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Land-use impact on ecosystem functioning in eastern Colorado, USA

J. M. PARUELO,* I. C. BURKE† and W. K. LAUENROTH‡
*IFEVA and Departamento de Recursos Naturales y Ambiente, Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, 1417 Buenos Aires, Argentina, †Department of Forest Science, Colorado State University, Fort Collins, CO 80523, USA, ‡Department of Rangeland Ecosystem Science, Colorado State University, Fort Collins, CO 80523, USA

Abstract

Land-cover change associated with agriculture has had an enormous effect on the structure and functioning of temperate ecosystems. However, the empirical evidence for the impact of land use on ecosystem functioning at the regional scale is scarce. Most of our knowledge on land-use impact has been derived from simulation studies or from small plot experiments. In this article we studied the effects of land use on (i) the seasonal dynamics and (ii) the interannual variability of the Normalized Difference Vegetation Index (NDVI), a variable linearly related to the fraction of the photosynthetically active radiation (PAR) intercepted by the canopy. We also analysed the relative importance of environmental factors and land use on the spatial patterns of NDVI. We compared three cultivated land-cover types against native grasslands. The seasonal dynamics of NDVI was used as a descriptor of ecosystem functioning. In order to reduce the dimensionality of our data we analysed the annual integral (NDVI-I), the date of maximum NDVI (DMAX) and the quarterly average NDVI. These attributes were studied for 7 years and for 346 sites distributed across eastern Colorado (USA).

Land use did modify ecosystem functioning at the regional level in eastern Colorado. The seasonal dynamics of NDVI, a surrogate for the fraction of PAR intercepted by the canopy, were significantly altered by agricultural practices. Land use modified both the NDVI integral and the seasonal dynamics of this spectral index. Despite the variability within land-cover categories, land use was the most important factor in explaining regional differences of the NDVI attributes analysed. Within the range of environmental conditions found in eastern Colorado, land use was more important than mean annual precipitation, mean annual temperature and soil texture in determining the seasonal dynamics of NDVI.

Keywords: grasslands, land use, Normalized Difference Vegetation Index, NOAA/AVHRR, primary production, remote sensing

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Introduction

Land use is the component of human-driven global change that has been occurring for the longest period of time. Land-cover change associated with agriculture has had an enormous impact on the structure and functioning of temperate ecosystems. For example, agricultural practices have reduced soil carbon stocks by 35% in the U.S. Central Grassland Region over the past 50 years (Burke *et al*. 1989). On a world basis, Houghton (1999) reported carbon losses of 124 Pg between 1850 and 1980. Pielke *et al*. (1997) and Stohlgren *et al*. (1998) showed that land-use pattern has a critical influence on mesoscale atmospheric processes and, hence, on local climate. Stohlgren *et al*. (1998) presented evidence showing that land-use changes had reduced summer temperatures in the Front Range area of Colorado (USA) during the last

Correspondence: J. M. Paruelo, Fax: +54/11 45148730, e-mail paruelo@ifeva.edu.ar

several decades. They also suggested that atmospheric changes associated with the replacement of semiarid grasslands has increased water discharge and modified the dynamics of tree populations in mountain environments. Further effects of land use on climate have been reported by Bonan (1997) and Pan *et al*. (1999). Mosier *et al*. (1991) showed significant changes in trace gas fluxes associated with cultivation of a semiarid grassland: crop production increased the release of CH_4 and N_2O, two greenhouse gases. The additions of CO_2 and other trace gases to the atmosphere may represent significant feedbacks to global climate change, both from an ecological and a human economic perspective (Sala & Paruelo 1997).

Land use has increased the rate of extinction of species, not only by replacing natural ecosystems but also by changing the disturbance regime. Leach & Givnish (1996) showed that 8–60% of the original plant species of remnant prairie sites were lost after 50 years as a result of landscape fragmentation or fire suppression. Such changes can have local, regional and global consequences, including loss of the soil fertility, soil erosion, reduction of biological diversity, hydrological changes, climatic alteration and modification of the atmospheric composition.

The Central Grassland region of North America covers more than 3.02×10^6 km^2 and has been heavily influenced by agriculture (Lauenroth *et al*. 1999). As a consequence of this intensive agriculture, the region contains the most important corn and wheat production areas of the US and Canada. Within the Central Grassland region, the shortgrass steppe type is located on the western edge, characteristically receiving less than 400 mm of precipitation (Lauenroth & Milchunas 1992). The shortgrass steppe was the dominant land cover before European settlement. These grasslands are dominated by two C4 species: *Bouteloua gracilis* (blue grama) and *Buchloë dactyloides* (buffalo grass). Present land-cover includes a mix of native grasslands, rain fed crops (mainly wheat) and irrigated crops (mainly corn) (Fig. 1). Beginning in 1985, some agricultural fields have been converted into pastures under the Conservation Reserve Program (CRP). Under this programme landowners are paid to revegetate highly erodible land for a 10-y period (Osborn 1993). The species used in CRP areas of Colorado include primarily C3 grasses and legumes.

What are the consequences of replacing native grasslands with crops or sowed pastures on ecosystem functioning at the regional scale? How does the replacement of the dominant plant functional type (C4 grasses by C3 grasses) or irrigation modify the exchange of energy and matter of the ecosystem? Empirical evidence for the impact of land use on ecosystem functioning at the regional scale is scarce. Most of our knowledge on land-use impact has been derived from simulation studies (i.e. Burke *et al*. 1991; Pielke *et al*. 1997; Baron *et al*. 1998; Stohlgren *et al*. 1998; Defries *et al*. 1999) or from small plot experiments (i.e. Mosier *et al*. 1991; Robles & Burke 1997). In this paper, we analysed the effect of land use on the seasonal dynamics of the Normalized Difference Vegetation Index (NDVI), a variable positively related to the fraction of the photosynthetically active radiation (PAR) intercepted by the canopy (Dye & Goward 1993; Sellers *et al*. 1994). NDVI dynamics have been used extensively as an estimator of primary production (Goward *et al*. 1985; Tucker *et al*. 1985; Box *et al*. 1989; Burke *et al*. 1991; Hobbs 1995; Paruelo *et al*. 1997).

In the present paper we focused specifically on the study of the effects of land use on (i) the seasonal dynamics, and (ii) the interannual variability of NDVI; and on the analysis of the relative importance of environmental factors and land use on the spatial patterns of NDVI. Our null hypothesis was that land use does not modify ecosystem functioning. We compared three cultivated land-cover types to native grasslands. We considered grazed grasslands to approximate native systems, as this area has a long evolutionary history of grazing by large generalist herbivores (Milchunas *et al*. 1988).

Materials and methods

We used the seasonal dynamics of the Normalized Difference Vegetation Index (NDVI) calculated from NOAA/AVHRR LAC data as a descriptor of ecosystem functioning. McNaughton *et al*. (1989) showed that primary production is an integrative descriptor of ecosystem functioning. It has been shown that NDVI is a powerful tool to describe the dynamics of primary production (Tucker *et al*. 1985; Malingreau 1986; Lloyd 1990; Loveland *et al*. 1991; Prince 1991; Fischer 1994a,b; Paruelo *et al*. 1997). NDVI is computed from the reflectance in channel 1 (red, 580–680 nm) and channel 2 (near infrared, 725–1100 nm) from the AVHRR sensors on board the NOAA satellites [NDVI = (Channel 2 – Channel 1)/(Channel 1 + Channel 2)]. The use of NOAA/AVHRR data to characterize vegetation at regional and global scales is receiving a great deal of attention (Running *et al*. 1995; Nemani & Running 1997; Loveland and Beldwar 2000).

NDVI data were obtained from the EROS Data Center in Sioux Falls (ND). We obtained biweekly images per year for 7 years (1990–96). Each image corresponded to the maximum NDVI composites (Holben 1986) of Large Area Coverage (1.1 km) images from the daily orbital passes of the NOAA satellite (Eidenshink 1992). Images

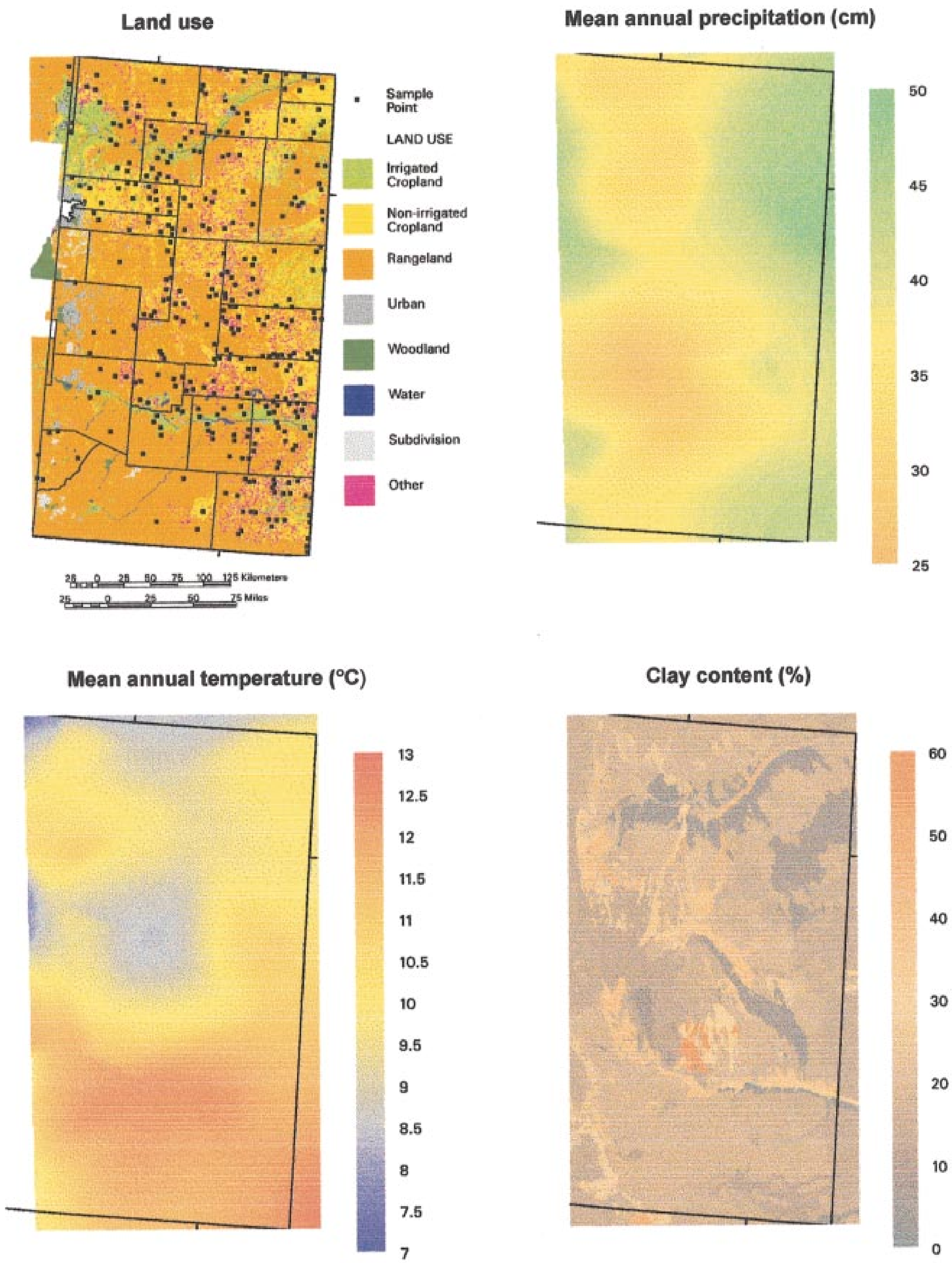

Fig. 1 (a) Land-use categories from the Natural Resource Conservation Service database for eastern Colorado. Points correspond to the study sites, (b) Mean annual temperature, (c) Mean annual precipitation, and (d) Clay content of the soils.

were geometrically registered to the Lambert Azimuthal Equal Area map projection.

Using a Colorado land-use database, we identified 346 sites that corresponded to four different land-use classes: irrigated crops (I) (50 sites), nonirrigated crops (NI) (129 sites), rangelands (RL) (96 sites) and Conservation Reserve Program fields (CRP) (71 sites) (Fig. 1). Sites corresponded to areas large enough to minimize misregistration errors. The proportion of eastern Colorado occupied by the four land covers was 7.8%, 20.3%,

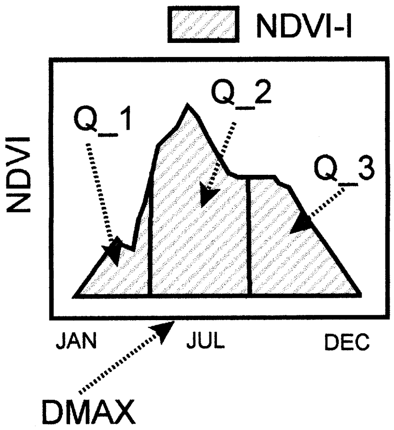

Fig. 2 Schematic view of the seasonal dynamics of the NDVI and the attributes of the curves used in the analyses.

Table 1 Mahalanobis distances between the centroids of each group of sites (irrigated crops (I), nonirrigated crops (NI), grasslands (RL) and Conservation Reserve Program (CRP)) (lower left side of the matrix); and F statistics for the distances (upper right side of the matrix)

		F-values (d.f. 21,2378)			
	Landuse	I	NI	RL	CRP
Mahalanobis	I	–	141**	136**	110**
distances	NI	13.03	–	74 **	29 **
	RL	11.49	4.05	–	7 **
	CRP	11.37	2.13	0.44	–

**$P < 0.01$,*$P < 0.05$

63.14% and 5.0% for I, NI, rangelands and Conservation Reserve Program fields. The land-use database was constructed by digitizing county maps of land use provided by the Natural Resource Conservation Service (NRCS) in 1985. We updated these maps manually in order to represent new Conservation Reserve Program lands and other land-use changes accurately, by incorporating the most recent records from each county NRCS office. The allocation of land among the different land-cover types showed almost no change throughout the period studied. Each site was at least 400 ha (4 pixels in the NDVI image) to allow for a proper localization within the images. For each site we obtained the NDVI values for the 21 images of each of the 7 years available. Thus, our basic dataset consisted of a matrix of 21 variables times 7 years and 346 sites (2422 total observations).

We performed discriminant analysis on this matrix, grouping the cases by land cover (four groups). We used the Mahalanobis (Afifi & Clark 1990) distance to identify differences in the seasonal dynamics of NDVI among land uses and years. From the seasonal curves of NDVI, we derived five attributes that describe basic aspects of ecosystem function: (i) the fraction of the total intercepted PAR (IPAR) [the annual integral of NDVI (NDVI-I)], (ii) the seasonality of the fraction of PAR intercepted [the day of maximum NDVI (DMAX) and (iii–v)the NDVI average for three periods of the year [(iii) Q_1: Julian dates 1–153, late winter-spring; (iv) Q_2: Julian dates 154–237, summer; (v) Q_3: Julian dates 238–365, autumn–early winter)] (Fig. 2). Analyses were performed both for individual years and the 7-y averages.

Eastern Colorado is a near ideal area to study the impact of land use because of the homogeneity of its potential vegetation (a shortgrass steppe) and the smooth environmental gradient. We characterized the physical environment of each site from the mean annual precipitation (MAP), mean annual temperature (MAT) and the percentage of clay of the soils (CLY) (Fig. 1). Environmental data were interpolated from existing databases for the US Central Grassland region compiled by the Shortgrass Steppe Long-term Ecological Research project. For each of the five attributes of the NDVI curves we used the three environmental variables as covariates in an ANCOVA. In order to capture differences in the seasonal dynamics, we also studied the differences among sites in the quarterly NDVI average using MANOVA.

Results and discussion

Effect of land use on the seasonal dynamics of NDVI

The analysis of the 7-year average of the seasonal curves of NDVI (Discriminant Analysis) showed significant differences among the four land-use categories studied (Wilks's Lambda test: 0.24981, $F_{63,7158} = 67.214$, $P < 0.001$). In the hyperspace defined by the 21 dates, irrigated crops showed the farthest distance from any other land-use category (Table 1). The most distinct land-cover types were the two crop systems (Fig. 3, Table 1). The analysis of each individual year showed similar distances among land-use categories as the average curve (results not shown).

The analysis of the NDVI integral (NDVI-I) and the date of maximum NDVI (DMAX) also showed differences among land-cover types (Fig. 4). Land-use categories differed in the integral and timing of the NDVI peak (Figs 3 and 4). The average NDVI integral was 46% and 7% higher in irrigated and rain-fed crops, respectively, than in grasslands (Fig. 3a) (ANCOVA, $F = 139$, d.f. 3, 339, $P < 0.001$, see Table 2). CRP areas and rangelands did not differ significantly in their NDVI-I (Fig. 4a). Land use had an important effect on the seasonality of PAR

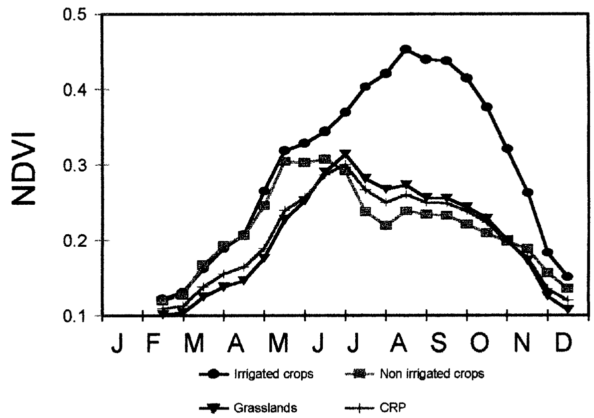

Fig. 3 Average seasonal dynamics for the four land-use categories for the period 1990–96. The standard errors of the single points ranged between 0.006 and 0.022, and the coefficients of variation between 6% and 48%.

absorption (Fig. 3). On average, NDVI peaked more than 20 days later in irrigated fields than in native grasslands (Fig. 4b) (ANCOVA, $F_{3,339}$= 71, $P < 0.001$, see Table 2). Maximum NDVI occurred 20 days earlier in nonirrigated fields than in grasslands (Fig. 4b) ($P < 0.001$). CRP areas did not differ significantly from grasslands in the timing of the NDVI peak.

Multiple Analysis of Variance (MANOVA) of the seasonal NDVI averages also indicated a significant effect of land use on the seasonal dynamics of NDVI (Wilks's Lambda test: 0.20578, F_{9827} = 84.121, $P < 0.001$). During late winter and spring (Q_1), native grasslands showed the lowest NDVI (Fig. 5). CRP areas and native rangelands presented a higher average NDVI than nonirrigated crops during the summer (Q_2). During the last part of the year (Q_3), CRP areas, native grasslands and nonirrigated crops showed the same average NDVI (Fig. 5). Irrigated crops showed the highest NDVI during the three portions of the year (Fig. 5, $P < 0.001$). The analysis of the NDVI-I, DMAX and seasonal NDVI averages for each of the seven years available showed the same pattern as the average values presented here.

The major change in the dynamics of NDVI was associated with irrigation. On average, adding water increased the NDVI-I, a measure of the amount of PAR intercepted by the canopy by 47% compared to native grasslands (Fig. 4a). The replacement of grasslands by wheat–fallow systems produced a modest increase in the NDVI integral (7%) (Fig. 4a). Of course, this increase is not only a consequence of the replacement of the dominant species and irrigation. Large amounts of nitrogen are added to crops annually. Nitrogen significantly increases carbon gains in this area even under rainfed conditions. Lauenroth *et al.* (1978) observed an

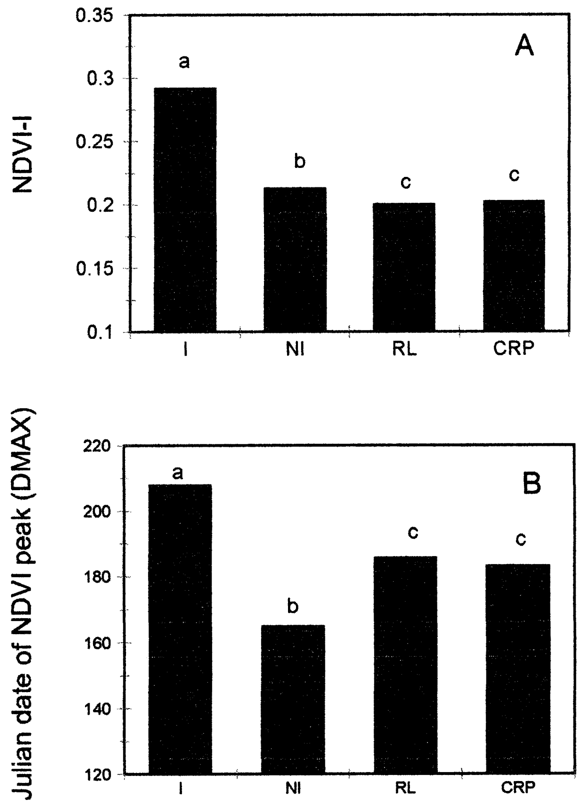

Fig. 4 Average NDVI integral (NDVI-I) (a)and date of maximum NDVI (DMAX) (b)for the period 1990–96 for the four land-use categories: irrigated crops (I), nonirrigated crops (NI), grasslands (RL) and Conservation Reserve Program (CRP). Different letters indicate significant differences (ANCOVA, $P < 0.001$, see Table 2).

Table 2 *F*-values for the ANCOVA performed on the 7-year average of the NDVI integral (NDVI-I), the date of maximum NDVI (DMAX), and the average NDVI for three periods of the year (Q_1: Julian dates 1–153, late winter–spring; Q_2: Julian dates 154–237, summer; Q_3: Julian dates 238–365, autumn–early winter). Land-use classes were: irrigated crops, nonirrigated crops, native grasslands, and Conservation Reserve Program areas. The covariates included in the model were mean annual precipitation (MAP), mean annual temperature (MAT) and percentage of clay content of the soil (CLY)

		F-values (n = 346)				
Attributes		NDVI-I	DMAX	Q_1	Q_2	Q_3
Landuse		139**	71**	82 **	141**	168**
Covariates	MAP	48 **	3	53 **	35 **	23 **
	MAT	37**	19**	2	99**	7**
	CLY	2	3	3	2	1

$^{**}P < 0.01$, $^{*}P < 0.05$

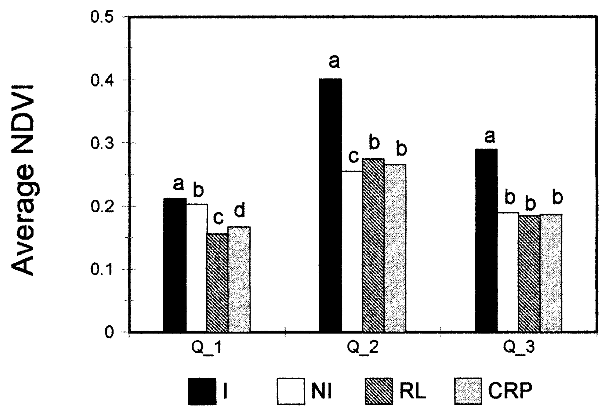

Fig. 5 Average NDVI for three periods of the year (Q_1: Julian dates 1–153, late winter–spring; Q_2: Julian dates 154–237, summer; Q_3: Julian dates 238–365, autumn–early winter) for the four land-use categories: irrigated crops (I), nonirrigated crops (NI), grasslands (RL) and Conservation Reserve Program (CRP). Different letters indicate significant differences (ANCOVA, $P < 0.001$, see Table 2).

increase of up to 57% in primary production in the shortgrass steppe when nitrogen was added. In these rangelands, adding water and nitrogen increased aboveground net primary production by a factor of almost 10.

Using a simulation approach, Baron *et al.* (1998) reported, for the South Platte basin in Colorado, Wyoming and Nebraska, a 237% and a 20% increase in net photosynthesis when irrigated and nonirrigated crops replace grasslands, respectively. Baron *et al.*'s (1998) simulation analysis reported that net carbon gain increased by a factor of 4 following replacement of grasslands by irrigated crops in a particular watershed of the area. Estimates of aboveground net primary production (ANPP) for wheat–fallow systems in eastern Colorado and Kansas showed that wheat is more productive than grasslands in areas with mean annual precipitation lower than 570 mm (Lauenroth *et al.* 2000b). The observed differences in ANPP between wheat and natural grasslands for Colorado counties receiving 320 mm y^{-1} is 154 g m^{-2} (or 142%) CRP areas did not differ significantly from grasslands in total light interception.

Our approach ignored completely the differences in belowground allocation between crops and grasslands. Milchunas & Lauenroth (1992) reported for the shortgrass steppe similar values for above- and belowground net primary production. In contrast, the belowground net primary production for crops is a small fraction of ANPP (less than 20%) (Fischer 1983; Anderson 1988; Eghball & Maranville 1993). Knowing the amount of carbon allocated belowground is crucial to estimating the carbon balance of the different land-cover types.

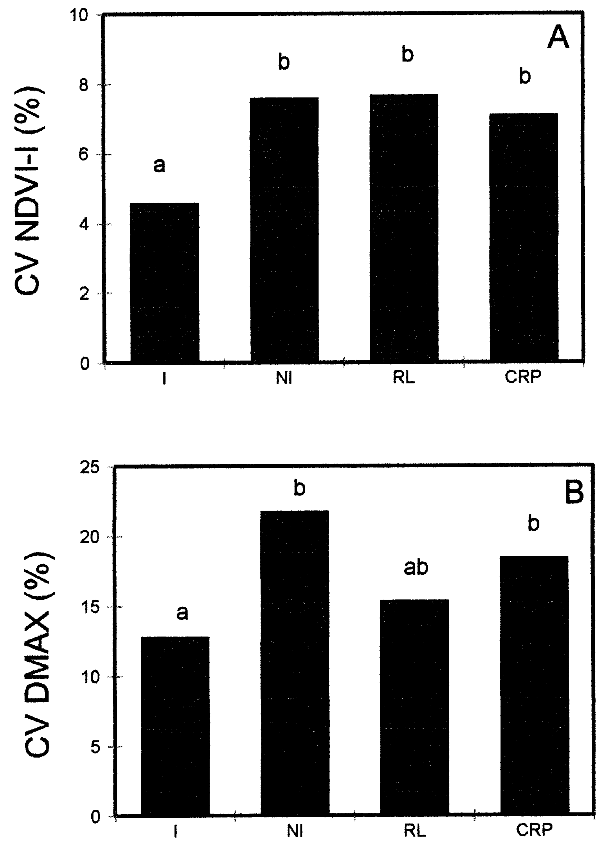

Fig. 6 Coefficient of Variation (CV (%) = (Standard Deviation/Mean)*100) of the NDVI integral (NDVI-I) (a)and date of maximum NDVI (DMAX) (b)for the period 1990–96 for the four land-use categories: irrigated crops (I), nonirrigated crops (NI), grasslands (RL) and Conservation Reserve Program (CRP). Different letters indicate significant differences (ANCOVA, $P < 0.001$, see Table 2).

Effect of land use on the interannual variability of NDVI

Irrigation significantly reduced the interannual variability of both the NDVI-I and the date of maximum NDVI (Fig. 6). We used the Coefficient of Variation (CV = standard deviation/mean) to characterize the interannual variability of the NDVI integral (NDVI-I) and the date of maximum NDVI (DMAX). Irrigated crops displayed a significantly lower interannual variability (ANOVA, $F_{3,342}= 16$, $P < 0.001$) than the other land-use categories (Fig. 6a). The interannual variability of the day of maximum NDVI also differed among land-cover types (ANOVA, $F_{3,342} = 19$, $P < 0.001$) (Fig. 6b). Irrigated crops showed the lowest CV of DMAX and nonirrigated crops the highest. Summer was the least variable season and the spring the most variable for all the land-use categories (Fig. 7). For every portion of the year, irrigated crops displayed the lowest interannual variability.

Paruelo & Lauenroth (1998) and Jobbágy *et al*. (1999) reported a decrease in the interannual variability of the NDVI integral as water availability increases for native grasslands of North American and semiarid steppes of Patagonia. Irrigation may contribute to decouple plant production and precipitation, generating a more stable system. Nonirrigated crops showed a similar interannual variability to grassland and CRP areas. In this case the predominant cultivation system (wheat–fallow) may contribute to increase interannual variability. Our data cannot separate fallow and wheat areas because the fields, as a consequence of strip cropping, are always smaller than the size of our sites (400 ha). The date of maximum NDVI was between two and three times more variable than the integral of the NDVI. Paruelo & Lauenroth (1998) found the same pattern for unmodified areas across the Central Grassland region of US.

All of the land-use categories displayed the highest interannual variability during late winter and spring (Q_1) (Fig. 7). In this period the difference between irrigated crops and the other land-use categories was lower than during the rest of the year. During late winter and early spring, water is not the main determinant of light interception and temperature exerts an important control over the start of the growing season (Paruelo & Lauenroth 1998).

Environmental vs. land-use controls of NDVI dynamics

Sites corresponding to different land-use categories did not differ significantly in mean annual precipitation (MAP) or mean annual temperature (MAT) (ANOVA, NS). MAP ranged between 272 and 494 mm and MAT between 7 and 12.5 °C. These values corresponded to the full range of spatial climatic variability observed in eastern Colorado (Fig. 1). Irrigated crops were found on finer textured soils than the rest of the land covers. Irrigated crop sites showed a significantly higher clay content in their soils (24.98%) than the other categories (19.27%, 17.20%, 18.29%, respectively, for nonirrigated crops, grasslands and CRP areas) ($F_{3,342} = 12.54$, $P < 0.0001$). Land use was more important than any environmental variable in accounting for spatial differences in the integral of the NDVI, the date of maximum NDVI or the quarterly average NDVI. When MAT, MAP or clay content (CLY) was included in an ANCOVA their effect on the NDVI attributes was always lower than the effect of land use. (Table 2).

At the regional scale the interannual changes of the mean NDVI-I of grasslands, nonirrigated crops and CRP sites were highly correlated (Table 3). This indicates a strong environmental control of the temporal changes of the NDVI-I of the three land-cover types operating at a regional scale. Water availability has been referred to as the most frequent control on carbon gains in the shortgrass steppe, both in time and space (Sala *et al*. 1988; Lauenroth & Sala 1992). Nonirrigated crops always had a higher NDVI-I than grassland and CRP areas, but the interannual changes in NDVI-I are similar to those observed in grasslands and CRP fields. The average NDVI of irrigated crops was not correlated with the NDVI in grasslands suggesting that irrigation decouples this system from the environmental factors that operate on grasslands, CRP areas and nonirrigated crops.

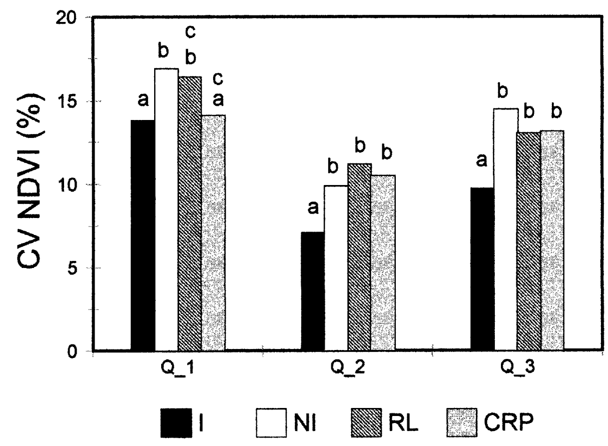

Fig. 7 Coefficient of Variation (CV (%) = (Standard Deviation/Mean)*100) of the NDVI for three periods of the year (Q_1: Julian dates 1–153, late winter–spring; Q_2: Julian dates 154–237, summer; Q_3: Julian dates 238–365, fall–early winter) for the four land-use categories: irrigated crops (I), nonirrigated crops (NI), grasslands (RL) and Conservation Reserve Program (CRP). Different letters indicate significant differences.

Table 3 Correlation matrix (lower-left) and *F*-values (upper-right) among the average integral of NDVI for sites pertaining to the different landuse categories (I, Irrigated crops; NI, nonirrigated crops; RL, grasslands; CRP, Conservation Reserve Program areas) across the seven year period analysed

		F-values (d.f. 1,5)			
	Landuse	I	NI	RL	CRP
Correlation	I	–	1	2	1
Coefficients	NI	0.50	–	45**	35 **
	RL	0.55	0.95	–	114**
	CRP	0.42	0.94	0.98	–

**$P < 0.01$, *$P < 0.05$

Conclusions

We rejected our null hypothesis. We found that land use did modify ecosystem functioning at the regional level in eastern Colorado. The seasonal dynamics of the NDVI and the annual integral, a good estimator of the fraction of light intercepted by the canopy, was significantly altered by agricultural practices (Fig. 3). Despite the variability within land-cover categories in the NDVI integral and seasonality (Fig. 4), land use was the most important factor in explaining regional differences of the NDVI attributes analysed (Table 2). Within the range of environmental conditions found in eastern Colorado, land use was more important than mean annual precipitation, mean annual temperature and soil texture in determining the seasonal dynamics of NDVI and hence carbon gains. The replacement of plant communities dominated by C4 species (the shortgrass steppe) by C3 species, either totally (wheat) or partially (CRP areas), significantly increased the NDVI during the first quarter of the year (Fig. 5). Considering the proportion of eastern Colorado occupied by the different land covers considered, land use increased the NDVI integral 9.5%, 2.2% and 5.4% during the first, second and third quarter, respectively.

Our results represent one of the few pieces of empirical evidence of the impact of land-use and land-cover change on ecosystem functioning at the regional scale. Irrigated agriculture transformed the shortgrass steppe of eastern Colorado into a system that, based on the dynamics of NDVI, resembles a tallgrass prairie in Minnesota (Paruelo & Lauenroth 1995). Colorado non-irrigated agricultural fields had NDVI dynamics similar to a sagebrush steppe of eastern Oregon (Paruelo & Lauenroth 1995).

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