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Two decades of Normalized Difference Vegetation Index changes in South America: identifying the imprint of global change

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Abstract. Estimates of carbon uptake at the continental scale become urgently needed as the role of countries as net sinks or sources of carbon gains political and economic importance. Despite uncertainties related to radiation use efficiency, the amount of photosynthetically active radiation (PAR) intercepted by the canopy is a reliable estimator of primary production. Theoretical and empirical data support the relationship between the Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer sensor on National Oceanic & Atmospheric Administration satellites and the fraction of PAR intercepted by green canopies. It is shown, for the period 1981–2000, that there is an overall increase in the radiation intercepted by the canopy over South America by 1.3%, with rainforests making the largest absolute contribution (45%), followed by savannas (23%). Under conditions of minimal agricultural use, disturbance and anthropogenic N deposition, humid temperate forests showed the highest proportional increase in NDVI during the last two decades (4.9%). Deserts showed a net reduction in NDVI relative to the 1981–1985 average (−4.4%). The expansion of agriculture over the last two decades was associated with NDVI reductions over subtropical forests. NDVI trends in South American region highlight a biome-dependent imprint of major global change noticeable in only two decades.

1. Introduction

Estimates of carbon uptake at the continental scale become urgently needed as the role of countries and biomes as net sinks or sources of carbon gains political and economic importance. Global changes, either in atmospheric composition, climate, or land use/land cover, affect the carbon balance of terrestrial ecosystems. In recent years, various complementary approaches have supported the concept of a terrestrial carbon sink but its geographical distribution and magnitude are still under discussion (Houghton 2001, Gurney *et al.* 2002). Studies of ecosystem gas

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exchange at the site level (Grace *et al.* 1995, Goulden *et al.* 1996), forest inventories at the continental level (Birdsey and Heath 1995, Phillips *et al.* 1998, Houghton *et al.* 1999, Fang *et al.* 2001) and tracer transport inversion methods at the global level (Fan *et al.* 1998, Pacala *et al.* 2001) have all suggested a net gain of carbon in terrestrial ecosystems. Satellite data for the 1981–1992 period suggest an increase in light absorption and, consequently, on Net Primary Production (NPP), over extensive areas of the Northern Hemisphere, particularly at high latitudes (Myneni *et al.* 1997). During the last decades all the available studies on carbon budgets focused on Northern Hemisphere forests or the Amazon basin. No data are available for the non-tropical areas of the Southern Hemisphere. Notwithstanding, most carbon budgets assume a net source in the temperate portions of the Southern Hemisphere (Fan *et al.* 1988). The emphasis on Northern Hemisphere environments arises for practical reasons: most of the databases have been developed there (Prentice *et al.* 2000) and most of the scientific community devoted to global change issues concentrates on the Northern Hemisphere. The lack of a detailed analysis of carbon balances for the Southern Hemisphere restricts our ability to understand the global cycle of this element and may have important political consequences: a misunderstanding of the potential to capture carbon may put developing countries in a disadvantageous position in the context of international carbon-trade agreement discussions.

In addition to its contribution to the global C cycle, the Southern Hemisphere presents a useful combination of environmental changes taking place across a broad range of biomes. Large areas of native prairies experiencing agricultural expansion or temperate deciduous forests subjected to the global warming trend but virtually unaffected by anthropogenic nitrogen deposition (Galloway and Cowling 2002), offer a unique opportunity to isolate the effects of global change drivers on carbon gains. The analysis of these scenarios, complementary to those found in the Northern Hemisphere, has the potential to yield new insights into global change effects on terrestrial ecosystem carbon budgets.

In this article are analysed the temporal trends of the Normalized Difference Vegetation Index (NDVI), a spectral index linearly related to the fraction of the photosynthetically active radiation (400–700 nm) intercepted by the canopy (fPAR) over the past two decades in the South American continent. The fraction of PAR intercepted is the main determinant of NPP of the ecosystem (Monteith 1981). To simplify the connection with biophysical processes the continental changes are expressed as total amount of PAR absorbed by the canopy (APAR). Taking advantage of the spatially explicit nature of satellite data, differences in NDVI trends among countries and biomes are investigated. For particular areas of the continent, the links between NDVI trends and current changes in land use/land cover – namely agricultural expansion – are explored. The analysis sought to answer the following questions:

1. By how much has NDVI changed over South America during the last two decades?
2. How did the magnitude and sign of NDVI trends vary among biomes and countries?
3. Is land use/land cover change controlling these changes?

2. Materials and methods

The analyses were based on NDVI data derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor on board the National Oceanic & Atmospheric Agency (NOAA) satellites. The NDVI was calculated as the difference between the reflectance registered by the AVHRR sensor in the near-infrared (channel 2, 730–1100 nm) and visible (channel 1, 580–680 nm) portion of the electromagnetic spectrum divided by the sum of both channels. An NDVI database compiled by NASA (Pathfinder AVHRR Land database, James and Kalluri 1994) with a spatial resolution of $64\,km^2$ and a temporal resolution of ten days (ftp://daac.gsfc.nasa.gov/data/avhrr/) was used. The monthly maximum composites of NDVI were used to reduce additional sources of contamination of the spectral response of the surface. Anomalous data were detected during 1991 and 1994, probably related to the Pinatubo eruption (Tucker *et al.* 2001) and sensor malfunction (Cihlar *et al.* 1998). The analyses were performed both including and removing these data, without observing significant changes in the results. For each pixel the mean annual NDVI was calculated – a linear estimate of fPAR (Sellers *et al.* 1992). The fPAR by terrestrial vegetation is a radiometric surrogate of the Leaf Area Index (Running *et al.* 2000). Monteith (1981) showed that the total amount of radiation absorbed by a plant canopy over a year (APAR, the product of fPAR and the total incoming photosynthetically active radiation, PAR) is positive and linearly related to the net primary production, the rate of plant biomass accumulation in the ecosystem ($gC\,m^{-2}\,a^{-1}$). fPAR was calculated from the annual average NDVI by linear interpolation between the NDVI corresponding to areas with zero light absorption (the Atacama desert, 69°5′ W, 22°5′ S) and near 100% of light absorption (an Amazonian rainforest) ($\mathrm{fPAR} = -0.055 + 1.11 \times \mathrm{NDVI}$).

Radiation data derived from 588 sites distributed over South America were interpolated (FAO 1985). Yearly data on radiation at the continental scale for the period 1981–2000 were not available. Average values were used because the spatial differences in annual incoming radiation are far more important than annual changes. PAR was estimated as 50% of the total incoming radiation (Monteith and Unsworth 1990).

A map of biomes of South America was digitized (Hueck and Seibert 1981). The original units were re-coded into 11 classes: deserts (De), shrub steppes (SS), grass steppes (GS), prairies (Pr), wetlands (We), savanna (Sa), dry temperate forests (DteF), humid temperate forests (HteF), dry tropical/subtropical forests (DtrF), humid tropical/subtropical forests (HtrF) and rainforests (RF) (figure 1). The units and their boundaries were checked with more detailed maps available for the region. The Lambert Azimuthal Equal Area projection was used.

In order to identify APAR trends, a linear regression analysis was performed of the temporal trend of the annual APAR for the 19-year period for each individual pixel using a program written 'ad hoc'. Two images were generated, one for the slope of the relationship APAR–time and one for the significance (p-value) of the relationship. We calculated APAR changes at the biome, country and continental level in two ways: (1) considering the slopes of all pixels; and (2) considering the slope of only those pixels with a significant NDVI–time relationship (F-test, $p < 0.05$) and setting as zero the slopes of the remaining pixels.

Three areas were selected for analysis of the influence of land use/land cover changes on the temporal trends of light interception. These areas corresponded to the western Chaco/Yungas (Dry Tropical Forests and Rainforest), the Pampas

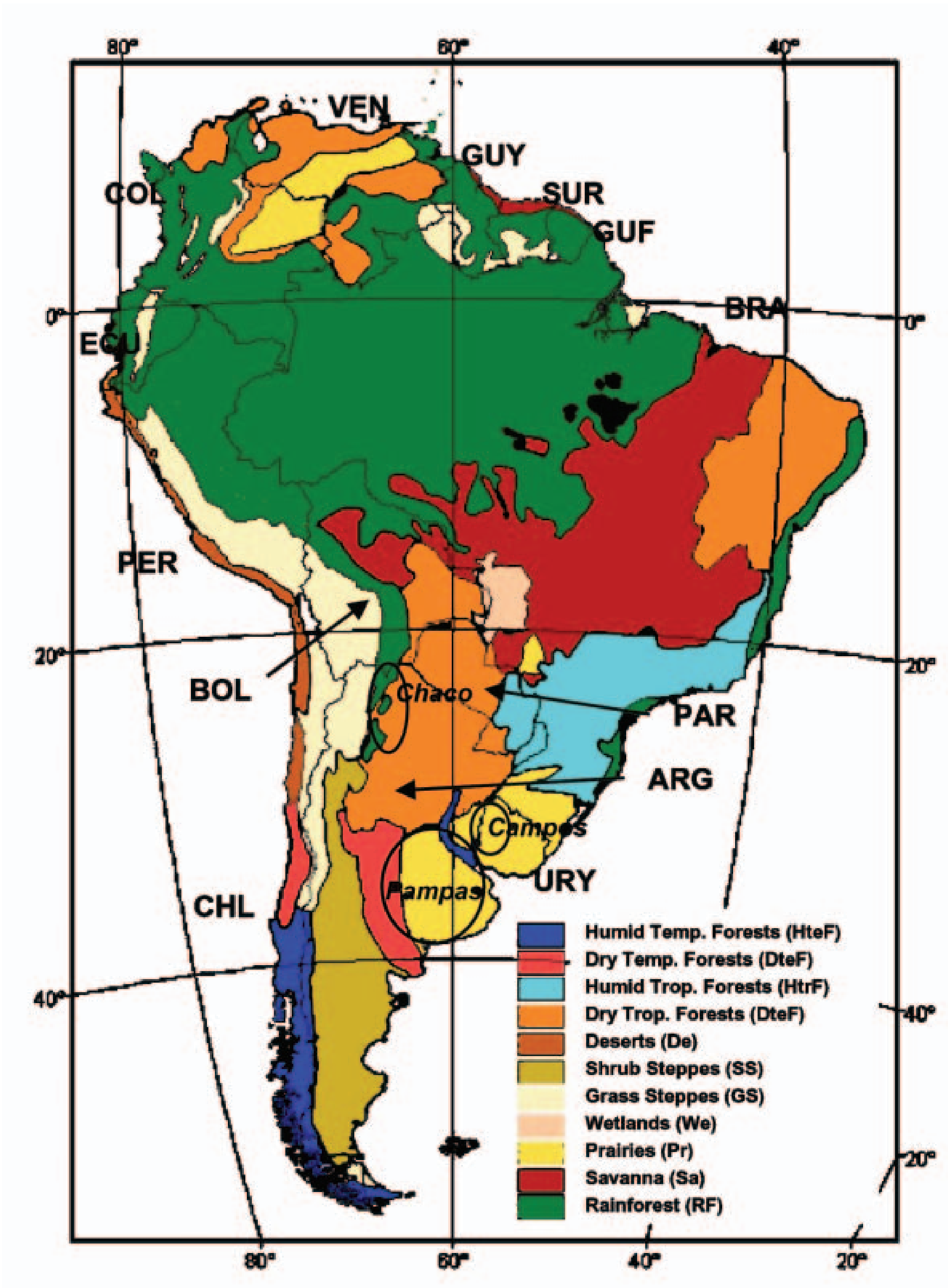

Figure 1. Biomes of South America. Re-elaborated from Hueck and Seibert (1979). ARG, Argentina; BOL, Bolivia; BRA, Brazil; CHL, Chile; COL, Colombia; ECU, Ecuador; GUF, French Guiana; GUY, Guyana; PER, Peru; PAR, Paraguay; SUR, Suriname; URY, Uruguay; VEN, Venezuela. For the circled areas the relationship between land use and NDVI change was analysed.

(Praire) and the Campos (Praire) (figure 1). Contrasting land cover/use changes took place in these areas during the study period: native forest to annual crops in the Chaco/Yungas, native grassland to annual crops in the Pampas and native grasslands to tree plantation (pines and eucalyptus) in the Campos. For these areas data were collected on the area occupied by annual crop/tree plantation for the period 1981–2000. The minimum spatial unit for land use data (county) set the spatial resolution of the analysis ($500\,\mathrm{km}^2$ to $26\,000\,\mathrm{km}^2$). For each county (i.e. 'departamento' in Argentina, 'sección censal' in Uruguay) percent changes in the area devoted to annual crops/tree plantations were calculated. Satellite information was aggregated at the county level.

3. Results

APAR and NDVI significantly increased during the last two decades over South America. The slope of the temporal trend of the NDVI for the whole continent was $1.114\,\mathrm{MJ\,m^{-2}\,a^{-1}}$ considering only those pixels with significant trends ($p<0.05$, $n=37\,225$) (figure 2, inset). This value would represent an average change of 1.26% in APAR, over the 19-year period, with respect to the 1981–1985 average.

Sixteen per cent of the area of South America showed significant temporal

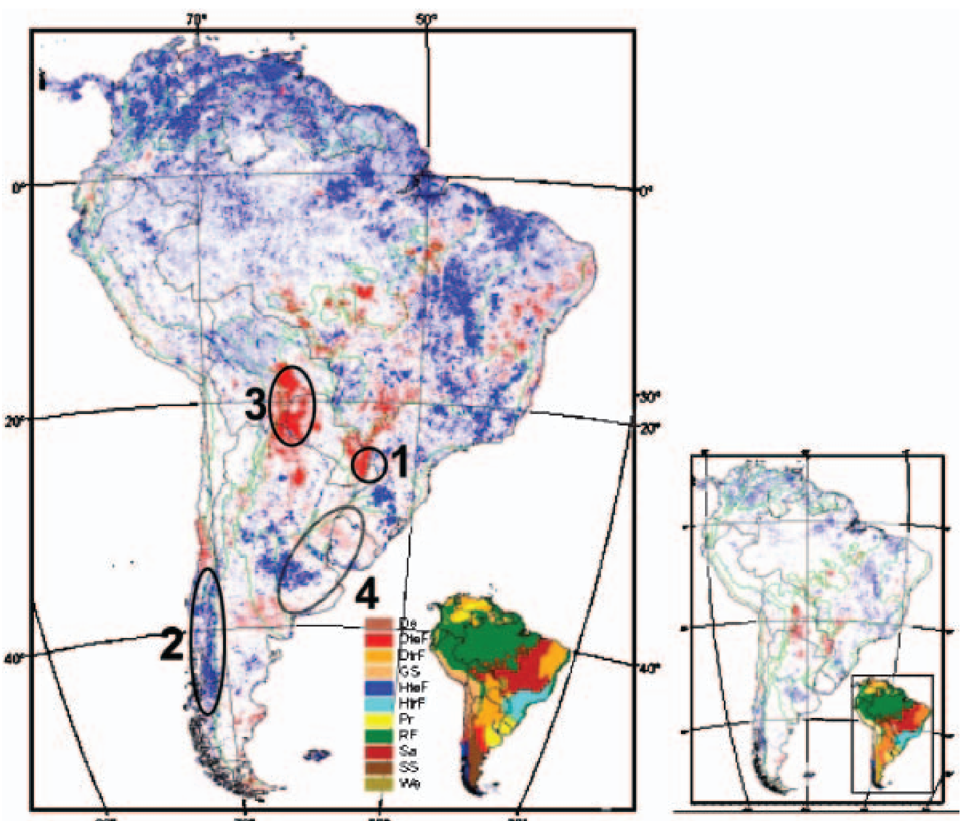

Figure 2. Map of South America displaying the slope of the relationship between the photosynthetically active radiation absorbed by the vegetation (APAR) and time, for the 1981–2000 period. Blue and red pixels represent positive and negative slopes, respectively. The darker the colour, the greater the slope. Green lines correspond to biome boundaries (see lower right inset) and black lines to international boundaries. APAR was calculated from the Normalized Difference Vegetation Index (NDVI) derived from the AVHRR/NOAA satellites. The small map shows only those pixels with a statistically significant trend ($p<0.05$).

Table 1. Percentage of the South American continent (%SA) cover under different biomes and changes in the amount of APAR over the period 1981–2000.

Biome	%SA	% +	% −	dAPARall	dAPAR ($p<0.05$)
De	1.7	5.5	13.7	−4.4	−0.7
SS	5.2	3.8	4.2	−3.6	0.0
GS	7.9	10.9	2.4	3.3	2.5
Pr	6.3	25.5	0.8	3.7	4.0
We	0.9	14.9	1.2	4.0	1.6
Sa	14.7	17.9	4.4	2.1	1.8
DteF	2.1	10.8	5.5	−1.2	0.9
HteF	2.4	20.7	1	4.9	5.1
DtrF	15.7	9.6	8	0.4	0.1
HtrF	5.8	15.1	8	1.2	0.2
RF	37.6	10.4	1.3	3.4	1.1
Total continent	12.5	3.7	2.6	1.3	

Biomes: deserts (De); shrub steppes (SS); grass steppes (GS); prairies (Pr); wetlands (We); savanna (Sa); dry temperate forests (DteF); humid temperate forests (HteF); dry tropical forests (DtrF); humid tropical forests (HtrF); rainforest (RF).

% +, percentage of the area of each biome showing positive changes in the amount of APAR ($p<0.05$).

% −, percentage of the area of each biome showing negative changes in the amount of APAR ($p<0.05$).

dAPARall, percentage of change in APAR for each biome as estimated from all the pixels.

dAPARp <0.05, percentage of change in APAR for each biome as estimated from those having a statistically significant trend ($p<0.05$).

Changes in APAR were calculated with respect to the 1981–1985 average.

APAR was estimated from the NDVI derived from NOAA/AVHRR satellites.

changes of NDVI over the 19-year period, with increases being dominant (12.5% increases vs 3.7% decreases) (figure 2, table 1). Individual biomes differed in the magnitude and direction of the changes. More than 25% of the area occupied by prairies displayed a significant increase in NDVI (NDVI decreased in less than 1% of the area of this biome), whereas desert and shrub-steppes showed the lowest proportion of significant changes, with NDVI decreases being most common. Both dry and humid tropical forests showed a relatively high proportion (8%) of pixels with a negative trend (table 1). Figure 3 presents examples of the temporal dynamics for individual pixels located in the areas highlighted in figure 2.

APAR/NDVI changes over the 19-year period, relative to the 1981–1985 average, ranged from 5.1% for humid temperate forests to −0.7% for deserts when only significant pixels were considered (table 1). When all the pixels were included, NDVI changes ranged from 4.9% to −4.4% for the same extreme biomes (table 1). Only for dry temperate forests the sign of the NDVI trends changed depending on the criteria used (all pixels or those with a significant trend, $p<0.05$).

Spurious patterns resulting from the influence of atmospheric contamination, bidirectional reflectance or sensor degradation on the NDVI data calculated from the reflectance measured by the AVHRR sensor cannot be ruled out (Rasool 1999, Burgess and Pairman 1997). However, the analysis of areas with highly predictable behaviour suggests a negligible impact of such artefacts on these results. For example, those biomes severely limited by water (shrub steppes and deserts) and, hence, with the lowest probability of responding to changes in atmospheric CO_2, showed negative or null changes in NDVI. In addition, potential artefacts on the

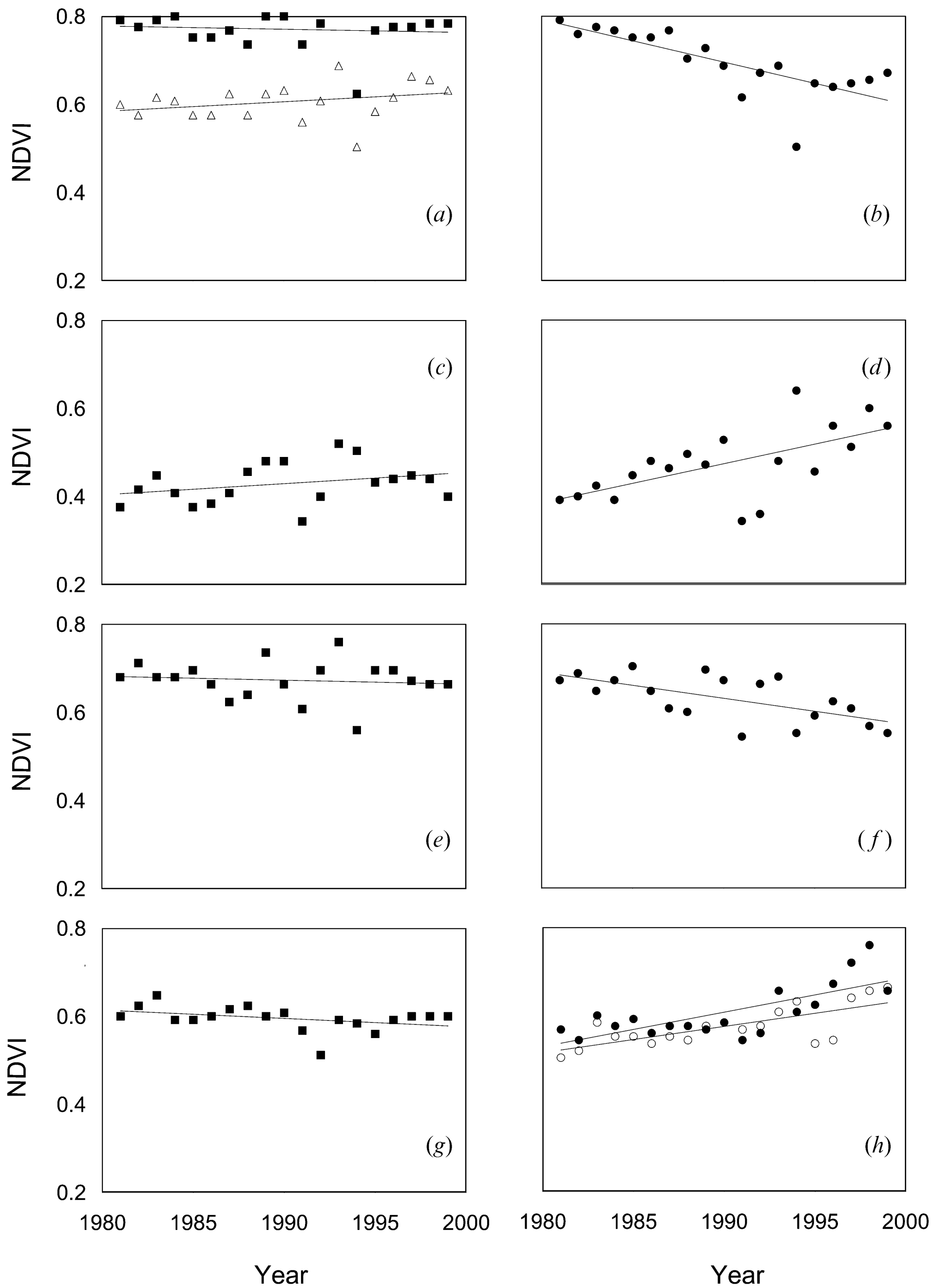

Figure 3. NDVI temporal trajectories of individual pixels showing no changes (left panels, white pixels in figure 2) and significant ($p < 0.05$) changes (right panels, blue and red pixels in figure 2) for (*a*) Humid Tropical Forest (1 in figure 2) in Argentina (squares, protected areas), Brazil (triangles, croplands since before the studied period) and (*b*) Paraguay (circles, areas recently transformed into croplands); (*c*), (*d*) Humid Temperate Forest (2 in figure 2) in Argentina; (*e*), (*f*) Dry Tropical Forests (3 in figure 2) in Bolivia (*e*, forests; *f*, deforested areas); (*g*), (*h*) Prairies in Argentina and Uruguay (4 in figure 2) (*g*, natural grasslands; *h*, agricultural areas – open circles correspond to annual crops and closed circles to afforested areas).

origin of the temporal trends were checked for by inspecting the NDVI slope of continental glaciers in southern Argentina and Chile (73°30′ W, 49°38′ S) and in the Salar de Uyuni in Bolivia (68° W, 20° S). None of the pixels in these areas showed a significant trend in NDVI. Net Primary Production was not calculated from APAR because of the uncertainties associated with the NPP estimates derived from Monteith's model. A critical assumption is the value of ε. The available values in the literature (i.e. Ruimy *et al.* 1994, Field *et al.* 1995) provide a unique value for the whole biome (no spatial variability) and there are no descriptions of the temporal variability of ε. On the other hand, to assign an ε value to a pixel based on the actual vegetation requires reliable maps of land cover of the continent. Guerschman *et al.* (2003) showed that the available land cover maps of South America represent poorly the spatial heterogeneity of the actual vegetation and most of them were developed using NOAA-AVHRR imagery, which for the purpose here would cause a problem in circularity. At the country level the most positive and negative changes of NDVI and APAR per unit of area were observed in Venezuela and Paraguay, respectively (figure 4). Paraguay, originally covered by subtropical forests, displays the largest rate of agricultural expansion in the continent (1.84% per annum, according to FAO, http://apps.fao.org). The highest localized decrease in NDVI was observed in south-eastern Bolivia, an area displaying one of the largest deforestation rates in the world (Steininger *et al.* 2001). The magnitude of NDVI change at the country level showed a statistically marginal negative association with the rate of change of the area devoted to agriculture (FAO, http://apps.fao.org) ($R=0.54$, $n=12$ (countries), $p=0.067$). Both cases are exemplified at the pixel level in figure 3(*b*) and 3(*f*).

For the three areas of the southern portion of South America analysed (figure 1) a significant relationship was found between the rate of change of the NDVI and a measure of land use change during the 1981–2000 period (figure 5). In

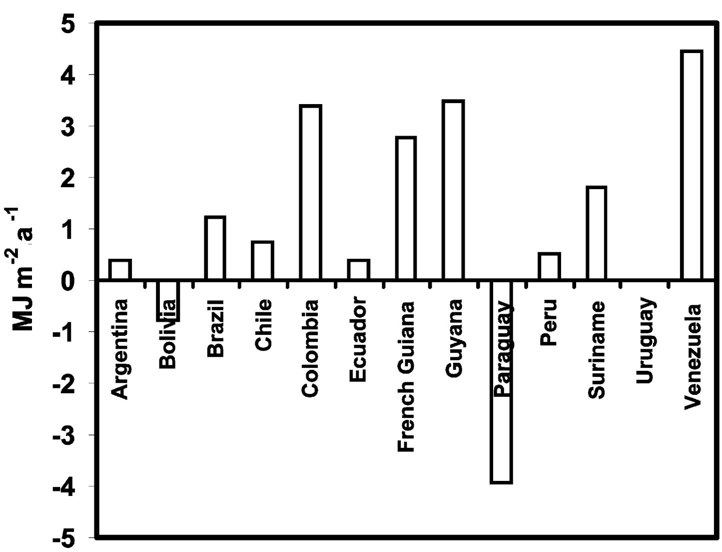

Figure 4. Average change in the photosynthetically active radiation absorbed by the vegetation (APAR) over the period 1981–2000 for the South American countries. Data derived from computing only those pixels displaying a statistically significant trend.

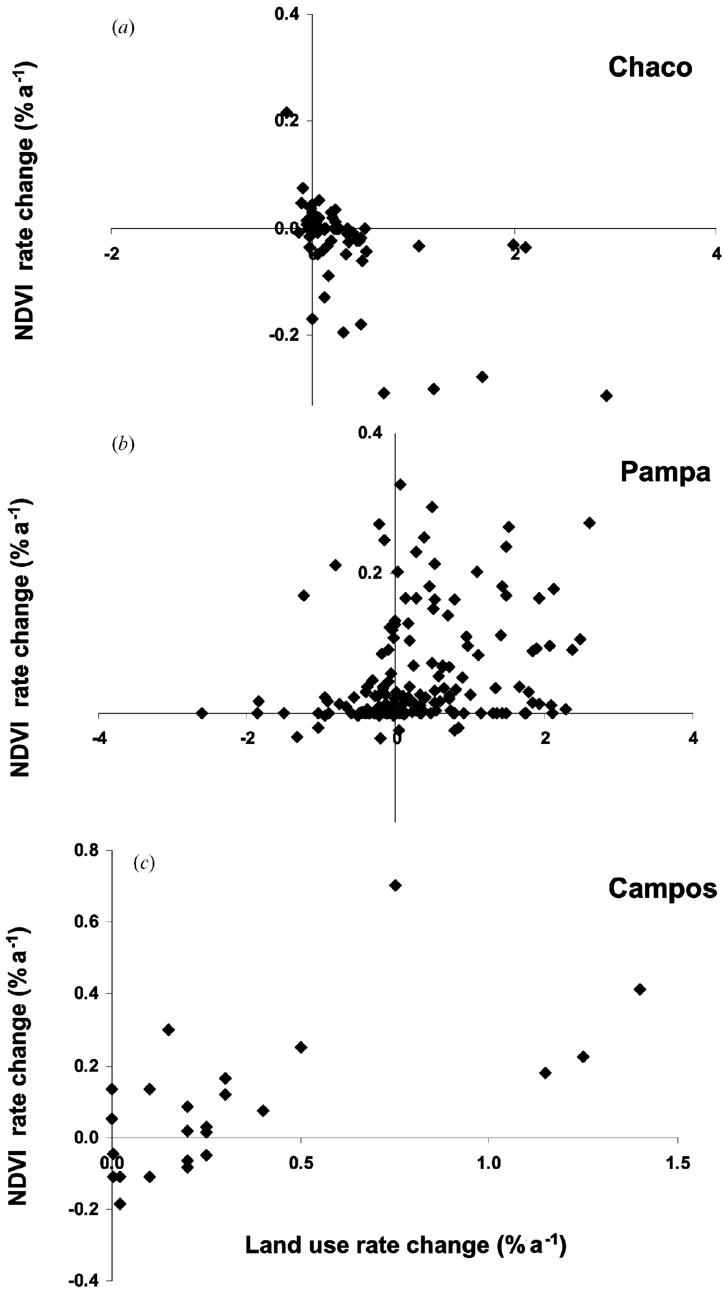

Figure 5. Relationship between the annual change in the annual mean NDVI (% a^{-1}) and the annual change in the percentage of cropland area for counties located in (*a*) humid and dry tropical/subtropical forest of the Salta, Jujuy, Formosa, Chaco and Tucumán provinces of Argentina (% a^{-1}) and (*b*) the prairies and the border of the dry temperate forests of the Argentine pampas (Provinces of Buenos Aires, Santa Fe, Córdoba and La Pampa). (*c*) Relationship between the annual change in the annual mean NDVI (% a^{-1}) and the annual change in the percentage of afforested area for counties ('secciones censales') of the departments of Paysandú and Río Negro (Uruguay). Land use/land cover data were obtained from SAGPyA (2000) (Argentina) and MGAP (2000) (Uruguay).

north-western Argentina, agriculture expanded rapidly during the last decade over subtropical forests (SAGPyA 2000). For these forests, NDVI at the county level decreased as the area devoted to agriculture increased ($R=0.61$, $n=74$, $p<0.01$) (figure 5(*a*)). A similar trend of agricultural expansion took place in the Argentine Pampas, where native prairies were replaced by crops. For counties within this region, the rate of increase of cropland area was not significantly associated with the rate of change in NDVI (figure 5(*b*)). However, most of the positive changes occurred in counties where the agricultural area increased during the period 1981–2000. The average increase in NDVI was 0.031% a^{-1} ($SE=0.0074$, $n=68$) for counties with a negative trend in agriculture expansion and 0.069% a^{-1} ($SE=0.0087$, $n=93$) for counties with a positive trend. Open circles in figure 3(*h*) exemplified the temporal change in NDVI on such cropped areas.

In western Uruguay, *Eucalyptus* and *Pinus* plantations have replaced native grasslands during the last two decades. The rate of change of NDVI showed a positive relationship with the percentage of the county area implanted with trees ($R=0.63$, $n=24$, $p<0.01$) (figure 5(*c*)). The behaviour of a pixel located in areas dominated by *Eucalyptus* plantations is represented by the closed circles in figure 3(*h*). The results suggest that land use may have different effects on NDVI depending on the biomes being replaced (grasslands or forests) and the type of crop (annual vs perennial). The replacement of forests by crops and pastures would reduce NDVI, whereas the replacement of native grasslands by forests would increase NDVI.

4. Discussion

Evidence is presented for an increase in the annual mean Normalized Difference Vegetation Index for South America over the last two decades. Estimates of the magnitude of the change in carbon uptake of the region are not provided because of the uncertainties associated with the biome/crop-specific radiation use efficiency coefficients and with the lack of annual data of radiation on a monthly basis over the whole continent. The analyses do provide, however, figures for a variable clearly related to carbon exchange over an understudied zone of the globe. The magnitude and sign of the changes in NDVI varied among biomes and countries. Rainforests, savannas and prairies cover 58% of South America but accounted for more than 80% of the total annual increases in continental NDVI. Rainforests made the largest contribution to the increase in NDVI at the continental scale.

Pixels showing positive or negative NDVI trends were not randomly interspersed across the continent, but aggregated displaying clear spatial patterns. The biotic and political controls of land use/land cover changes were evidenced by some sharp boundaries (figure 2). Three areas were selected to exemplify these effects. In eastern Paraguay, (area 1 in figure 2) the zone showing negative changes (red) was sharply constrained by the international boundaries of the country, suggesting that agricultural expansion was the responsible factor. During the last two decades, soybean production increased dramatically in Paraguay. In the adjacent Brazilian territory, agricultural expansion took place earlier and the area occupied by annual crops remained high and stable throughout the study period. In the adjacent Argentine territory, native forest has been protected and little conversion to agriculture occurred. The positive changes in south-western South America (blue) (area 2 in figure 2) were clearly restricted to the Andean humid temperate forests and did not extend eastward into the Patagonian shrub-steppes. It is speculated that temperature increases are responsible for these changes. Towards the west of this region, where NDVI increases are observed, precipitation levels are high and plant productivity is constrained by temperature through its effect on the length of the growing season (Jobbágy *et al.* 2002). Towards the east, water becomes the main constraint on carbon uptake (Paruelo *et al.* 2000, Jobbágy *et al.* 2002) and, consistently, NDVI changes vanished. Finally, on the southern part of the Yungas (rainforest) and the western Chaco (dry tropical forest), the area of negative NDVI changes (area 3) did not protrude beyond the border with the grass steppes of the Puna (grass-steppe) where either rain-fed agriculture is absent or does not create significant NDVI changes.

Multiple causes may be responsible for the described changes in NDVI and, hence, on light interception: atmospheric CO_2 increment, increases in air temperature, biological invasions, deforestation, afforestation and agricultural expansion. Unlike the Northern Hemisphere, anthropogenic nitrogen deposition can be ignored as an important driver of NPP changes in South America (Bouwman *et al.* 1997, Holland *et al.* 1999). CO_2 fertilization may account for a background increase in carbon gain over the whole area, irrespective of land use (Melillo *et al.* 1995). Experimental studies have shown an important increase in forest productivity with rising atmospheric CO_2 concentration (Norby 1999).

The NDVI and APAR increases in Southern Chile may be explained not only by increases in temperature, as indicated above (area 2 in figure 2), but also by CO_2-mediated effects on the humid temperate forest. More than 96% of this area (XIth region of Chile) is under native vegetation (INE 1997) and forests are mostly in a late (old growth) successional stage (Armesto *et al.* 1994) and experience negligible nitrogen input (Hedin *et al.* 1995). Hence, the significant rise in APAR observed for 20.7% of the pixels of the region is likely to be due to CO_2 fertilization and/or temperature increases and cannot be attributed to successional changes and/or nitrogen input, as proposed for temperate humid forests of the Northern Hemisphere. Prairies and dry tropical forests in Venezuela and Colombia also showed increases in light interception. In addition to temperature and CO_2 fertilization effects, the invasion by African C_4 grasses may account for the regional changes in NDVI in this part of the continent (Williams and Baruch 2000). In contrast, an important area dominated by native prairies (the south-eastern portion of the Argentine Pampas) did not show any trend in APAR.

One basic problem to evaluate quantitatively the influence of some of the climatic or atmospheric factors on light interception changes is to quantify their spatial patterns. The spatial patterns of land use/land cover changes can be characterized, at least at certain temporal and spatial scales. Correlative evidence is presented of a relationship between land use/land cover changes and the rate of NDVI change. Such quantitative hypotheses on the impact of agriculture on carbon uptake may provide important information to policy makers regarding carbon trade issues. These results suggest that the pressure to increase the income of less developed countries of southern South America (mainly through exporting agricultural commodities) will result in a net reduction of carbon fixation if croplands replace subtropical forests. The consequences of land use change on the ability of a whole country to provide ecosystem services (i.e. carbon sequestration) would be incorporated into the design of environmental, as well as socio-economic policies.

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