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LAND USE IMPACTS ON THE NORMALIZED DIFFERENCE VEGETATION INDEX IN TEMPERATE ARGENTINA

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Abstract. We studied the impacts of land use in temperate Argentina on the normalized difference vegetation index (NDVI), which has often been used to estimate the interception of photosynthetically active radiation and carbon uptake by terrestrial vegetation. The NDVI was derived from the National Oceanic and Atmospheric Administration (NOAA) satellites. We incorporated land use, climate, soil, and NDVI data into a geographic information system with a county-level spatial resolution. Land use was characterized in terms of the proportion of different crop types at the county level. Three attributes were derived from the seasonal dynamics of the NDVI: the annual integral (NDVI-I), the difference between the maximum and minimum NDVI divided by the integral (RREL), and the date of maximum NDVI (DMAX). The environmental controls of the NDVI attributes for the counties showing the lowest proportion of croplands (''low-impacted vegetation'' areas, LIV) were analyzed using stepwise multiple regressions with the three NDVI attributes as dependent variables and the climatic and soil variables as independent variables. Mean annual precipitation, evapotranspiration, and the seasonality of precipitation were the main determinants of the spatial distribution of the NDVI attributes in the LIV areas. We applied these models to counties with a high proportion of croplands, and we analyzed the magnitude of the difference between the observed and predicted values and their correlation with land use variables. The LIV model for NDVI-I did not differ by more than 15% from the observed values in the counties with a high proportion of crops. This indicates a low impact of land use on the NDVI-I. In contrast, the LIV models for RREL and DMAX, two indices that describe the seasonality of NDVI, did not predict accurately these attributes in the highly cropped areas. Annual crops increased RREL up to 80%. Winter crops advanced DMAX and summer crops delayed DMAX, in both cases up to 150 d compared to the LIV areas. The interannual variability of NDVI-I was negatively correlated with the mean NDVI-I. This agrees with previous observations on unmodified areas of the Northern Hemisphere. The interannual variability of the three attributes of the NDVI curve decreased as the proportion of the cropped area of the county devoted to summer crops increased. Our results are relevant to the impacts of land use on the timing and magnitude of energy and carbon exchange in temperate agricultural systems and clarify how agricultural land use can be better represented in regional and global models of energy and carbon exchange.

Key words: aboveground net primary production (ANPP); agriculture; Argentina; land use change; NDVI; NOAA/AVHRR; remote sensing; temperate ecosystems.

Introduction

Land use is an important component of global change (Vitousek 1992, IPCC 2000). Urbanization, desertification, and agriculture are three examples of human-driven land use changes that have dramatically altered the surface of the earth. These changes affect many processes in temperate areas, including mesoscale atmospheric circulation (Pielke et al. 1998), trace gas emission (Mosier et al. 1991), soil properties (Burke et al. 1989, Robles and Burke 1997), erosion (Pimentel et al. 1995), and carbon dynamics (Baron et al. 1998).

The characterization of the carbon cycle at global and regional scales is receiving a great deal of attention (e.g., Melillo et al. 1993, Myneni et al. 1997). Agriculture plays an important role in the carbon cycle. The replacement of natural vegetation by annual crops produces a rapid loss of organic matter of the soils through microbial respiration (Burke et al. 1989). The impact of agriculture on carbon uptake is, however, not completely understood (Kicklighter et al. 1999, Paruelo et al. 2001). For instance, it is not clear whether it increases or decreases the amount of radiation absorbed by the canopy (and, thus, net primary productivity) compared to potential vegetation (Ruimy et al. 1999). It is also unclear how agriculture changes the seasonality of carbon uptake. In an analysis that compared

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how four global biogeochemical models represented the effects of changes in atmospheric carbon dioxide, climate, and agricultural land use during the 20th century, variability in the simulated dynamics of agricultural production, harvest, and decomposition of agricultural products contributed substantially to uncertainty among the models (McGuire et al. 2001). To reduce these uncertainties, there is a need to develop regional and global data sets that define the spatial distribution and temporal changes in agricultural management practices (McGuire et al. 2001). We also argue that there is a need to better understand how different management practices influence carbon dynamics in agricultural systems at regional scales.

The temperate portion of South America provides a great opportunity for analyzing the impacts of land use on ecosystem functioning because of its strong climatic gradient, both in precipitation (from east to west) and temperature (from north to south). The potential vegetation of the region includes humid and dry savannas, temperate forests, humid and semiarid grasslands, shrublands, and grass-steppes. Several studies show a climatic similarity (Paruelo et al. 1995) that leads to an ecological convergence (Paruelo et al. 1998) between the temperate areas of North and South America. As in the Great Plains of North America, agriculture was introduced in the 18th century and intensified in the 20th century. However, irrigation and fertilization did not expand as widely as in the Great Plains (Hall et al. 1992). Anthropogenic nitrogen deposition is negligible in the area (Hedin et al. 1995). This indicates that the biogeochemical cycles have not been altered to the same degree as in other areas of the world. Despite the importance of land use change, reliable estimates of land cover types distribution in South America are scarce (Ramankutty and Foley 1998).

Carbon uptake (net primary production) integrates many important features of ecosystem functioning (McNaughton et al. 1989). Total carbon uptake is positively related to the total amount of energy intercepted by the canopy (Monteith 1981). The proportion of photosynthetic active radiation (PAR) intercepted is linearly related to the normalized difference vegetation index (NDVI), a spectral index derived from the red and infrared reflectance recorded by the National Oceanic and Atmospheric Administration (NOAA) meteorological satellites (Dye and Goward 1993, Sellers et al. 1994). The NDVI has been used as a surrogate of carbon uptake in many studies at local, regional, and global scales (e.g., Paruelo et al. 1995, Myneni et al. 1997, Jobbágy et al. 2002). Its coarse spatial resolution (1 km) is adequate for monitoring actual vegetation over large areas and its high temporal resolution (10- or 15-d composites) allow for a good repeatability in time.

Paruelo et al. (2001) mapped the current ecosystem functional types in temperate South America using remotely sensed data. They suggested that in grasslands and savannas the conversion of natural vegetation to croplands caused changes in the amplitude and date of maximum NDVI but did not change the NDVI annual integral. The differences in NDVI between natural vegetation and croplands have implications for regional energy and carbon exchange. Therefore, in this study we extend the work of Paruelo et al. (2001) to evaluate the impacts of land use on the seasonal and interannual variability in NDVI of temperate grasslands and savannas of Argentina. To do this we used three attributes derived from the seasonal course of the NDVI that characterize the total amount of carbon intercepted by the vegetation and its seasonality. Land use was described as the proportion of the land occupied by crops. Using correlative models we analyzed the relationships between environmental factors (climatic and edaphic) and the spatial patterns of the NDVI attributes in areas with low anthropogenic impact. We assumed that these models provide the best possible representation of the relationship between the environment and ecosystem functioning of the potential vegetation of the area. We applied these models to areas with high proportion of croplands, and we analyzed the magnitude of the deviation between the observed and predicted patterns. Also, we analyzed the effect of land use on the interannual variability of these NDVI attributes. We sought to answer the following specific questions: (1) What is the relationship between environmental factors and the NDVI dynamics in areas where the vegetation has been slightly modified (''low-impacted vegetation'' areas) of temperate Argentina? (2) How does land use modify the NDVI dynamics compared to low-impacted vegetation areas? (3) What is the impact of land use on the interannual variability of the NDVI dynamics? Before addressing these objectives we examined the spatial distribution of the land use descriptors as well as the climatic and edaphic variables. Based on this analysis we decided to restrict the analysis of the NDVI dynamics to a subarea of temperate Argentina.

METHODS

The region

We focused our study on the temperate portion of Argentina. We set the northern boundary of the temperate zones at 30° S latitude. From a phytogeographical viewpoint the study area included the Chaco and Espinal savannas, the Pampa grasslands, the Monte shrub-steppes and the Patagonian steppes and semideserts and the Subantartic forests in western Patagonia (Soriano 1956, 1993, Morello 1958, Cabrera and Willink 1976, Paruelo et al. 1991). Land use practices in temperate areas of Argentina both converted and modified the original land cover. Large areas of the arid and semiarid portions of South America have been modified by grazing since the beginning of the 20th century, producing changes in both the structure and functioning of the ecosystems (León and Aguiar 1985, Ares et al. 1990, Aguiar et al. 1996, Perelman et al.

1997, Bertiller and Bisigato 1998). The more humid areas have been grazed for more than 400 yr (Soriano 1993). Cultivation became a major disturbance in the subhumid and humid grasslands a century ago (Hall et al. 1992). The main annual crops in these areas are wheat, oat, maize, sunflower, and soybean. Perennial crops include pastures for direct grazing or hay production. Croplands are mostly rain-fed; irrigation is restricted to some valleys in the Patagonian steppes and the Monte shrub-steppes and is not important at the scale of our analysis.

The data

We integrated land use, climate, soils, and NDVI information into a database. This database was associated with a Geographic Information System. Land use data were extracted from the most recent Argentine National Agricultural Census (INDEC 1988). The spatial resolution of the census is the county. This fact determined the spatial resolution of the entire database. We derived five variables from the census. The proportion of the area of the county occupied by croplands (PCROP) included both annual and perennial crops. Non-cultivated areas (1 − PCROP) corresponded to natural grasslands, natural forests, roads, urban, federal lands, and national parks. We accounted for the different crops and management practices of the region by using four additional variables: the proportion of the cropped area of the county devoted to summer crops (PSUM; mainly maize, sunflower, soybean, and sorghum), winter crops (PWIN; mainly wheat, oats, and barley), and perennial crops (PPERNN; cultivated pastures; PSUM + PWIN + PPERNN = 1). The wheat–soybean double cropping system was introduced in Argentina in the early 1970s and expanded rapidly (INDEC 1996). Because of its importance in extent and its potential for high carbon uptake we included this land use type in our analyses (PSOY). Only counties located south of latitude 30° S were considered. Subtropical areas were excluded from our analysis. Urban counties close to Buenos Aires and other major cities were also excluded.

Climatic data were extracted from FAO (1985). We interpolated and aggregated to the county level data from 190 meteorological stations in Argentina, Uruguay, Chile, and southern Brazil. The FAO database includes mean monthly values of precipitation, temperature, and potential evapotranspiration for the period 1930–1960. The more recent climatic data available have a poorer spatial resolution than FAO's database and a very heterogeneous temporal extent. We used this data to calculate for each county mean annual precipitation, mean annual temperature, the proportion of annual precipitation falling in summer, fall, winter, and spring, and mean annual potential evapotranspiration. Paruelo et al. (1995) showed that these variables summarized most of the spatial climatic variability of temperate South America. We extracted edaphic information from the Soil Atlas of Argentina (SAGyP-INTA 1990). For each county we calculated the mean values of the proportions of clay, sand, and silt of the shallowest horizon, the degree of soil salinity and alkalinity, the mean soil depth, and drainage characteristics.

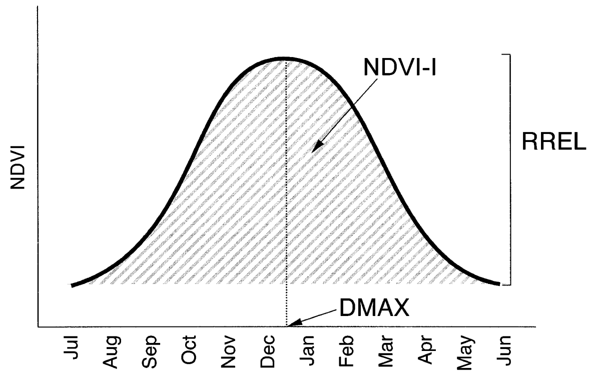

FIG. 1. Schematic representation of the normalized difference vegetation index (NDVI) seasonal dynamics and the three attributes derived: NDVI-I, NDVI annual integral; RREL, relative range of the NDVI (difference between the maximum and minimum NDVI divided by the integral); DMAX, date (month) of maximum NDVI (July = 1, August = 2, etc., June = 12). The three attributes were calculated for the period 1981–1999 in temperate Argentina.

We used the normalized difference vegetation index (NDVI) derived from the advanced very high resolution radiometer (AVHRR) sensor on board the NOAA satellites to characterize ecosystem functioning. NDVI combines spectral data of channel 1 (red, 580–680 nm) and channel 2 (near infrared, 725–1100 nm): NDVI = (channel 2 − channel 1)/(channel 2 + channel 1). Green vegetation shows a differential reflectance in these two bands. Active photosynthetic surfaces reflect a higher proportion of the incoming radiation in the infrared band and a lower proportion in the red band. We used the NOAA/NASA Pathfinder AVHRR land data set, created by NASA (James and Kalluri 1994). This data set comes from NOAA-7, -9, -11, and -14 satellites and was radiometrically and spatially corrected (for details see James and Kalluri 1994, Rao and Chen 1995). The scenes have a spatial resolution of 8 × 8 km and cover the whole globe. We used the 10-d maximum value composite for the 1981–1999 period (a total of 684 images) for the portion of the images south of 30° S. The maximum NDVI value represents the highest count registered by the satellite during the 10-d period. This method minimizes the effects of clouds, snow, or geometric problems such as low solar zenith or observation angles. We calculated three traits from the seasonal curves of NDVI: the annual integral, the relative annual range of NDVI, and the date of maximum NDVI (Fig. 1). These three attributes characterize most of the spatial heterogeneity of the NDVI curves (Tucker et al. 1985*a*, Loveland et al. 1991, Paruelo et al. 1991, Paruelo and Lauenroth 1995). They also capture important features of the ecosystem func-

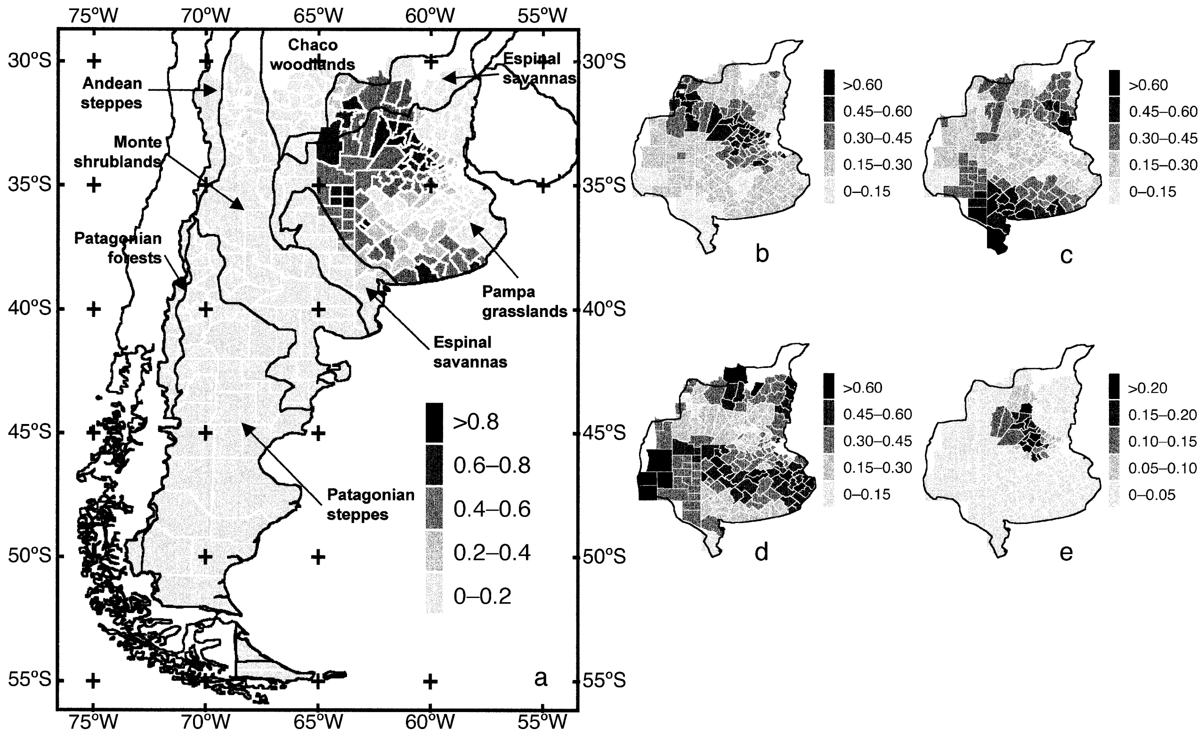

FIG. 2. (a) Proportion of the area of each county devoted to crops in temperate Argentina. (b–e) Proportion of the total cropped area occupied with (b) summer crops, (c) winter crops, (d) perennial crops, and (e) wheat–soybean double cropping in the Pampa and Espinal phytogeographic units. White lines indicate inter-county boundaries. Phytogeographic units were adapted from Cabrera and Willink (1976), Soriano (1993), and Paruelo et al. (1991).

tioning (Nemani and Running 1997, Paruelo and Lauenroth 1998). The NDVI annual integral was calculated by summing up the products of the 10-yr mean NDVI for each period and the proportion of the year represented by that date (NDVI-I $= \Sigma^n$ NDVI$_i \times T_i$, where n is the total number of composites per year, NDVI$_i$ is the ith composite and T_i is the proportion of the year covered by the ith composite, usually 10 d). The NDVI annual integral is a good estimator of the fraction of the photosynthetic active radiation absorbed by the canopy (Sellers et al. 1992) and, hence, of primary production (Tucker et al. 1985*b*, Prince 1991, Paruelo et al. 1997). The relative range of NDVI corresponded to the difference between the maximum and minimum NDVI recorded throughout the year, divided by the NDVI annual integral. The date of maximum NDVI corresponded to the month showing the highest frequency (mode) of peak NDVI for the period analyzed. The relative range and the date of maximum NDVI capture essential features of the seasonality of carbon uptake (Paruelo and Lauenroth 1998, Paruelo et al. 2001, Jobbágy et al. 2002). For the three attributes, we averaged the values of the pixels included in each county. Finally, we characterized the interannual variability of the three attributes of the seasonal course of the NDVI. To do this, we calculated the coefficient of variation of the NDVI annual integral, the relative range of the NDVI, and the date of maximum NDVI for the 19 yr under analysis. The coefficients of variation provide a measure of how variable the three attributes of the NDVI curve are among years. We used here land use data from a single year (1988) and NDVI data from 19 yr (1981–1999). More recent land use data aggregated to the county level are not available for Argentina. However, data at the province level show that the year 1988 can be used as a good representation of the average cropping conditions of the studied period (INDEC 1996).

In order to restrict the analysis to such areas where obvious relationships between environmental variables and land use patterns do not mask the effect of land use change over the NDVI dynamics, we evaluated the spatial distribution of croplands across the main environmental gradients. Based on the results of this analysis we studied only those counties corresponding to the Espinal and Pampa regions (Fig. 2).

Statistical analyses

We divided the data set including the counties of the Espinal and Pampa regions into two separate groups based on the proportion of croplands (PCROP). The first group included the quarter of the counties with the lowest PCROP ($n = 41$). These counties had less than 18.2% of their area under cropping (10.4 $\pm$ 5.3%, mean $\pm$ 1 SD). For these counties, we analyzed the environmental (climatic and edaphic) controls of the three

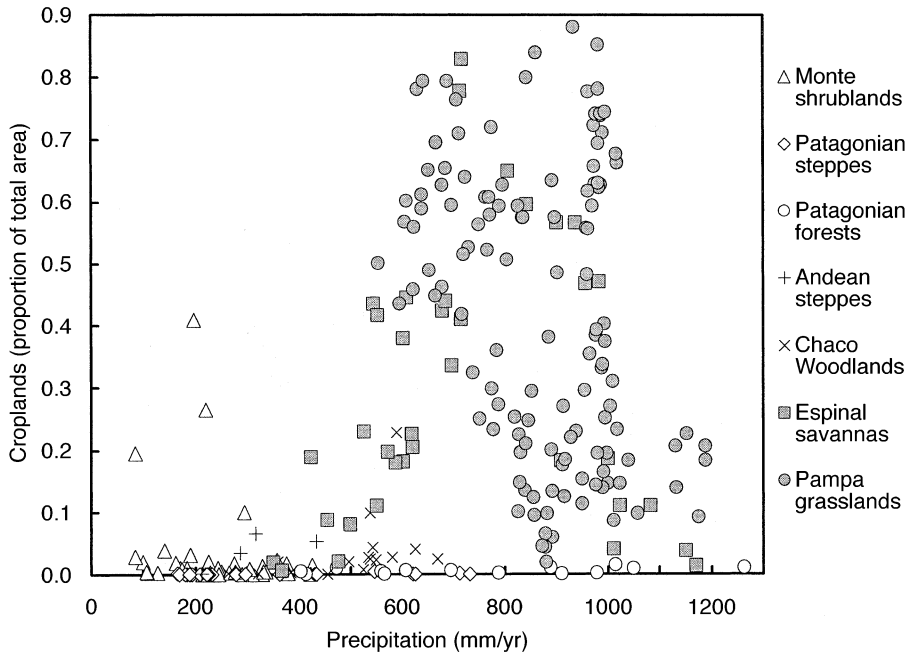

FIG. 3. Relationship between the proportion of the area of the counties with croplands and mean annual precipitation.

NDVI attributes using stepwise regression models (Kleinbaum and Kupper 1978). In the regression models, the NDVI annual integral, the relative range of the NDVI, and the date of maximum NDVI were the dependent variables (one at a time) whereas the climatic and edaphic variables were the independent ones. These were called ''low-impacted vegetation'' models.

Stepwise multiple regression has been criticized because it has severe problems in the presence of collinearity. For minimizing these problems we took a series of precautions: we set the *F*-to-enter to a value that produced a *P* level lower than 0.01 (all the independent variables must be significant for entering in the model). We also tested the significance of the variables in the model by including a random variable among the independent variables and checking whether this variable was included in the final model. We stopped the stepwise process when the increase in r^2 was lower than 0.02 to keep the model as simple (with as few variables) as possible. We compared the model obtained with all the possible alternative models with the same number of independent variables. In such a way, we explored whether the model that was obtained using the stepwise procedure was the ''best'' model.

We applied the low-impacted vegetation models, generated from the less modified areas, to those counties with more than 18.2% of the area under cropping ($n = 122$, 48.9 ± 19.7% [mean ± 1 SD]). We analyzed the relationship between the observed and predicted values for the three NDVI attributes. We studied the magnitude of this difference (in relative terms) and its correlation with land use variables. Finally, we also used correlation to explore the relationship among the interannual variability of the NDVI attributes and land use descriptors.

RESULTS

Patterns and controls of land use in temperate Argentina

In temperate Argentina, croplands were restricted to the Pampa grasslands and the Espinal savannas (Fig. 2). Mean annual precipitation was the main control of cropland distribution in the region ($R^2 = 0.27$, $P < 0.001$, $n = 164$; Fig. 3). Counties with less than 500 mm/yr had almost no agriculture, except for a few counties in the Monte phytogeographic unit. In those counties agriculture is performed under irrigation. In counties with precipitation higher than 500 mm/yr, the proportion of croplands ranged from 0% to 86% (Fig. 3). In these counties, the proportion of the area under irrigation is lower than 0.045 and it represents less than 7% of the total cropped area. Considering the whole temperate areas the variability in the proportion of croplands not accounted for by mean annual precipitation was marginally correlated with soil variables such as clay content and salinity. Socioeconomic factors, not considered here, could play an important role in determining the spatial distribution of croplands. We eliminated the strong influence of precipitation on land use patterns by restricting our analysis to areas with more than 500 mm/yr. Almost all of the counties in the Patagonian and Andean steppes and the Monte shrublands are very dry (mean annual precipitation [MAP] < 500 mm/yr) and have a very low proportion of croplands. Counties in the Espinal savannas and the Pampa

TABLE 1. Relationships between the attributes derived from the normalized difference vegetation index (NDVI) curve and environmental characteristics of the low-impacted vegetation counties in temperate Argentina.

Dependent variables	y-intercept	r^2	F	Independent variables	Slope	r^2_p	P
NDVI-1	0.4674	0.89	173.9	MAP	0.000235	0.80	<0.0001
			30.5	MPET	−0.000186	0.09	<0.0001
RREL	0.8077	0.78	112.0	MPET	−0.000334	0.40	<0.0001
			34.0	MAM/MAP	−0.8328	0.30	<0.0001
			13.2	JJA/MAP	−0.31852	0.08	0.0001
DMAX	−2.8764	0.73	62.0	MPET	0.0113	0.63	<0.0001
			9.2	SILT	−2.353	0.03	0.0044
			9.1	DEPTH	−0.01114	0.07	0.0048

Notes: The relationships were determined by stepwise multiple regression. These models were performed using the counties with a proportion of crops lower than 0.182. The r^2 is the coefficient of determination of the model fitted, F is the F-Snedecor statistic for the whole model, r^2_p is the partial coefficient of determination of each of the variables included in the model, and p is the probability of F ($n = 41$). Abbreviations are: NDVI-I, NDVI annual integral; RREL, relative range of NDVI (difference between the maximum and minimum NDVI divided by the integral), DMAX, date of maximum NDVI (values for DMAX range from 1 [July] to 12 [June]); MAP, mean annual precipitation; MPET, mean potential evapotranspiration; MAM/MAP, proportion of mean annual precipitation that falls in fall; JJA/MAP, proportion of mean annual precipitation that falls in winter; SILT, average proportion of soil silt; DEPTH, mean soil depth.

grasslands are wetter and the cropland proportion extends from 0 to almost 90%. Based on these observations we decided to restrict the analysis of the controls of NDVI patterns to the Pampa grasslands and the Espinal savannas. Because of the negligible presence of croplands we also excluded from the analysis the Patagonian forests and Chaco woodlands. These biomes are located in areas where topography imposes additional constraints to agriculture.

Relationship between environmental variables and the NDVI dynamics

Environmental variables explained 89% of the spatial variability of the NDVI annual integral (NDVI-I) for the counties with a proportion of croplands lower than 0.183 (Table 1). NDVI-I increased linearly with mean annual precipitation and decreased with potential evapotranspiration. Mean annual precipitation accounted for 80% of the variability while potential evapotranspiration increased the variance explained by 9%.

Climatic variables accounted for 78% of the variability in the proportion of the difference between the maximum and minimum NDVI in the year (RREL), a measure of the seasonality of radiation interception (Table 1). RREL decreased as potential evapotranspiration and the proportion of fall and winter precipitation increased. As for the NDVI-I, soil variables did not improve the model. The spatial variability in the date of maximum NDVI (DMAX) accounted for by environmental variables was 73% (Table 1). In areas with high potential evapotranspiration NDVI peaked late in the growing season. NDVI tended to peak earlier during the growing season in counties with deeper soils and with high silt content.

Impact of land use on NDVI dynamics

When we applied the previous models to highly cropped areas (PCROP > 0.18) the predicted and observed values of the NDVI annual integral showed a good agreement ($r = 0.864$, $P < 0.001$, $n = 122$; see Fig. 4a). The slope of the fitted regression line was significantly <1 and the y-intercept >0 ($P < 0.01$), suggesting a slight underestimation of NDVI-I in the driest areas. The residuals of the prediction ranged from −13% to 15% (RES = [observed − predicted]/observed). This indicates that the model adjusted for the less cropped areas described reasonably well the patterns of NDVI-I in the more modified areas. Higher values of the NDVI annual integral than the predicted were positively associated with the proportion of perennial crops, whereas lower values than the expected were positively associated with the proportion of summer crops and the wheat–soybean double crop (Fig. 5).

The correlation between predicted and observed values of the relative range of the NDVI (RREL) was low ($r = 0.30$, $P < 0.01$, $n = 122$; see Fig. 4b). The slope of the regression was significantly <1. For 18% of the sites, the residuals of the predicted values were less than −20% and for 11% of the sites were >20%. Higher values of RREL than the predicted were positively associated with the proportion of winter and wheat–soybean crops in the county, whereas lower values than the expected were positively associated with the proportion of perennial crops (Fig. 5).

The model adjusted to the counties with a low proportion of croplands failed to predict the date of maximum NDVI (DMAX) in the counties with a higher area of croplands ($r = -0.28$, $P < 0.001$, $n = 122$; see Fig. 4c). For 61% of the counties the predicted

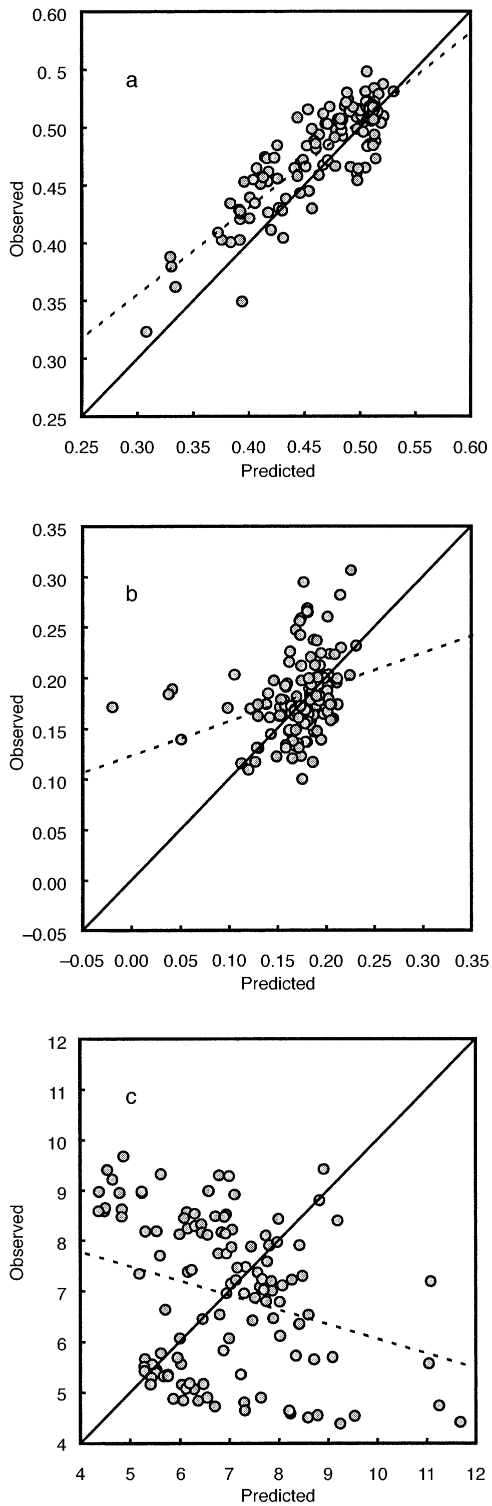

FIG. 4. Predicted and observed values of (a) NDVI-I, (b) RREL, and (c) DMAX in the counties with a proportion of croplands >0.183 (n = 122). Predicted values were generated using the models described in Table 1. Abbreviations: NDVI-I, normalized difference vegetation index (NDVI) annual integral; RREL, relative range of the NDVI (difference between the maximum and minimum NDVI divided by the integral); DMAX, date (month) of maximum NDVI (October = 4, November = 5, etc., June = 12).

values of DMAX differed from the observed for more than 30 d and for 37% of the counties the difference was higher than 60 d. In the extreme cases, the model predicted peak NDVI in October when it was observed in February (a difference of 145 d) or it predicted maximum NDVI in May when it occurred in October (a difference of 215 d). There was a strong correlation among the difference between the observed and predicted DMAX and the proportion of summer and winter crops (Fig. 5). In the first case, the correlation was positive, indicating that summer crops delayed the occurrence of the maximum NDVI. The negative correlation among the residuals and the proportion of winter crops suggests that these crops advanced the occurrence of the NDVI peak.

Interannual variability in the NDVI attributes

The three NDVI attributes differed in the magnitude of their interannual variability. The coefficient of variation of the NDVI annual integral (CV NDVI-I) ranged from 4% to 13%. The CV NDVI-I was strongly and negatively correlated with the mean NDVI annual integral both for counties with a low proportion of crops ($r = -0.71$, $P < 0.001$, $n = 38$) and with a high proportion of crops ($r = -0.90$, $P < 0.001$, $n = 118$; see Table 2). This indicates that the driest counties showed the highest NDVI-I variability.

The CV of the relative range of the NDVI (CV RREL) ranged from 20% to 54%. Half of the counties had CV RREL between 32% and 43%. RREL was also negatively correlated with its interannual variability both in counties with a low cropland proportion ($r = -0.44$, $P = 0.005$, $n = 38$) and in those with a high cropland proportion ($r = -0.74$, $P < 0.001$, $n = 118$). The interannual variability in the date of maximum NDVI (CV DMAX) ranged from 5% to 51%. Half of the counties presented values of CV DMAX between 15% and 30%. The CV DMAX was negatively correlated with the relative range in NDVI (RREL), indicating that those counties with a high NDVI amplitude showed a lower variability among years in the occurrence of peak NDVI (Table 2).

In the low-impacted vegetation areas, the NDVI relative range (RREL) was negatively correlated with the date of maximum NDVI ($r = -0.62$, $P < 0.001$, $n = 38$) indicating that areas with a high difference between maximum and minimum NDVI had the maximum NDVI early in the growing season. In areas with a high proportion of croplands (PCROP > 0.183), in contrast, the correlation among these variables was positive ($r = 0.43$, $P < 0.001$, $n = 118$). A similar situation was observed among NDVI-I and DMAX. Their correlation was negative in the low-impacted vegetation counties and positive in the counties with a high proportion of croplands.

The proportion of the variance of the CV of the NDVI attributes for counties with a low-impacted vegetation explained by environmental variables was low (NDVI-I,

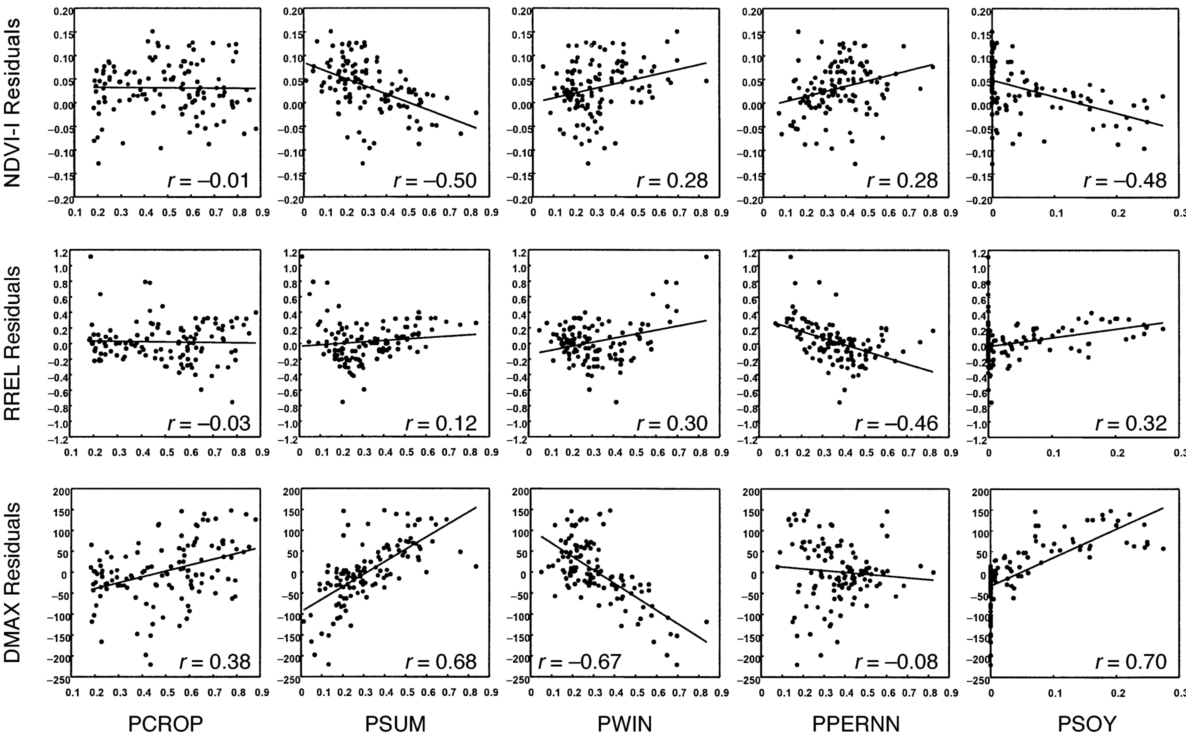

FIG. 5. Scatterplots of the residuals of the predicted and observed values of the normalized difference vegetation index (NDVI) attributes and land use variables in the counties with proportion of croplands >0.183 (n = 122). Abbreviations: NDVI-I, NDVI annual integral; RREL, relative range of the NDVI (difference between the maximum and minimum NDVI divided by the integral); DMAX, date of maximum NDVI. For NDVI-I and RREL we calculated the relative difference: RESID = (observed − predicted)/observed. For DMAX we calculated the absolute difference, expressed in days: RESID = (observed − predicted). Land use variables: PCROP, proportion of the county devoted to croplands; PSUM, PWIN, PPERNN, and PSOY, proportion of the cropped area in county with summer, winter, perennial crops, and wheat–soybean double cropping, respectively.

r^2 = 0.48; RREL, r^2 = 0.46; DMAX, r^2 = 0.34). We did not generate, then, low-impacted vegetation models for the relationship between the interannual variability in NDVI attributes and environmental variables. Instead, we analyzed directly the relationship between the interannual variability of the NDVI attributes and land use descriptors. The proportion of summer crops (PSUM) and the proportion of wheat–soybean (PSOY)

TABLE 2. Coefficients of correlation among the mean normalized difference vegetation index (NDVI) attributes and their interannual variability.

Variable	RREL	DMAX	CV NDVI-I	CV RREL	CV DMAX
a) Counties with proportion of croplands < 0.183 (n = 38).					
NDVI-I	0.03	−0.42*	−0.71**	0.30	0.26
RREL		−0.62**	−0.15	−0.44**	0.44**
DMAX			0.38*	0.05	0.18
CV NDVI-I				0.10	0.02
CV RREL					0.27
CV DMAX					
b) Counties with proportion of croplands ≥ 0.183 (n = 118).					
NDVI-I	0.02	0.24*	−0.90**	0.19*	0.29**
RREL		0.43**	−0.17	−0.74**	−0.64**
DMAX			−0.23*	0.26**	−0.60**
CV NDVI-I				−0.07	0.32**
CV RREL					0.42**
CV DMAX					

Note: Abbreviations are defined as follows: NDVI-I, NDVI annual integral; RREL, relative range of NDVI (difference between the maximum and minimum NDVI divided by the integral); DMAX, date of maximum NDVI (values for DMAX range from 1 [July] to 12 [June]); CV, coefficient of variation (19 yr).

* $P < 0.05$; ** $P < 0.01$.

TABLE 3. Correlation coefficients among the interannual variability of the normalized difference vegetation index (NDVI) attributes and land use variables.

Variable	CV NDVI-I	CV RREL	CV DMAX
PCROP	0.06	−0.17*	−0.59**
PSUM	−0.35**	−0.45**	−0.64**
PWIN	0.54**	0.09	0.39**
PPERNN	−0.15	0.34**	0.26**
PSOY	−0.25**	−0.31**	−0.54**

Note: PCROP is the proportion of the county devoted to croplands; PSUM, PWIN, PPERNN, and PSOY are the proportions of the cropped area in the county with summer, winter, perennial crops, and wheat–soybean double cropping, respectively.

* $P < 0.05$; ** $P < 0.01$.

were negatively correlated with the interannual variability of NDVI-I, RREL, and DMAX (Table 3). However, as we described earlier, NDVI-I was less variable among years than RREL and DMAX. Winter crops were positively correlated with CV NDVI-I and with CV DMAX, but had no significant correlation with CV RREL. Perennial crops were positively correlated with CV RREL and CV DMAX (Table 3).

DISCUSSION

Environmental controls of NDVI dynamics

A high proportion (80%) of the spatial variability in the annual integral of NDVI in areas with a low human impact was accounted for by mean annual precipitation. This result supports previous observed trends using remotely sensed data (Paruelo and Lauenroth 1995, Paruelo et al. 1997, Jobbágy et al. 2002) and direct measurements of aboveground net primary production (Lauenroth 1979, Sala et al. 1988, McNaughton et al. 1993, Milchunas and Lauenroth 1993, Knapp and Smith 2001). Mean potential evapotranspiration was negatively associated with NDVI-I. This variable accounted for an additional 9% of the spatial variability in NDVI-I. Epstein et al. (1997) showed that temperature (a variable that affects the atmospheric demand for water) and soil texture explained the regional variability of aboveground net primary productivity (ANPP) in the Central Plains of North America after accounting for the variability explained by mean annual precipitation. Yang et al. (1998) found a negative relationship between potential evapotranspiration and time-integrated NDVI in the Central Plains.

The spatial patterns in the relative range of NDVI (RREL; an index that has been related to radiation interception and carbon uptake) of low-impacted vegetation areas were negatively related to the potential evapotranspiration and the proportion of precipitation falling in autumn and winter. Similarly, the regional patterns of the date of maximum NDVI (DMAX) were associated to the mean annual evapotranspiration and soil silt content and depth, two variables connected to the soil water-holding capacity. It has been shown for grasslands and shrublands of North America that climatic factors account for a large proportion of the spatial variability in C_3 and C_4 grasses and shrubs (Paruelo and Lauenroth 1996). Changes in the relative proportion of these plant functional types across the environmental gradients might be responsible for differences in the seasonality of radiation interception and carbon uptake in low-impacted vegetation areas.

Impact of land use on NDVI dynamics

The model on the environmental controls of the NDVI annual integral adjusted for the low-impacted vegetation areas satisfactorily predicted the NDVI-I of the more cropped counties. This suggests that cropland management did not modify fundamentally the strong relationship observed between NDVI-I and precipitation and evapotranspiration. Given the same environmental conditions the difference between counties differing in the cropland proportion was less than 15%. An analysis of the residuals suggests that summer crops and the wheat–soybean cropping system increased NDVI-I and that winter and perennial crops reduced NDVI-I in comparison to the low-impacted vegetation areas. Lauenroth et al. (2000) showed for the central grasslands of the USA that wheat (a winter crop) had a lower ANPP compared to native grasslands in areas with MAP higher than 600 mm/yr.

The environmental variables that accounted for most of the variance of the NDVI relative range (RREL) in low-impacted vegetation areas explained only partially the spatial variability of this attribute in counties with a high proportion of croplands. This suggests a strong impact of land use on the seasonality of the radiation interception and carbon uptake. Perennial crops tended to decrease RREL and annual crops produced the opposite effect. The phenological characteristics of these crops may explain the observed patterns. Annual crops have a well-defined growing season, shorter than grasslands', followed by a fallow period, with a very low or null leaf area index (LAI). This produces a higher maximum NDVI and a lower minimum NDVI than in the grasslands. Perennial crops, in contrast, have a less variable LAI throughout the year, producing a lower difference between maximum and minimum NDVI. Most of the perennial crops in the region are pastures with a higher proportion of C_3 grasses than the native grasslands, which tend to increase the minimum NDVI.

The date of maximum NDVI in the year (DMAX), another important descriptor of the seasonality in radiation interception and carbon uptake, was also strongly affected by cropland management. The DMAX calculated from the low-impacted vegetation model did not match the values observed in cropped areas. Summer crops delayed the occurrence of peak NDVI by 140 d and winter crops advanced peak NDVI by 210 d. Paruelo et al. (2001) showed a similar pattern in eastern Colorado, USA, where irrigated corn (a summer crop) delayed peak NDVI and rain-fed wheat (a spring crop) advanced it, compared to native grasslands.

We found a strong negative relationship between the mean NDVI annual integral (NDVI-I) and its interannual variability (CV NDVI-I). This relationship was observed in undisturbed grasslands and shrublands using remotely sensed data (Paruelo and Lauenroth 1998, Fang et al. 2001, Jobbágy et al. 2002) and direct measurements of ANPP (Sims and Singh 1978). Here we show that the relationship between the NDVI-I and its coefficient of variation was not affected by the dramatic changes that agriculture caused in the structure of temperate grasslands and savannas. The attributes of the NDVI curve related to seasonality were more variable among years than the NDVI annual integral (CV RREL and CV DMAX > CV NDVI-I). The same pattern was observed on native vegetation (Paruelo and Lauenroth 1998).

The interannual variability of the NDVI seasonal attributes was correlated to the land use variables (Table 3). This suggests that besides modifying the mean values of the NDVI relative range and date of maximum, cultivation modified the interannual variability of these attributes. Summer crops and wheat–soybean decreased the interannual variability of both attributes, perennial crops increased them, and winter crops increased only the interannual variability of the date of maximum NDVI. Although annual crops in temperate Argentina are mostly rain fed and slightly fertilized, agricultural practices (plowing, fallow, and weed control) produce an important change in the timing of water use, transferring water to the crop-growing season. In such a way, the high interception of radiation of crops become less dependent of the particular weather of a given year (mainly precipitation) compared to natural vegetation. This could be responsible for the lower interannual variability of the seasonality of NDVI in annual crops.

Our results suggest that in temperate Argentina, the major impact of land use was on the seasonal dynamic of NDVI (RREL and DMAX), while the annual integral of the NDVI was slightly affected. In other words, cultivation changed the shape of the NDVI curve, but did not change the area under the curve. We selected five counties for illustrating these results (Fig. 6). Pila, located in the eastern portion of the pampas, was almost completely covered by native grasslands and was consequently used as a reference for comparisons. The NDVI annual integral was higher in Federal (wetter than Pila) and lower in Chadileo (drier than Pila), two counties with a low proportion of croplands (Fig. 6a). The NDVI relative range was much higher in Caseros than in Pila (Fig. 6b). Given their similar climate, the higher proportion of summer crops in Caseros than in Pila should be responsible for this difference. Caseros had the highest maximum NDVI and a very low minimum NDVI (Fig. 6b). The maximum NDVI in Caseros occurred in February (late summer), much later than that predicted by the model generated for the low-impacted vegetation areas. Again, summer crops might account for this pattern. In Saavedra, a county with a high proportion of winter crops (mostly wheat), NDVI peaked in October (middle of spring).

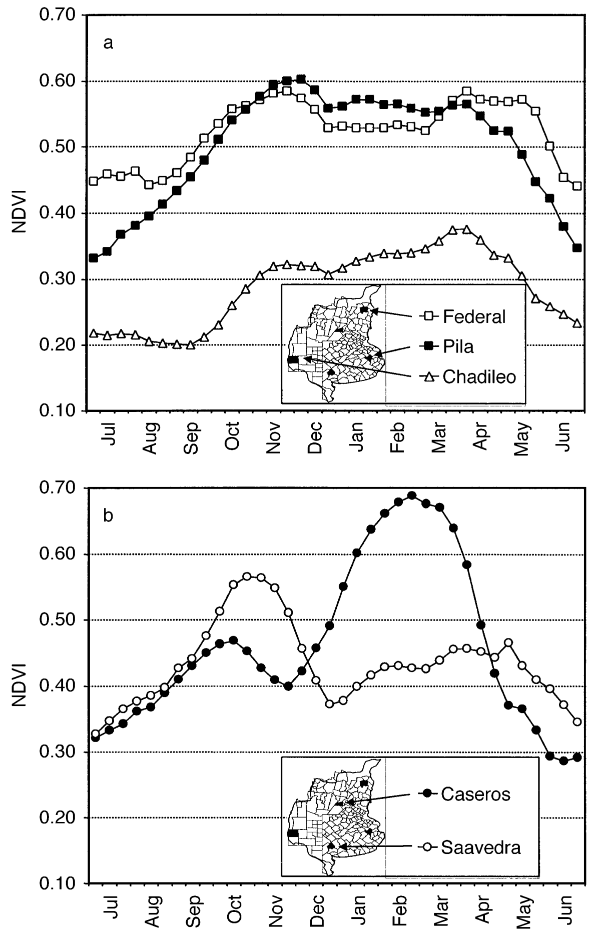

FIG. 6. Mean seasonal patterns of the normalized difference vegetation index (NDVI) for five counties in the Pampa and Espinal phytogeographical regions. Each point corresponds to the mean value for the 1981–1999 period ($n = 19$). Environmental and land use data for each county: Pila, MAP = 892 mm/yr, MAT = 15.0°C, MPET = 935 mm/yr, PCROP = 0.06, PSUM = 0.21, PWIN = 0.12, PPERNN = 0.67; Federal, MAP = 1151 mm/yr, MAT = 18.9°C, MPET = 1161 mm/yr, PCROP = 0.04, PSUM = 0.24, PWIN = 0.40, PPERNN = 0.35; Chadileo, MAP = 350.4 mm/yr, MAT = 15.6°C, MPET = 1227 mm/yr, PCROP = 0.02, PSUM = 0.03, PWIN = 0.08, PPERNN = 0.89; Caseros, MAP = 934 mm/yr, MAT = 16.8°C, MPET = 1054 mm/yr, PCROP = 0.88, PSUM = 0.57, PWIN = 0.27, PPERNN = 0.17; Saavedra, MAP = 698 mm/yr, MAT = 13.8°C, MPET = 1068 mm/yr, PCROP = 0.59, PSUM = 0.21, PWIN = 0.59, PPERNN = 0.22. Abbreviations: MAP, mean annual precipitation; MAT, mean annual temperature; MPET, mean potential evapotranspiration; PCROP, proportion of the county devoted to croplands; PSUM, PWIN, PPERNN, and PSOY, proportions of the cropped area in county with summer, winter, perennial crops, and wheat–soybean double cropping, respectively.

Caseros and Saavedra showed a bimodal pattern in the NDVI temporal profile. This is because these counties have a mixture of winter and summer crops, a very common situation in the region. Federal had also a bimodal NDVI pattern possibly due to the mixture of C_3 and C_4 species in its grasslands. None of the three NDVI attributes calculated in the present work accounts for the bimodal pattern.

The connection between NDVI and the fraction of photosynthetic active radiation intercepted (FPAR) has been largely documented, both theoretically (Sellers et al. 1992) and empirically (Asrar et al. 1984). Changes in the NDVI curves can be interpreted as modifications of the seasonal patterns of radiation interception. These changes have an important implication per se for understanding the functioning of terrestrial ecosystems, because they are associated with strong modifications of the exchange of energy between the surface and the atmosphere. Monteith's (1981) model provided the conceptual framework to convert the amount of radiation intercepted by the canopy into net primary production: ANPP= $\varepsilon_a \times [\int \text{APAR}]$, where APAR is the absorbed photosynthetic active radiation (in megajoules per square meter), ε_a is the energy conversion efficiency (in grams of carbon per megajoule), and $\int$ is the annual integral. APAR is determined by APAR = FPAR $\times$ PAR, where PAR is the photosynthetic active radiation and FPAR is the fraction of PAR intercepted by the canopy. If land cover is relatively homogeneous ε_a can be assumed to be constant, and, then, NDVI can be used as a direct surrogate for ANPP. In our study, however, we monitored areas with an heterogeneous land cover; therefore, the assumption that differences in the NDVI integral mean differences in ANPP could lead to spurious results because ε_a could be different. Knowing the conversion efficiency values for different crop types is, then, crucial to the conversion of NDVI data into NPP. Ruimy et al. (1994) collected values of energy conversion efficiency (ε_a) measured during the growing season in both natural vegetation and croplands. They found that crops have much higher ε_a than natural vegetation due to the high relative growth rate of cultivated species, a high shoot/root index, and optimal conditions of water and nutrients. This could indicate that in temperate Argentina, cultivation management did not modify total radiation interception, but it did increase aboveground net primary production. This difference may be lower or even reversed if total (above- and belowground) NPP is considered because crops allocate proportionally less carbon to roots than grasslands (Whittaker and Marks 1975). One way to reduce these uncertainties would be to estimate ANPP and NPP over the region from crop production data, harvest indexes (carbon in kernel/total carbon aboveground), and root:shoot ratios (Prince et al. 2001).

Potential applications

The regional analysis performed provides new elements to assess the possible changes in the exchange of energy and matter between the surface and the atmosphere under climate and land use change scenarios. The equations derived from the multiple regression analyses suggest important changes in the fraction of radiation intercepted if precipitation or temperature change. Changes in the cropland area or changes in the spatial distribution of crops, in contrast, would not significantly modify total radiation interception. However, it would probably change the timing and interannual variability of this functional attribute. Of course, a proper analysis should consider changes in atmospheric CO_2 concentration and its direct effects on carbon uptake. The use of spatially derived models of the relationship between environmental factors and functional attributes to evaluate temporal change, though, could lead to erroneous results because it does not take into account variables that only change in time (CO_2), response lags, or interactions (Burke et al. 1998).

An important effort is devoted to monitor carbon balance in terrestrial ecosystems. Our study provides new insights on the complex consequences of land use change over the carbon cycle. The replacement of natural vegetation by croplands produced important changes in the carbon uptake dynamics in temperate Argentina. These changes tend to be oversimplified in global carbon models (Esser 1995, McGuire et al. 2001). None of these models accounted for the differences in the effects of agriculture in tropical and temperate areas, neither between crops with different phenology or different management practices. This has been highlighted as one of the major uncertainties in global biogeochemical models (McGuire et al. 2001). Our results showed important differences in the NDVI dynamics of temperate areas depending on the crop type that replaced the natural vegetation (perennial, summer cycled annual, and winter cycled annual). A proper characterization of land cover is of course a requirement to reduce uncertainties in global biogeochemical models. The inaccuracy of the land use maps of South America may account for anomalous results for this part of the globe (compare, for example, Fig. 2 of this paper and Plate 1b in Ramankutty and Foley [1998] or Fig. 8 in Hansen et al. [2000]).

Our results provide a direct connection between ecological and atmospheric processes. We showed that the conversion of large areas of former grasslands and savannas into croplands modified the timing of radiation interception. This may alter the dynamics of the boundary layer and the energy exchange between the surface and the atmosphere. It has been shown that similar changes in other areas of the world lead to changes in local temperatures and precipitation (Stohlgren et al. 1998). Whether the same is occurring in temperate South America remains an open question.

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Literature Cited

Aguiar, M. R., J. M. Paruelo, O. E. Sala, and W. K. Lauenroth. 1996. Ecosystem cosequences of plant functional types changes in a semiarid grassland. Journal of Vegetation Science **7**:381–390.

Ares, J., A. M. Beeskow, M. Bertiller, M. Rostagno, M. Irrisarri, J. Anchorena, G. Defosse, and C. Merino. 1990. Structural and dynamics characteristics of overgrazed lands of northern Patagonia, Argentina. Pages 149–175 *in* A. I. Breymeyer, editor. Managed grasslands. Elsevier Science, Amsterdam, The Netherlands.

Asrar, G., M. Fuchs, E. T. Kanemasu, and J. L. Hatfield. 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agronomy Journal **76**:300–306.

Baron, J., M. Hartman, T. Kittel, L. Band, D. Ojima, and R. Lammers. 1998. Effects of land cover, water redistribution, and temperature on ecosystem processes in the South Platte Basin. Ecological Applications **8**:1037–1051.

Bertiller, M. B., and A. Bisigato. 1998. Vegetation dynamics under grazing disturbance: the state-and-transition model for the Patagonian steppes. Ecología Austral **8**:191–200.

Burke, I. C., W. K. Lauenroth, and C. A. Wessman. 1998. Progress in understanding biogeochemistry at regional to global scales. Pages 165–194 *in* P. Groffman and M. Pace, editors. Successes, limitations, and challenges in ecosystem science. Springer-Verlag, New York, New York, USA.

Burke, I. C., C. M. Yonker, W. J. Parton, C. V. Cole, K. Flach, and D. S. Schimel. 1989. Texture, climate, and cultivation effects on organic matter in U.S. grassland soils. Soil Science Society of America Journal **53**:800–805.

Cabrera, A. L., and A. Willink. 1976. Biogeografia de America latina. Organización de los Estados Americanos, Washington, D.C., USA.

Dye, D. G., and S. N. Goward. 1993. Photosynthetically active radiation absorbed by global land vegetation in August 1984. International Journal of Remote Sensing **14**:3361–3364.

Epstein, H. E., W. K. Lauenroth, I. C. Burke, and D. P. Coffin. 1997. Productivity patterns of C_3 and C_4 functional types in the U.S. Great Plains. Ecology **78**:722–731.

Esser, G. 1995. Contribution of monsoon Asia to the carbon budget of the biosphere, past and future. Vegetatio **121**: 175–188.

Fang, J., S. Piao, Z. Tang, C. Peng, W. Ji, A. K. Knapp, and M. D. Smith. 2001. Internannual variability in net primary production and precipitation. Science **293**:1723.

FAO [Food and Agriculture Organization of the United Nations]. 1985. Datos Agroclimáticos para America Latina y el Caribe. Food and Agriculture Organization of the United Nations, Rome, Italy.

Hall, A. J., C. M. Rebella, C. M. Ghersa, and J. P. Culot. 1992. Field-crop systems of the Pampas. Pages 413–440 *in* C. J. Pearson, editor. Ecosystems of the world: field crop ecosystems. Elsevier, Amsterdam, The Netherlands.

Hansen, M. C., R. S. DeFries, J. R. G. Townshend, and R. Sohlberg. 2000. Global land cover classifcation at 1 km spatial resolution using a classification tree approach. International Journal of Remote Sensing **21**:1331–1364.

Hedin, L. O., J. J. Armesto, and A. H. Johnson. 1995. Patterns of nutrient loss from unpolluted old-growth temperate forests: evaluation of biogeochemical theory. Ecology **76**: 493–509.

INDEC [Instituto Nacional de Estadística y Censos]. 1988. Censo Nacional Agropecuario 1988. Resultados generales. Instituto Nacional de Estadísticas y Censos, Buenos Aires, Argentina.

INDEC [Instituto Nacional de Estadística y Censos]. 1996. Encuesta Nacional Agropecuaria 1995. Resultados generales. Ampliados. INDEC, Buenos Aires, Argentina.

IPCC [Intergovernmental Panel on Climate Change]. 2000. Special report on land use, land-use change, and forestry. Cambridge University Press, Cambridge, UK.

James, M. E., and S. N. V. Kalluri. 1994. The pathfinder AVHRR land data set: an improved coarse resolution data set for terrestrial monitoring. International Journal of Remote Sensing **15**:3347–3363.

Jobbágy, E. G., O. E. Sala, and J. M. Paruelo. 2002. Patterns and controls of primary production in the Patagonian steppe: a remote sensing approach. Ecology **83**:307–319.

Kicklighter, D. W., et al. 1999. Comparing global models of terrestrial net primary productivity (NPP): comparison of NPP to climate and the normalized difference vegetation index. Global Change Biology **5**:16–24.

Kleinbaum, D., and L. L. Kupper. 1978. Applied regression analysis and other multivariate methods. Duxbury, North Scituate, Massachusetts, USA.

Knapp, A. K., and M. D. Smith. 2001. Variation among biomes in temporal dynamics of aboveground primary production. Science **921**:481–484.

Lauenroth, W. K. 1979. Grasslands primary production. Pages 3–24 *in* N. R. French, editor. North American grasslands in perspective. Springer Verlag, New York, New York, USA.

Lauenroth, W., I. Burke, and J. Paruelo. 2000. Patterns of production of winter wheat and native grasslands in the Central Grassland region of the United States. Ecosystems **3**:344–351.

León, R. J. C., and M. R. Aguiar. 1985. El deterioro por uso pasturil en estepas herbáceas patagónicas. Phytocoenologia **13**:181–196.

Loveland, T. R., J. W. Merchant, D. O. Ohlen, and J. F. Brown. 1991. Development of a land cover characteristics database for the conterminous US. Photogrametric Engineering and Remote Sensing **57**:1453–1463.

McGuire, A. D., et al. 2001. Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land-use effects with four process-based ecosystem models. Global Biogeochemical Cycles **15**:183–206.

McNaughton, S. J., M. Oesterheld, D. A. Frank, and K. J. Williams. 1989. Ecosystem-level patterns of primary productivity and herbivory in terrestrial habitats. Nature **341**: 142–144.

McNaughton, S. J., O. E. Sala, and M. Oesterheld. 1993. Comparative ecology of African and South American arid to subhumid ecosystems. Pages 548–567 *in* P. Goldblatt, editor. Biological relationships between Africa and South America. Yale University Press, New Haven, Connecticut, USA.

Melillo, J. M., A. D. McGuire, D. W. Kickkighter, B. Moore, C. J. Vorosmarty, and A. L. Schloss. 1993. Global climate change and terrestrial net primary production. Nature **363**: 234–240.

Milchunas, D. G., and W. K. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecological Monographs **63**:327–366.

Monteith, J. L. 1981. Climatic variation and the growth of crops. Quarterly Journal of the Royal Meteorological Society **107**:749–774.

Morello, J. 1958. La provincia fitogeográfica del Monte. Opera Lilloana 2.

Mosier, A., D. Schimel, D. Valentine, K. Bronson, and W. Parton. 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. Nature **350**:330–332.

Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar, and R. R. Nemani. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature **386**:698–702.

Nemani, R., and S. Running. 1997. Land cover characterization using multitemporal red, near-IR, and thermal-IR data from NOAA/AVHRR. Ecological Applications **7**:79–90.

Paruelo, J. M., M. R. Aguiar, R. J. C. Leon, R. A. Golluscio, and W. B. Batista. 1991. The use of satellite imagery in quantitative phytogeography: a case study of Patagonia (Argentina). Pages 183–204 *in* P. L. Nimis and T. J. Crovello, editors. Quantitative approaches to phytogeography. Kluwer Academic, The Hague, The Netherlands.

Paruelo, J. M., H. E. Epstein, W. K. Lauenroth, and I. C. Burke. 1997. ANPP estimates from NDVI for the Central Grassland Region of the United States. Ecology **78**:953–958.

Paruelo, J. M., E. G. Jobbagy, and O. E. Sala. 2001. Current distribution of ecosystem functional types in temperate South Amerca. Ecosystems **4**:683–698.

Paruelo, J. M., E. G. Jobbagy, O. E. Sala, W. K. Lauenroth, and I. C. Burke. 1998. Functional and structural convergence of temperate grassland and shrubland ecosystems. Ecological Applications **8**:194–206.

Paruelo, J. M., and W. K. Lauenroth. 1995. Regional patterns of normalized difference vegetation index in North American shrublands and grasslands. Ecology **76**:1888–1898.

Paruelo, J. M., and W. K. Lauenroth. 1996. Climatic controls of the distribution of plant functional types in grasslands and shrublands of North America. Ecological Applications **6**:1212–1224.

Paruelo, J. M., and W. K. Lauenroth. 1998. Interannual variability of the NDVI curves and their climatic controls in North American shrublands and grasslands. Journal of Biogeography **25**:721–733.

Paruelo, J. M., W. K. Lauenroth, H. E. Epstein, I. C. Burke, M. R. Aguiar, and O. E. Sala. 1995. Regional climatic similarities in the temperate zones of North and South America. Journal of Biogeography **22**:2689–2699.

Perelman, S. B., R. J. C. León, and J. P. Bussacca. 1997. Floristic changes related to grazing intensity in a Patagonian shrub steppe. Ecography **20**:400–406.

Pielke, R. A., R. Avissar, M. Raupach, H. Dolman, X. Zeng, and S. Denning. 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. Global Change Biology **4**:461–475.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science **267**:1117–1123.

Prince, S. D. 1991. A model of regional primary production for use with coarse resolution satellite data. International Journal of Remote Sensing **12**:1313–1330.

Prince, S. D., J. Haskett, M. Steininger, H. Strand, and R. Wright. 2001. Net primary production of U.S. Midwest croplands from agricultural harvest yield data. Ecological Applications **11**:1194–1205.

Ramankutty, N., and J. A. Foley. 1998. Characterizing patterns of global land use: an analysis of global croplands data. Global Biogeochemical Cycles **12**:667–685.

Rao, C. R. N., and J. Chen. 1995. Inter-satellite calibration linkages for the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAA-7, -9 and -11 spacecraft. International Journal of Remote Sensing **16**:1931–1942.

Robles, M. D., and I. C. Burke. 1997. Legume, grass, and Conservation Reserve Program effects on soil organic matter recovery. Ecological Applications **7**:345–357.

Ruimy, A., B. Saugier, and G. Dedieu. 1994. Methodology for the estimation of terrestrial net primary production from remotely sensed data. Journal of Geophysical Research **99**:5263–5283.

Ruimy, A., et al. 1999. Comparing global models of terrestrial net primary productivity (NPP): analysis of differences in light absorption and light-use efficiency. Global Change Biology **5**:56–64.

SAGyP-INTA [Secretaría de Agricultura, Ganadería y pesca—Instituto Nacional de Tecnología Agropecuaria]. 1990. Atlas de suelos de la República Argentina. Proyecto PNUD ARG/85/019. SAGyP-INTA, Buenos Aires, Argentina.

Sala, O. E., W. J. Parton, L. A. Joyce, and W. K. Lauenroth. 1988. Primary production of the Central Grassland region of the United States. Ecology **69**:40–45.

Sellers, P. J., J. A. Berry, G. J. Collatz, C. B. Field, and F. G. Hall. 1992. Canopy reflectance, photosynthesis, and transpiration. III. A reanalysis using improved leaf models and a new canopy integration scheme. Remote Sensing of Environment **42**:187–216.

Sellers, P. J., C. J. Tucker, G. J. Collatz, S. O. Los, C. O. Justice, D. A. Dazlich, and D. A. Randall. 1994. A global 10 by 10 NDVI data set from climate studies. Part 2: the generation of global fields of terrestrial biophysical parameters from the NDVI. International Journal of Remote Sensing **15**:3519–3545.

Sims, P. L., and J. S. Singh. 1978. The structure and function of ten western North American grasslands. II. Intra-seasonal dynamics in primary producer compartments. Journal of Ecology **66**:547–572.

Soriano, A. 1956. Los distritos floristicos de la Provincia Patagonica. Revista Investigaciones Agropecuarias **10**:323–347.

Soriano, A. 1993. Rio de la Plata Grasslands. Pages 367–407 *in* R. T. Coupland, editor. Natural grasslands: introduction and Western Hemisphere. Elsevier, Amsterdam, The Netherlands.

Stohlgren, T. J., T. N. Chase, R. A. Pielke, T. G. F. Kittel, and J. Baron. 1998. Evidence that local land use practices influence regional climate and vegetation patterns in adjacent natural areas. Global Change Biology **4**:495–504.

Tucker, C. J., J. R. Townshend, and T. E. Goff. 1985*a*. African land-cover classification using satellite data. Science **227**:369–375.

Tucker, C. J., C. L. Vanpraet, M. J. Sharman, and G. Van Ittersum. 1985*b*. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–1984. Remote Sensing of the Environment **17**:233–249.

Vitousek, P. M. 1992. Global environmental change: an introduction. Annual Review of Ecology and Systematics **23**:1–14.

Whittaker, R. H., and P. L. Marks. 1975. Methods of assessing terrestrial productivity. Pages 55–118 *in* H. Lieth and R. H. Whittaker, editors. Primary productivity of the biosphere. Springer-Verlag, New York, New York, USA.

Yang, L., B. K. Wylie, L. L. Tieszen, and B. C. Reed. 1998. An analysis of relationships among climate forcing and time-integrated NDVI of grasslands over the U.S. northern and central Great Plains. Remote Sensing of the Environment **65**:25–37.