds, global trends. Forest vegetation now persists as fragments where there was formerly continuous cover. Most of undisturbed Chaco forest has now been converted to pasture or is undergoing secondary succession. Today, these new vegetation types, resulting mainly from agricultural expansion, have increased 10-fold in cover and now represent the commonest land cover types. The increased intensity of agricultural usage, possibly triggered by an increase in annual rainfall during the last decades, has been accompanied by changes in agricultural practices and a relative decline in the rural population.

Keywords: Agricultural expansion; Deforestation; Historical map; Landsat TM; Land use change

1. Introduction

Land use and land cover change are crucial components in all considerations of sustainability (Houghton, 1994; Turner et al., 1994; IGBP and IHDP, 1999). Land use practices such as deforestation, grazing and agriculture can profoundly affect regional climate and ecosystem functioning (Baron et al., 2000; Bonnie et al., 2000; Loreau, 2000; Díaz and Cabido, 2001; Loreau et al., 2001). Moreover, land use change is also the driver expected to have the largest global impact on biodiversity by the end of the 21st century (Sala et al., 2000). At present, however, there are inadequate data on historical land use practices and on the changes associated with land cover (Hannah et al., 1994; Lambin, 1997; Ramankutty and Foley, 1999). Before we can accurately assess the impact of human activities we must compile accurate, geographically explicit data sets describing changes in land use and land cover. Traditionally, the analysis of historical sequences of aerial photographs and vegetation maps has been an efficient method for determining changes in land cover types at the local and landscape scales (van der Maarel et al., 1985; Kadmon and Harari-Kremer, 1999; Pascarella et al., 2000; Bowman et al., 2001). Recently, methods of quantifying vegetation cover have benefited from advances in computer techniques and the availability of remotely sensed data, which make comparisons possible at the regional and even global scales (Skole and Tucker, 1993; Lambin and Ehrlich, 1997; Defries and Townshend, 1999; IGBP and IHDP, 1999; Mas, 1999; Woodcock et al., 2001). In this context, the comparison between old paper maps and accurate digital maps derived from remote sensing products representing the

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0006-3207/$ - see front matter
doi:10.1016/j.biocon.2004.03.034

present status of vegetation may be of great importance for detecting changes in land cover and may provide a valuable tool for environmental monitoring and management (Riaza et al., 1998).

Most studies using satellite imagery to map plant communities and to assess changes in land cover have concentrated upon tropical and/or temperate ecosystems (Ratcliffe, 1984; Buse, 1992; Skole and Tucker, 1993; Ojima et al., 1994; Hannah et al., 1995; Vogelmann, 1995; Matson et al., 1997; Noble and Dirzo, 1997; Vitousek et al., 1997; Ramankutty and Foley, 1998; Riaza et al., 1998; Ramankutty and Foley, 1999; Baban and Luke, 2000; Steininger et al., 2001; Wang and Moskovits, 2001). Consequently, there is remarkably little information on land cover and land use changes in the sub-tropical biomes of the world, especially the seasonally dry forests of South America (Janzen, 1988; Redford et al., 1990; Mooney et al., 1995; Pennington et al., 2000). Here, we attempt to partially redress this imbalance by studying the Gran Chaco, the most geographically extensive seasonally dry forest in South America (Hannah et al., 1994; Moglia and Giménez, 1998). This study is particularly timely since this little studied vegetation, formerly one of the least disturbed worldwide, appears to be undergoing very rapid change (Redford et al., 1990; Steininger et al., 2001) and its status is of concern to ecologists and conservation authorities alike. Here, we quantify changes in the spatial patterns of Chaco plant communities within central Argentina during the second half of the 20th century using a 1969 paper map and 1997 classified Landsat TM images and relate patterns of vegetational change to those of land use.

2. Study area

The Gran Chaco extends through the quaternary plains and low ranges of northern Argentina, western Paraguay and south-eastern Bolivia, and the extreme western edge of Mato Grosso do Sul state in Brazil (Fig. 1) (Prado, 1993; Pennington et al., 2000). This natural region covers about 1,200,000 km^2 and its vegetation comprises a mosaic of xerophytic forests, woodlands, scrubs, savannas and grasslands (Bucher and Saravia Toledo, 2001). Xerophyllous subtropical forests and woodlands are the climax vegetation on zonal soils in the Chaco region, while edaphic grassland savannas on flooded areas and fire-maintained grasslands are also important components of the natural Chaco landscape (Adamoli et al., 1972; Morello and Adamoli, 1974). The Gran Chaco comprises one of the few areas in the world where the transition between the tropics and the temperate belt does not occur in the form of a desert, but as semi-arid forests and woodlands (Morello and Adamoli, 1968; Prado, 1993).

Our study area is at the southern edge of the Gran Chaco. It comprises about 27,000 km^2 and is located in the northern part of Córdoba Province, central Argentina (Fig. 1). The area consists of an eastern and a western plain and centrally running from north to south a mountain range (700–1800 m a.s.l.). Both plains are covered by quaternary sediments and at the northern end of each there are saline depressions originating from closed basins (salinas).

The climate is warm temperate to subtropical, with a mean annual temperature increasing from 18.6 °C in the east–southeast to 19.9 °C in the north-western part of the area. Rainfall (which mainly falls in summer, between November and March) follows a similar pattern: decreases in the same direction from >700 mm $year^{-1}$ in SE to <550 mm $year^{-1}$ in NW. These lead to a higher water deficit in the western part of the territory.

The vegetation of this region has been described in detail by Sayago (1969) and Zak and Cabido (2002). The study area belongs to the Chaco Phytogeographical Province (Cabrera, 1976): the lowlands are part of the Western Chaco District, while the mountain ranges are part of the Sierra Chaco District. The dominant vegetation in the lowlands is *Aspidosperma quebracho-blanco* and *Schinopsis lorentzii* xerophytic forests, alternating with patches of secondary woodlands and scrubs in a matrix of cultivated lands. Succulent shrubs predominate in the saline depressions. In temporarily flooded areas this vegetation type is replaced by sclerophyllous grasslands, and in more elevated unflooded sites with lower salinity by fragments of woody Chaco vegetation. In the mountains the vegetation occupies altitudinal zones with successively mountain Chaco semi-deciduous woodlands, scrub and tussock grassland at the highest altitudes (>1000 m).

3. Methods

In order to study vegetation changes during the second part of the 20th century in the study area, we compared a paper map which provides base line data for land cover, and a Landsat TM based digital map (Zak and Cabido, 2002), revealing the current land cover situation. The detailed reference-state vegetation cover map used was the Vegetation Types of Northern Córdoba paper map published in 1969 (Sayago, 1969). This vegetation map was produced after 21 years of intensive field work. At that time, no aerial photographs were available for the study area. For this reason the exact boundaries of vegetation units may not be delimited with total precision. Nevertheless, features as small as 7.5 ha are defined and the global surface covered by the different vegetation types would be essentially accurate. The map by Sayago (1969) provides a unique

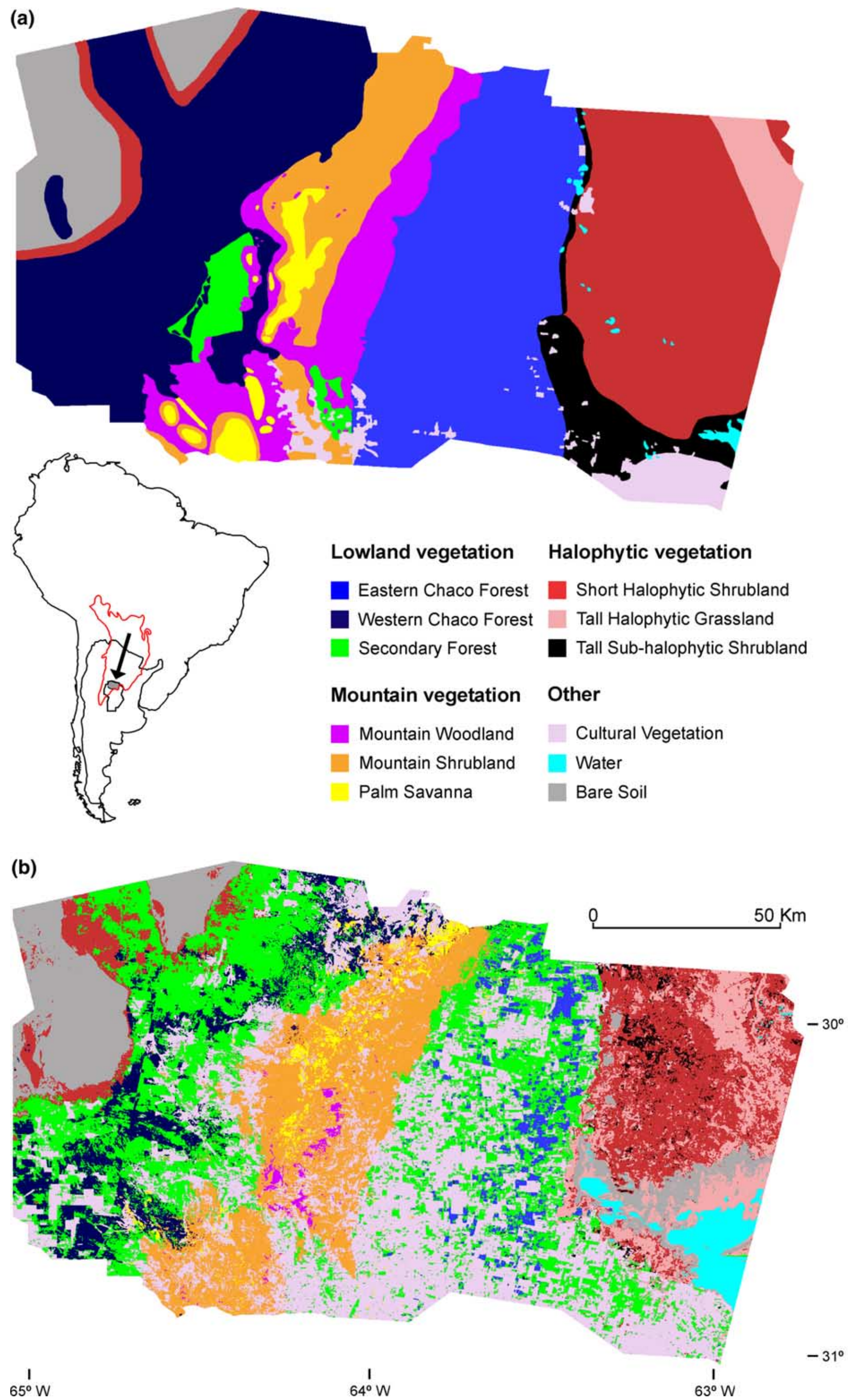

Fig. 1. Thematic maps for the study area: (a) 1969 map; (b) 1999 map. Coincident colors in both maps identify the same land cover types. The South American map shows the location of the study area (pointed with an arrow) at the southern edge of the Gran Chaco (red outline) in the northern part of the Córdoba Province, Argentina.

and reliable record of the vegetation cover of northern Córdoba more than 30 years ago. Sayago (1969) originally defined 35 vegetation types on the basis of subtle changes in composition detected through floristic field surveys. We have grouped these 35 types into 10 major units (vegetation zones and cultivated lands). These new units closely resemble the units presented in the 1999 digital map (Table 1).

Table 1
Correspondence between vegetation types in both thematic maps

1969 Thematic map	1999 Thematic map
Vegetation zones	
Lowland forests	*Lowland vegetation*
Quebrachal with two quebrachos[a]	Eastern Chaco forest
Quebrachal with cardón[b]	Western Chaco forest
Disturbed/degraded quebrachal	Secondary forest
Halophytic steppes	*Halophytic vegetation*
Jumial[c]	Short halophytic shrubland
Cardonal[d]	Tall sub-halophytic shrubland
Espartillar[e]	Tall halophytic grassland
Vegetation belts	*Mountain vegetation*
Mountain woodland	Mountain woodland
Mountain steppe	Mountain shrubland
Palm woodland/grassland	Palm savanna
Other	*Other*
Cultivated	Cultural vegetation
Water	Water
Bare/saline soils	Bare soil

[a] Local denomination for a community dominated by *Aspidosperma quebracho-blanco* and *Shinopsis lorentzii*.
[b] Local denomination for a community dominated by the evergreen tree *Aspidosperma quebracho-blanco*.
[c] Local term for a community dominated by succulent Chenopodiaceae.
[d] Local term for a community dominated by the cacti *Stetsonia coryne*.
[e] Local term for a community dominated by the tussock grass *Spartina argentinensis*.

Our 1999 map was obtained from the classification of two 1997 cloudless early summer Landsat 5 TM images together with phytosociological data, for a territory of more than 40,000 km^2 (Zak and Cabido, 2002). This was the first vegetation map for the study area for 30 years and the first of the type using Landsat TM for all of Argentina. We identified, described and mapped 10 clearly differentiated vegetation cover units (see Zak and Cabido (2002) for detailed descriptions of the different land cover types). In brief, the classification of the Landsat imagery (Path/Row: 229/081 and 230/081, 14 November 1997 and 23 December 1997, respectively) was based on the application of a maximum likelihood classifier using the seven bands of the TM images. Training sites were determined after analysis and field reconnaissance of clusters defined by previous unsupervised classifications and the multivariate analysis of Braun-Blanquet (1950) phytosociological relevés (see Zak and Cabido (2002) for further details on the construction of the digital map).

The comparison between the paper map published in 1969 and the digital map published in 1999 was carried out using the Idrisi for Windows 2.0 software (Eastman, 1997), utilized in the production of the 1999 map. The 1969 paper map was firstly scanned using a CONTEX FSS-8300 Full Scale Scanner. The resulting digital image was then co-registered using a nearest-neighbor resampling algorithm to the 1997 georreferenced TM images (for which the geographical coordinates – Gauss-Krüger coordinate system – were extracted from 1:50,000 topographical maps (Argentinean Military Topographic Office, 1996)) by using as ground control points land features such as rivers, road intersections, and other unchanging sites and landmarks. All the features and the boundaries of the various land cover units of the 1969 map were then on-screen digitized.

To minimise the noise produced by the discrepancy between the more detailed outlines of the 1999 map and the hand-drawn outlines of the 1969 paper map units, and to emphasise the wider areas of vegetation change, the 1999 map was filtered (mode filter shown appropriate), to produce outlines that better resembled those of the digitised paper map. Generally, comparisons of remotely sensed and purely ground-surveyed maps are complicated by, among other factors, the application of different land cover definitions in each (Defries and Townshend, 1999). This was not a substantial problem in our study, since the different cartographic units of the paper map (zones and belts – see Table 1) corresponded tightly (from the perspective of plant composition and structure) to the vegetation cover types shown in the digital map. Moreover, the criteria followed to discriminate plant communities (composition and physiognomy) coincided in both studies. The vegetation patterns and the area represented by each land cover unit were compared for the two maps in order to identify the main trends of vegetation change over the 30 years period.

4. Results

Recast data from the 1969 and 1999 maps are presented in Fig. 1(a) and (b). Visual comparison of the co-registered maps indicates major changes in land cover. Even though all of the original vegetation units from the 1969 map are still present in the 1999 map, their general patterns have markedly changed. Six communities (eastern and western Chaco forests, mountain woodlands, palm savannas, short halophytic scrubs, and tall sub-halophytic scrubs) have declined in abundance, while four land cover units (secondary forests, mountain scrubs, tall halophytic grasslands, and cultural vegetation) have increased.

Forest has been most adversely affected. During the 30 years period about 1.2 million ha of original lowland and mountain subtropical dry forests and woodlands have been cleared (Table 2). Approximately 85% of what was originally virtually undisturbed Chaco forest is now in various stages of arable agriculture, pasture or

Table 2
Total cover of each land cover unit, and recent changes (+ or −) to the vegetation of Central Argentina

Land cover unit	1969		1999		% Change
	Hectares	% of study area	Hectares	% of study area	
>70% decline since 1969					
Mountain woodland	228,800	8.4	13,700	0.5	−94
Eastern Chaco forest	554,800	20.5	57,900	2.1	−90
Western Chaco forest	638,600	23.6	150,800	5.6	−76
Intermediate status					
Tall sub-halophytic scrub	110,000	4.1	46,300	1.7	−58
Short halophytic shrublands	549,600	20.3	284,200	10.5	−48
Palm savanna	55,900	2.1	51,300	1.9	−10
Bare soil	165,200	6.1	220,900	8.2	34
Mountain shrublands	206,200	7.6	300,900	11.1	46
Tall halophytic grasslands	59,300	2.2	173,100	6.4	191
Water	9000	0.3	52,300	1.9	533
>7-fold increase since 1969					
Cultural vegetation	83,600	3.1	746,000	27.5	787
Secondary forest	50,600	1.9	614,200	22.7	1095
Total	2,711,600	100.0	2,711,600	100.0	

secondary succession. In the lowlands, 9850 km^2 of forests dominated by hard-wood trees such as *Schinopsis lorentzii*, *Aspidosperma quebracho-blanco* and *Prosopis kuntzei* have been lost. Thus, the lowland Chaco forest has decreased from 44.1% to 7.7% of the study area (Table 2). Fragmentation of the formerly continuous forest canopy has been more severe on the plain to the east of the mountain range, where the forest has decreased almost 10-fold in the 30 years period, compared to a 76% contraction on the western plain. Consistent with the less severe deforestation, the number of patches (21,495 to the western side of the mountain range and 5852 to the eastern side) and the size of the larger patches (18,100 ha for the western forest and 4500 ha for the eastern forest) tend to be higher in the western lowland forests. Nevertheless Fig. 2 illustrates that fragmentation of the formerly continuous lowland forest cover has occurred everywhere on a massive scale. Mountain woodland has suffered even more with a 94% decrease in cover from more than 8% to 0.5% of the study area (Fig. 2, Table 2). Moreover, only six patches (out of a total of 1738) larger than 400 ha remain (with a largest patch of 1800 ha). Part of the former mountain woodland has been converted into mountain scrub, which has increased in cover from 7.6% to more than 11% of the study area and cultivated lands have replaced mountain woodland in the valley bottoms. By contrast, the *Trithrinax* palm savannas have changed little in abundance (2.1% and 1.9% coverage of the study area in 1969 and 1999, respectively, Table 2) but have a somewhat modified distribution. The saline depressions in the east and west of the study area also showed little changes in distribution and the outlines of most of the various halophytic communities in the 1999 map very much resemble those of the 1969 map (Fig. 1). Nevertheless saline communities have contracted from 26.6% in 1969 to 18.6% in 1999 (Table 2).

The habitat showing the greatest increase has been cultivated land. This has grown from just over 3% in 1969 to almost 30% of the study area in 1999. Thus, cultivated land now has a higher cover than any other land cover type. We now have a landscape where cultivated vegetation types are mainly concentrated in the lowlands and valley bottoms within the mountain range, while semi-natural vegetation, particularly forest, is mainly restricted to areas with some kind of constraint for agriculture (e.g., steep slopes and shallow soils).

5. Discussion

5.1. Validity of the method

This study indicates that the comparison between a detailed old paper map and an accurate digital map can provide an acceptable method of analysing patterns of long-term vegetation dynamics. Many authors (Kadmon and Harari-Kremer, 1999; Pascarella et al., 2000; Bowman et al., 2001) have proved the utility of the analysis of historical sequences of aerial photographs for determining changes in land cover. Nevertheless, in places where aerial data or other source of historical data are not available, the comparative analysis of historical maps and satellite data seems to be a useful approach (Carni et al., 1998; Riaza et al., 1998). In addition we can explain and predict trends of vegetation change occurring over large spatial and temporal scales. Thus, the method of analysis of vegetation change using old vegetation maps and remotely sensed data appears to have a promising future.

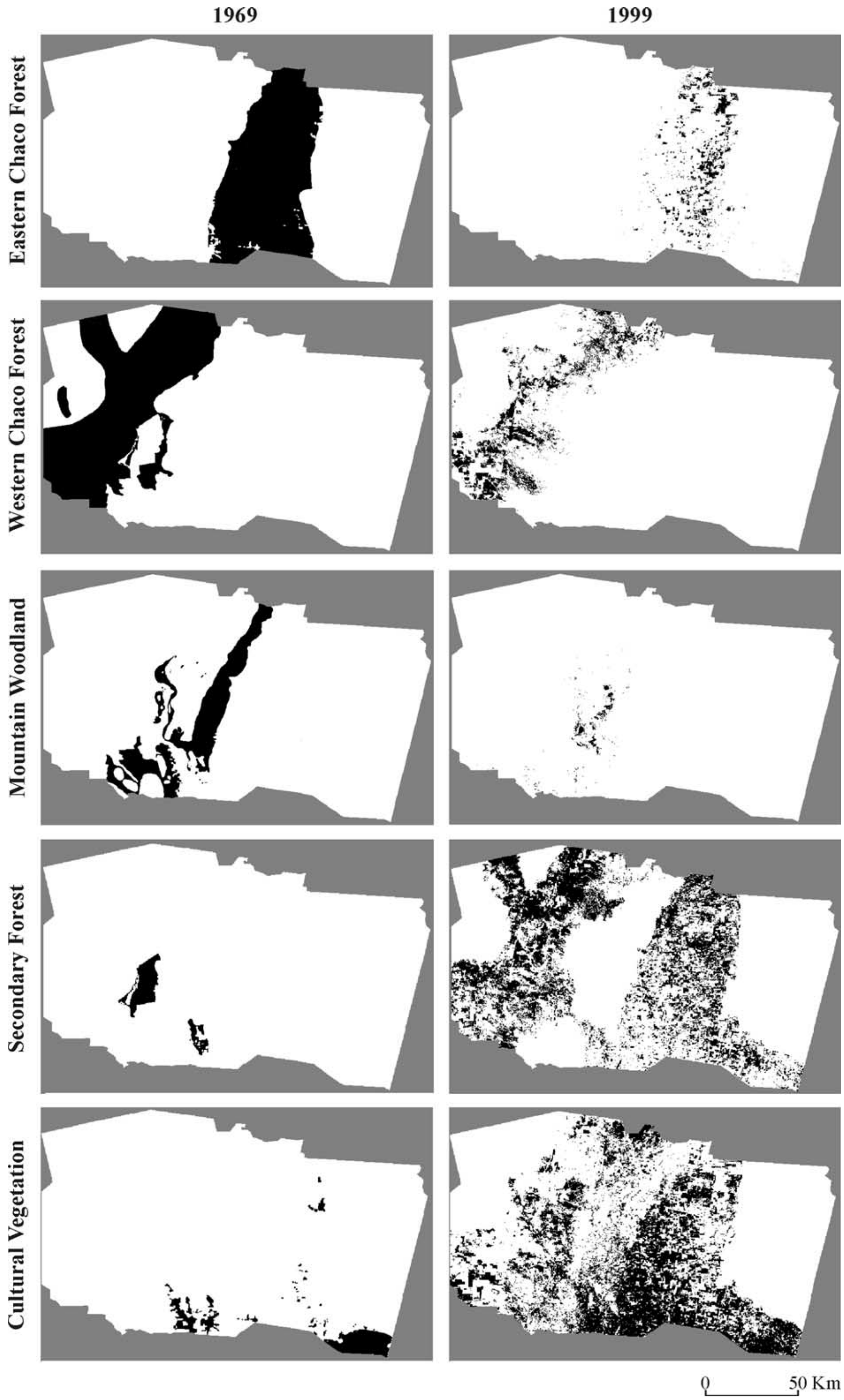

Fig. 2. Land cover changes in the Chaco region of central Argentina between 1969 and 1999. Vegetation patches are shown in black.

5.2. Significance of the results

Land use has long been important in defining the nature of the Chaco landscape. Fire has been used since ancient times to maintain the balance between woody and herbaceous vegetation in the Gran Chaco region (Bucher, 1982). In particular, Amerindians used fire skillfully for hunting and for maintaining grasslands to increase the abundance of herbivores (Eskuche, 1992). When the land was colonized by Europeans, this forests–grassland equilibrium maintained by native people through traditional management practices was disrupted and for a period of more than 400 years has been replaced by management by forest clearance (Morello and Saravia Toledo, 1959a,b; Schofield and Bucher, 1986). These management changes resulted in slow change in vegetational composition. However, recent agricultural expansion has led to an historically unprecedented degree of change. An area previously almost completely covered by forests and woodlands (Kurtz, 1904; Luti et al., 1979, Fig. 1(a)), has been transformed into a highly fragmented mosaic of isolated patches of forest, dense thorny scrubs (locally called "fachinales"), semi-natural grassland, and cultivated land (Fig. 2). Moreover, this process of replacement of forest by cultivated land is still ongoing. Forest clearance was not initially mediated by agricultural objectives. The railway data available for the 20th century indicate that the intensity of logging activities for wood products increased 450 times from 1901 to the 1940s and then declined until the 1980s (Natenzon and Olivera, 1994). Recent change, for the 30 years period of this study, does, however, appear to have been primarily instigated for agricultural purposes. Thus, between 1979 and 1997 landowners of the region requested legal permission to deforest 276,988 ha of the study area (unpublished data from Provincial Environmental Agency) in order to improve its agricultural potential. Agriculture was scarcely developed in the area at the time the paper map was produced by Sayago (1969) (with only 4840 ha declared by producers during the 1957–1958 campaign, unpublished data from the Provincial Secretariat of Agriculture), but since the 1980s the area devoted to agricultural use has shown a tremendous increase (with declared values of 105,925 ha for the 1987–1988 campaign and 149,665 ha for 1999–2000).

Recent changes in the distribution of lowland cover types appear to have been essentially driven by a search for higher agroeconomic yields that has resulted in the southern margin of the Great Chaco region being transformed from natural vegetation into soybean fields and ranches. This change is analogous to what has already happened in the Pampas (Soriano, 1992) and mirrors a general global trend for the 'agricultural improvement' of potentially productive land where agricultural yield is increased as a result of reclaiming marginal land and rendering existing agricultural land more productive. The pursuit of these two objectives generally leads to larger farms, and fewer people working the land, with a greater use of mechanisation, fertilizers, irrigation and higher yielding varieties of livestock and crops.

Data from our study are consistent with this scenario. The area is dry and a shortage of water has in the past been a major constraint to agricultural improvement (Sayago, 1969; Steininger et al., 2001). Since

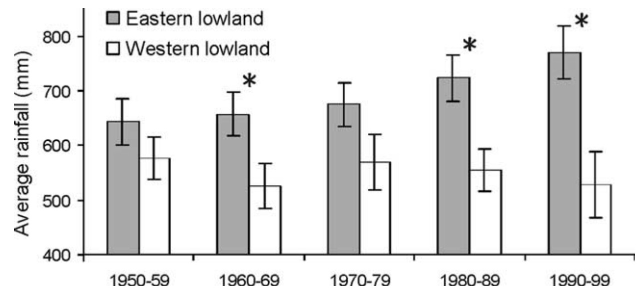

Fig. 3. Rainfall dynamics in the lowlands of the study area from 1950 to 1999. Values represent average rainfall (mm) for each decade. Standard error from the mean is also shown. Asterisks indicate significant differences ($P < 0.05$; t student's test) between annual rainfall in the eastern and western meteorological stations during the same decade.

irrigation is not economically available, a recent increase in annual rainfall has improved the agricultural potential of the region on the eastern plain and forest destruction has accelerated here in comparison to the western plain, where rainfall has not increased appreciably (Fig. 3). Arable agriculture (mainly for maize and soybeans) is now a more economically viable land use, particularly in wet years and has risen from 5% of the total non-saline area in 1969 to 39% by 1999. The price of the land has increased and the number of large farms is rising. Meanwhile, the population of the study area increased from 33,498 to 54,133 (62%) during the last 100 years, while the population of the entire Province increased from 351,223 to 2,766,683 (688%). Therefore, rural populations have declined relative to urban ones (the percentage of the regional population that is in the study area decreased from just below 10% to just above 2%) and there is general evidence that the conversion of forests to agricultural lands has contributed to rural depopulation in Central Argentina (Díaz et al., 1987).

In the agriculturally more marginal uplands the impacts of fire rather than agricultural intensification have had the greatest impact. Recent data show that between 1993 and 1999 more than 322,000 ha of the study area were burnt, with more than 500 different fires registered (Provincial Environmental Agency, unpublished data). These fire events facilitate the extraction of burnt trees for charcoal and wood for fuel in mountain woodland. As a result this cover type has been reduced almost 17-fold and has been largely replaced by scrub. Only in valley bottoms has some of the original woodland been cleared for cultivation. The impact of fire on palm savannas has affected distribution rather than abundance. We suspect that fires have disrupted palm savannas in some areas while facilitating their expansion in other northern sites previously covered by mountain scrub. Only the saline depressions, areas which are unsuited to agriculture, have remained largely unaffected by changing land use. These habitats have instead been modified by hydrological changes associated with fluctuations in the size of the large saline lake.

Similar general patterns of change, and comparable levels of arable expansion and the use of fire, have occurred in most of the South American Chaco region (Morello, 1983; Steininger et al., 2001). Moreover, the loss of Chaco forests coincides with world trends. These show that most changes in forest cover have occurred in the later half of the 20th century (FAO, 1999). The percentage loss of these Chaco forests is, however, much higher than the average 15% clearance since the 1850s for world forests as a whole (Rowe et al., 1992). We estimate that forest is being lost in the Chaco region at an annual rate of 2.2%, one of the highest rates of deforestation in recorded history for such a limited area, and as high, and in some cases even higher, than those recorded for some tropical rain forests (Levenson, 1981; Repetto, 1990; Whitmore and Sayer, 1992; Archibold, 1995; Downton, 1995; FAO, 1999; Ghazoul and Evans, 2001; Steininger et al., 2001). This wholesale habitat destruction is particularly alarming since human conversion of natural habitats is the largest single cause of loss of biodiversity (Hannah et al., 1995; Vitousek et al., 1997; Sala et al., 2000). Moreover, fragmentation of the natural landscape and changes to plant communities affect water and nutrients pathways and ecosystem function in general and potentially local and global climate (Ojima et al., 1994; Matson et al., 1997; Vitousek et al., 1997; Chapin III et al., 2000).

Understanding of the environmental impacts of land cover change requires knowledge of what is being lost due to human intervention. To their credit the Provincial Environmental Agency is already using our results to establish policies restricting further deforestation and have identified regions where no further deforestation should be allowed. Whether these efforts to counter current trends of deforestation in central Argentina will be successful is uncertain: land clearance is still perceived as very economically profitable for the landowners. Moreover, Tilman et al. (2001) predict an even greater expansion of agriculture in Latin America during the next 50 years to meet demands of a larger human population. If so, virtually all of the remaining Chaco forests of central Argentina, formerly the most extended territory with seasonally dry forests in South America (Moglia and Giménez, 1998), will be lost.

Acknowledgements

We thank the Comisión Nacional de Actividades Espaciales (CONAE) and Dr. J.C. Caretti (Instituto Gulich) for providing the satellite images. We are also thankful to Dr. A. Cingolani and an anonymous referee for useful comments on a previous version of the manuscript. Agrim. Gabriel Platzeck and Ing. C. Bartó kindly shared their GIS knowledge. This study was funded by CONICET (0786/98), CONICOR (4519/98), British Council-Fundación Antorchas (BNS 992/21), the National University of Córdoba through SECyT (257/98), the Inter-American Institute for Global Change Research (ISP-I), Agencia Córdoba Ciencia S.E. (Res. 179/2001), Darwin Iniciative (DETR-UK) and the United States Environmental Protection Agency (Contract 68-W6-0055).

References

Adamoli, J., Neumann, R., Ratier, A.D., Morello, J., 1972. El Chaco aluvional salteño. Revista de Investigaciones Agropecuarias 9, 165–237.

Archibold, O.W., 1995. Ecology of World Vegetation. Chapman & Hall, London.

Baban, S.M.J., Luke, C., 2000. Mapping agricultural land use using retrospective ground referenced data, satellite sensor imagery and GIS. International Journal of Remote Sensing 21, 1757–1762.

Baron, J.S., Rueth, H.M., Wolfe, A.M., Nydick, K.R., Allstott, E.J., Minear, J.T., Moraska, B., 2000. Ecosystem responses to nitrogen deposition in the Colorado front range. Ecosystems 3, 352–368.

Bonnie, R., Schwartzman, S., Oppenheimer, M., Bloomfield, J., 2000. Counting the cost of deforestation. Science 288, 1763–1764.

Bowman, D.M.J.S., Walsh, A., Milne, D.J., 2001. Forest expansion and grassland contraction within a Eucalyptus savanna matrix between 1941 and 1994 at Litchfield National Park in the Australian monsoon tropics. Global Ecology and Biogeography 10, 535–548.

Braun-Blanquet, J., 1950. Sociología Vegetal. ACME, Buenos Aires.

Bucher, E.H., 1982. Chaco and Caatinga – South American arid savannas, woodlands and thickets. In: Huntley, B.J., Walker, B.H. (Eds.), Ecology of Tropical Savannas. Springer, New York, pp. 48–79.

Bucher, E.H., Saravia Toledo, C., 2001. Restauración y manejo sustentable del Gran Chaco. In: Primack, R., Roíz, R., Feinsinger, P., Dirzo, R., Massardo, F. (Eds.), Fundamentos de conservación biológica. Perspectivas latinoamericanas. Fondo de Cultura Económica, México, pp. 579–580.

Buse, A., 1992. Environmental effects of land use change, as identified by habitat recording: a case study in the Llyn Peninsula, Wales. Journal of Environmental Management 35, 131–151.

Cabrera, A.L., 1976. Regiones fitogeográficas argentinas. Enciclopedia Argentina de Agricultura y Jardinería. ACME, Buenos Aires.

Carni, A., Jarnjak, M., Ostir-Sedej, K., 1998. Past and present forest vegetation in NE Slovenia derived from old maps. Applied Vegetation Science 1, 253–258.

Chapin III, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Díaz, S., 2000. Consequences of changing biodiversity. Nature 405, 234–242.

Defries, R.S., Townshend, J.R.G., 1999. Global land cover characterization from satellite data: from research to operational implementation? Global Ecology and Biogeography 8, 367–379.

Díaz, S., Bonnin, M., Laguens, A., Prieto, M.R., 1987. Estrategias de explotación de los recursos naturales y procesos de cambio de la vegetación en la cuenca del Río Copacabana (Dpto. Ischilín, Pcia. de Córdoba). I. Mediados del siglo XVI mediados del siglo XIX.

Publicaciones del Instituto de Antropología Nueva Serie 45, pp. 67–131.
Díaz, S., Cabido, M., 2001. Vive la différence: plant functional diversity matters to ecosystem processes. Trends in Ecology and Evolution 16, 646–655.
Downton, M.W., 1995. Measuring tropical deforestation: development of the methods. Environmental Conservation 22, 229–240.
Eastman, J.R., 1997. Idrisi for Windows 2.0. Clark Labs, Worcester.
Eskuche, U., 1992. Sinopsis cenosistemática preliminar de los pajonales mesófilos seminaturales del nordeste de la Argentina, incluyendo pajonales pampeanos y puntanos. Phytocoenologia 21, 237–312.
FAO, 1999. State of the World's Forests. Food and Agricultural Organization of the United Nations, Rome.
Ghazoul, J., Evans, J., 2001. Deforestation and land clearing. In: Levin, S.A. (Ed.), Encyclopedia of Biodiversity. Academic Press, San Diego, pp. 22–36.
Hannah, L., Lohse, D., Hutchinson, C., Carr, J.L., Lankerani, A., 1994. A preliminary inventory of human disturbance of world ecosystems. Ambio 23, 246–250.
Hannah, L., Carr, J.L., Lankerani, A., 1995. Human disturbance and natural habitat: a biome level analysis of a global data set. Biodiversity and Conservation 4, 128–155.
Houghton, R.A., 1994. The worldwide extent of land-use change. BioScience 44, 305–313.
IGBP and IHDP, 1999. Land-use and land-cover change. Implementation strategy. IGBP Report 48, IHDP Report 10, IGBP and IHDP, Stockholm.
Janzen, D.H., 1988. Tropical dry forests. The most endangered major tropical ecosystem. In: Wilson, E.O. (Ed.), Biodiversity. National Academy Press, Washington, DC, pp. 130–137.
Kadmon, R., Harari-Kremer, R., 1999. Studying long-term vegetation dynamics using digital processing of historical aerial photographs. Remote Sensing of Environment 68, 164–176.
Kurtz, F., 1904. Flora. In: Río, M., Achával, L. (Eds.), Geografía de la Provincia de Córdoba. I. Compañía Sudamericana de Billetes de Banco, Buenos Aires, pp. 270–343.
Lambin, E., 1997. Modelling and monitoring land-cover change processes in tropical regions. Progress in Physical Geography 21, 375–393.
Lambin, E.F., Ehrlich, D., 1997. Land-cover changes in sub-Saharan Africa (1982–1991): application of a change index based on remotely-sensed surface temperature and vegetation indices at a continental scale. Remote Sensing of Environment 61, 181–200.
Levenson, J.B., 1981. Woodlots as biogeographic islands in southeastern Wisconsin. In: Burgess, R.L., Sharpe, D.M. (Eds.), Forest Island Dynamics in Man-dominated Landscapes. Springer, New York, pp. 13–39.
Loreau, M., 2000. Biodiversity and ecosystem functioning: recent theoretical advances. Oikos 91, 3–17.
Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J.P., Hector, A., Hooper, D.U., Huston, M.A., Raffaelli, D., Schmid, B., Tilman, D., Wardle, D.A., 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294, 804–808.
Luti, R., Bertrán, M., Galera, M., Muller, N., Berzal, M., Nores, M., Herrera, M., Barrera, J.C., 1979. Vegetación. In: Vázquez, J., Miatello, R., Roqué, M. (Eds.), Geografía Física de la Provincia de Córdoba. Editorial Boldt, Buenos Aires, pp. 297–368.
Mas, J.F., 1999. Monitoring land-cover changes: a comparison of change detection techniques. International Journal of Remote Sensing 20, 139–152.
Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural intensification and ecosystem properties. Science 277, 504–509.
Moglia, G., Giménez, A.M., 1998. Rasgos anatómicos característicos del hidrosistema de las principales especies arbóreas de la región chaqueña argentina. Investigación Agraria: Sistemas y Recursos Forestales 7, 53–71.
Mooney, H.A., Bullock, S.H., Medina, E., 1995. Introduction. In: Bullock, S.H., Mooney, H.A, Medina, E. (Eds.), Seasonally Dry Tropical Forests. Cambridge University Press, Cambridge, pp. 1–8.
Morello, J., 1983. El Gran Chaco: proceso de expansión de la frontera agrícola desde el punto de vista ecológico-ambiental. In: Expansión de la Frontera Agropecuaria y Medio Ambiente en América Latina. CEPAL-PNUMA-CIFCA, Madrid, pp. 341–396.
Morello, J., Saravia Toledo, C., 1959a. El bosque chaqueño I. Paisaje primitivo, paisaje natural y paisaje cultural del oriente de Salta. Revista Agronómica del Noroeste Argentino, vol. 3, pp. 5–82.
Morello, J., Saravia Toledo, C., 1959b. El bosque chaqueño II. La ganadería y el bosque en el oriente de Salta. Revista Agronómica del Noroeste Argentino, vol. 3, pp. 209–258.
Morello, J., Adamoli, J., 1968. Las Grandes Unidades de Vegetación y Ambiente del Chaco Argentino, Primera Parte: Objetivos y Metodología. INTA, Buenos Aires.
Morello, J., Adamoli, J., 1974. Las grandes unidades de vegetación y ambiente del Chaco argentino. Segunda parte: Vegetación y ambiente del Chaco. La vegetación de la República Argentina, Serie Fitogeográfica. INTA, Buenos Aires.
Natenzon, C.E., Olivera, C., 1994. La tala del bosque en los llanos de La Rioja (1900–1960). Desarrollo Económico 34, 263–284.
Noble, I.R., Dirzo, R., 1997. Forests as human-dominated ecosystems. Science 277, 522–525.
Ojima, D.S., Galvin, K.A., Turner II, B.L., 1994. The global impact of land-use change. Bioscience 44, 300–304.
Pascarella, J.B., Aide, T.M., Serrano, M.I., Zimmerman, J.K., 2000. Land-use history and forest regeneration in the Cayey Mountains, Puerto Rico. Ecosystems 3, 217–228.
Pennington, R.T., Prado, D.E., Pendry, C.A., 2000. Neotropical seasonally dry forests and quaternary vegetation changes. Journal of Biogeography 27, 261–273.
Prado, D.E., 1993. What is the Gran Chaco vegetation in South America. I. A review. Candollea 48, 145–172.
Ramankutty, N., Foley, J.A., 1998. Characterizing patterns of global land use: an analysis of global croplands data. Global Biogeochemical Cycles 12, 667–685.
Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in land cover: North American croplands from 1850 to 1992. Global Ecology and Biogeography 8, 381–396.
Ratcliffe, D.A., 1984. Post-medieval and recent changes in British vegetation: the culmination of human interference. New Phytologist 98, 73–100.
Redford, K., Taber, A., Simonetti, J., 1990. There is more to diversity than the tropical rain forest. Conservation Biology 4, 328–330.
Repetto, R., 1990. Deforestation in the tropics. Scientific American 262, 36–42.
Riaza, A., Martinez-Torres, M.L., Ramon-Lluch, R., Alonso, J., Heras, P., 1998. Evolution of equatorial vegetation communities mapped using Thematic Mapper images through a geographical information system (Guinea, Equatorial Africa). International Journal of Remote Sensing 19, 43–54.
Rowe, R., Sharma, N.P., Browder, J., 1992. Deforestation: problems, causes and concerns. In: Sharma, N.P. (Ed.), Managing the World's Forests: Looking for Balance between Conservation and Development. Kendall/Hunt, Iowa, pp. 33–45.
Sala, O.E., Chapin III, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science 287, 1770–1774.

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.

Skole, D., Tucker, C.J., 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science 260, 1905–1910.

Soriano, A., 1992. Río de La Plata Grasslands. In: Coupland, R.T. (Ed.), Natural Grasslands. Introduction and Western Hemisphere. Elsevier, Amsterdam, pp. 367–407.

Steininger, M.K., Tucker, C.J., Ersts, P., Killeen, T.J., Villegas, Z., Hecht, S.B., 2001. Clearance and fragmentation of tropical deciduous forest in the Tierras Bajas, Santa Cruz, Bolivia. Conservation Biology 15, 856–866.

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

Turner II, B.L., Meyer, W.B., Skole, D.L., 1994. Global land-use/land-cover change: towards an integrated program of study. Ambio 23, 91–95.

van der Maarel, E., Boot, R., van Dorp, D., Rijntjes, J., 1985. Vegetation succession on the dunes near Oostwoorne, The Netherlands, a comparison of the vegetation in 1959 and 1980. Vegetatio 58, 137–187.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination on Earth's ecosystems. Science 277, 494–499.

Vogelmann, J.E., 1995. Assessment of forest fragmentation in Southern New England using remote sensing and geographic information systems technology. Conservation Biology 9, 439–449.

Whitmore, T.C., Sayer, J.A., 1992. Tropical deforestation and species extinction. Chapman & Hall, London.

Wang, Y., Moskovits, D.K., 2001. Tracking fragmentation of natural communities and changes in land cover: applications of Landsat data for conservation in an urban landscape (Chicago Wilderness). Conservation Biology 15, 835–843.

Woodcock, C.E., Macomber, S.A., Pax-Lenney, M., Cohen, W.B., 2001. Monitoring large areas for forest change using Landsat: generalization across space, time and Landsat sensors. Remote Sensing of Environment 78, 194–203.

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