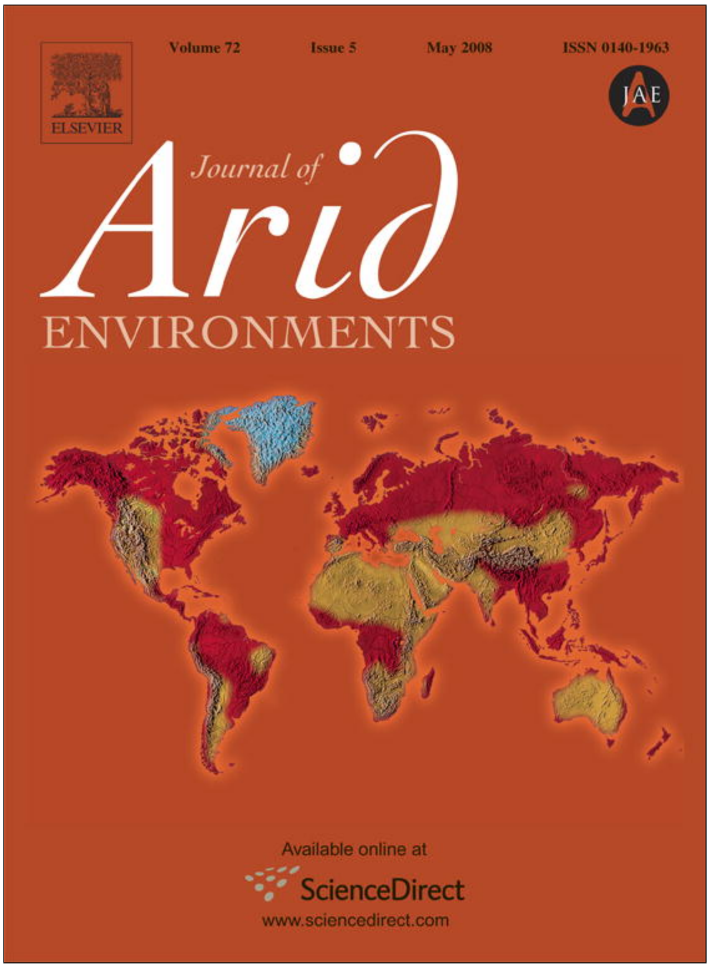
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Grazing effect on NDVI across an aridity gradient in Argentina

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Abstract

Grazing effects on aboveground net primary production (ANPP) have ever been controversial. Certain plant communities are very sensitive to grazing and others are not. We analyzed the grazing effect on ANPP across a gradient of mean annual precipitation (MAP) in rangelands of Central Argentina. We focused not only on the regional patterns of the grazing effect on ANPP but also on the response of the inter-annual variability of ANPP to this disturbance. We used the seasonal dynamics of the Normalized Difference Vegetation Index (NDVI), a spectral index calculated from the reflectance in the red and infrared portion of the spectrum as recorded by the AVHRR/NOAA sensor as an estimator of ANPP. This variable was recorded at increasing distances from the watering point in large paddock distributed through the MAP gradient (250–600 mm) of the extensive plains Arid Chaco in Argentina. Grazing effect on NDVI decreased along the regional gradient of MAP. The grazing effect on NDVI varied among years, being greater in dry than in wet years. Regional patterns changed among years because the NDVI close to the watering points had high inter-annual variability at the driest extreme of the gradient. Our findings contribute a conceptual framework to grazing management in semi-arid rangeland. Considering that grazing effect on NDVI-I was higher in arid than in wet sites implicates that appropriate grazing management strategies would be different in sites with different precipitation levels.

Keywords: Aboveground net primary production; Grazing disturbances; Normalized Difference Vegetation Index (NDVI); Rangelands

1. Introduction

Aboveground net primary production (ANPP) is a key functional attribute of terrestrial ecosystems because of its relationships with animal biomass, secondary productivity and nutrient cycling (McNaugthon et al., 1989). Precipitation has been referred to as the main control of the spatial variation of ANPP in grassland and shrubland areas (Briggs and Knapp, 1995; Lauenroth, 1979; Le Houérou et al., 1988; Paruelo et al., 1999;

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Rutherford, 1980; Sala et al., 1988; Walter, 1939). The slope of the relationship between annual precipitation and ANPP is related to the average precipitation-use efficiency (PUE) of the ecosystem. Grasslands from different geographic regions present very similar slopes (McNaugthon et al., 1993). Lauenroth and Sala (1992) and Paruelo et al. (1999) showed that the relationships between ANPP and annual precipitation for individual sites had different slopes than the relationship based on averages for sites located across the mean annual precipitation (MAP) gradient typical of rangeland areas. Aside from precipitation, temperature and soil texture have a significant influence on ANPP at regional and local scales (Epstein et al., 1997; Sala et al., 1988). Two disturbances have a large influence on ANPP: fire and grazing (Briggs and Knapp, 1995; Oesterheld et al., 1999). The effects of grazing on grasslands varied according to the variable considered. Even for the same variable, very different responses to grazing have been reported in the literature (Oesterheld et al., 1999). Certain ecosystems are very sensitive to grazing while others are not.

Milchunas et al. (1988) proposed that the effect of grazing varied across two main axes: MAP and the grazing evolutionary history. A meta-analysis of long-term grazing experiments across a wide variety of ecosystems indicates that grazing reduced ANPP in the less productive (driest) sites (Milchunas and Lauenroth, 1993). However, Oesterheld et al. (1999) found, for grasslands and savannas, that grazing effects on ANPP were similar across an MAP gradient. O'Connor et al. (2001) reported that annual variation of ANPP due to precipitation depended on the vegetation condition which in turn is modified by grazing. They found that the magnitude of ANPP annual variation was greater in degraded states of the grasslands. Many of the systems on which the referred articles based their generalizations of the effect of grazing on ANPP differed widely in functional and structural properties. Moreover, the meta-analyses of Milchunas and Lauenroth (1993) and Oesterheld et al. (1999) were based on experiments performed using different methodologies.

In this article, we tackle the issues of the impact of grazing on ANPP applying a mensurative approach. We analyzed the effect of grazing on ANPP across an MAP gradient in a region with a homogeneous vegetation structure and using a common methodology. We focused the study on two questions: (1) what are the effects of grazing on ANPP along a precipitation gradient? and (2) how does grazing modify the sensitivity of ANPP to inter-annual changes in precipitation along the aridity gradient?

2. Materials and methods

We selected large paddocks with unique watering points to define grazing gradients (Andrew, 1988; Graetz and Ludwig, 1978; Lange, 1969; Nash et al., 1999; Pickup and Chewings, 1994) over a rangeland area of 10 million ha. We used seasonal dynamics of the Normalized Difference Vegetation Index (NDVI), a spectral index derived from AVHRR/NOAA satellites as an estimator of ANPP (Box et al., 1989; Burke et al., 1991; Goward et al., 1985; Hobbs, 1995; Paruelo et al., 1997; Tucker et al., 1985). The NDVI was extracted from pixels located at increasing distances from the watering point in each paddock for the 1996/97, 1997/98, 1998/99 and 1999/2000 growing seasons. The paddocks were scattered through the Arid Chaco region of Argentina. These extensive plains dominated by shrublands show a westward decrease in MAP from 600 to 250 mm. (Cabido et al., 1993; Morello et al., 1985).

This study was conducted in the Arid Chaco region, located in central western Argentina (latitude 29–32°S, longitude 65–67°W) (Fig. 1). The climate is semi-arid, characterized by hot summers and mild winters. January has the highest average temperature (26 °C) while July is the coldest (11 °C) (Morello et al., 1985). Frost-free period is 289 days from August to June (Bazán, 1993). Precipitation shows a seasonal pattern (80% of total annual precipitation occurring between November and March, sensu Lasso 1997). According to Gómez et al. (1993), soils in the region are Aridisols and Entisols.

Current vegetation is characterized by a continuous shrubland with isolated trees and patches of grass (Morello et al., 1985). Dominant woody plant genera include *Larrea*, *Aspidosperma*, *Prosopis* and *Mimozyganthus*. Dominant grass genera are *Pappophorum*, *Trichloris*, *Setaria*, *Aristida*, *Chloris* and *Neobouteloua*. Growing season generally matches the seasonal precipitation distribution (Anderson et al., 1977), as described previously.

Cattle production based on cow-calf operations and goat breeding is the principal source of agricultural income (Ferrando and Namur, 1984). At least 1,000,000 cattle heads and 200,000 goats currently graze in the region (Secretaría de Agricultura, Ganadería, Pesca y Alimentos de la Nación 2002 National Census,

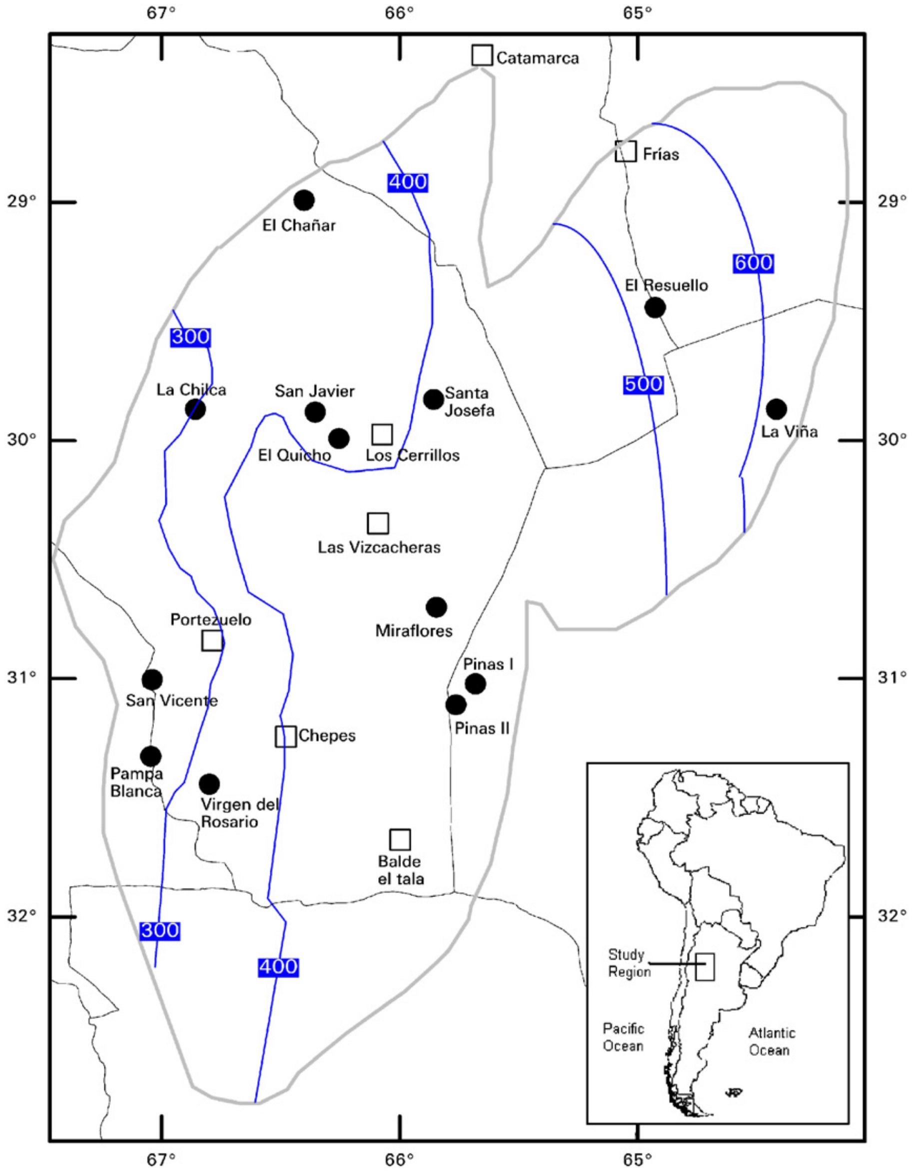

Fig. 1. Map of the region under study. The isohyets (blue lines) were interpolated linearly from 30 points spread over the region. Circles indicate geographic distribution of the 13 paddocks selected. Squares indicate geographic distribution of the seven sites selected to analyze the temporal variability of precipitation in the study region from 1996/97 to 1999/2000 growing seasons (Table 2). Gray line indicates the limits of Arid Chaco region. Black lines indicate province limits.

http://www.sagpya.mecon.gov.ar). Native plant species are the main forage source for grazers and browsers (Anderson et al., 1980; Ferrando et al., 2001).

Thirteen paddocks, corresponding to private ranches, were selected (Table 1) in the Arid Chaco region. To be selected a paddock must have had: (1) only one watering point, (2) more than 7 km from the watering point to the opposite fence and (3) a long-term grazing history. The corners of the paddocks and the watering points were georeferenced using a GPS receptor (Garmin 12 XL).

ANPP estimates were derived at intervals of 1 km from the watering point using remotely sensed data. We calculated the growing season (November to March) integral of NDVI (NDVI-Igs). NDVI was computed from the reflectance in the red (channel 1) and near-infrared (channel 2) bands of the NOAA/AVHRR 11 satellite (NDVI = (channel 2−channel 1)/(channel 1 + channel 2)). NDVI is a good estimator of the amount of photosynthetically active radiation intercepted by the green canopy and hence of ANPP (Sellers et al., 1992). To calculate the growing season integral, we used 10-day maximum composite (1-km-resolution) images for 1996/97, 1997/98, 1998/99 and 1999/2000. We used NOAA AVHRR information because such data allowed

Table 1
Geographic location and characteristics for the selected paddocks

Paddock name	Geographic location	Area (ha)	Maximum distance to watering point (km)	MAP (mm)[a]	Stocking rate (kg/ha)[b]
Pampa Blanca	31.33°S 67.01°W	10874	12	281	6.38
San Vicente	31.00°S 67.01°W	4683	8	288	15.37
La Chilca	29.90°S 66.71°W	9152	12	300	9.88
V. del Rosario	31.59°S 66.81°W	6265	12	326	18.45
El Quicho	30.03° S 66.24°W	10060	13	387	12.22
San Javier	29.92°S 66.32°W	18611	22	388	13.07
El Chañar	29.04°S 66.49°W	12341	10	388	13.07
Santa Josefa	29.81°S 65.78°W	3699	8	428	25.06
Miraflores	30.77°S 65.73°W	4890	9	430	38.86
Pinas I	30.99°S 65.68°W	10454	12	439	60.31
Pinas II	31.07°S 65.77°W	8300	10	444	50.42
El Resuello	29.44°S 64.74°W	8226	8	541	68.81
La Viña	29.90°S 64.45°W	2820	8	625	95.95

[a] MAP, mean annual precipitation.

[b] Stocking rate was estimated by using linear regression analysis (log stocking rate (kg/ha) = 2.7971 log NDVI-Igs + 4.1253, $p<0.001$, $R^2=0.85$) for 25 counties of Arid Chaco region. Livestock information was provided by 2002 National census (http://www.sagpya.mecon.gov.ar). Livestock data were converted to stocking rate according to the procedure of Oesterheld et al. (1998).

us to integrate temporally the ANPP estimates (many cloud-free scenes in a short rainy season where the probability of cloud cover is high). On the other hand, land degradation processes in the system studied occurred at spatial scale of square kilometers. The spatial variability in ANPP at a sub-pixel scale (less than 1 km^2) becomes then less important regarding our objectives (Lind et al., 2003).

NDVI-Igs were calculated by adding the products of NDVI for each date and the proportion of the year represented by that date: NDVI-Igs $= \Sigma^n \mathrm{NDVI}_j \times T_j$, where n is the number of composites per growing season from November to March, NDVI$_j$ is the jth composite and T_j is the proportion of the year covered by the jth composite: 10 days. The NDVI integral was calculated for the growing season (November to March) because vegetation activity is restricted to this period (Morello et al., 1985).

We fit straight-line regression models for the relationships between NDVI-Igs and watering point distance (representing the grazing gradient) for each paddock and for each growing season (1996/97, 1997/98, 1998/99 and 1999/2000). The slopes of the regression models were estimates of the intensity of grazing effects on NDVI for each paddock and for each year (Welden and Slawson, 1986). We considered the existence of a grazing gradient when the model slope was significant ($p<0.05$). We estimated the grazing effects on NDVI-Igs for each paddock from the average of the four growing seasons.

For each paddock and distance to the watering point, we calculated the coefficient of variation (CV = STD/mean, $n = 4$) of the NDVI-Igs, which describes the annual variability of ANPP. We fit straight-line regression models for the relationships between the NDVI-Igs CV and watering point distance for each paddock. The slopes of the regression models are estimates of the intensity of grazing effects on the inter-annual variability of NDVI-Igs, for each paddock.

MAP for each paddock (Table 1) was estimated using an algorithm of lineal geographic interpolation (IDRISI User's Guide, 1995). We used a georeferenced database of MAP constructed from published ($n = 24$; Cabido et al., 1993; Lasso, 1997) and unpublished ($n = 6$) data. The precipitation regime of the study region, for the four growing seasons analyzed, was characterized from a long-term database of seven sites (Table 2). We calculated the precipitation bias of the growing season for each site as the relative difference between the actual precipitation and growing season mean precipitation.

No data on the consumption level were available for the paddocks included in our study. However, stocking rate was estimated according to Oesterheld et al. (1998). We performed linear regression analysis between livestock stocking rate and NDVI-Igs for 25 counties of the Arid Chaco region. Livestock information was provided by 2002 National Census (http://www.sagpya.mecon.gov.ar). Livestock existences were converted to stocking rate using average individual mean body mass for each category (Oesterheld et al., 1998). We used

Table 2
Temporal variability of precipitation in the study region from 1996/97 to 1999/2000 growing seasons (November to March)

Site name	Mean (mm)	1996/97	1997/98	1998/99	1999/2000
Balde el tala	370	0.15	0.11	0.07	0.68
Las Vizcacheras	421	−0.16	0.36	0.20	0.47
Los Cerrillos	334	0.15	0.24	0.06	0.48
Frías	530	0.15	0.33	0.32	0.80
Portezuelo	293	−0.31	0.04	−0.05	0.36
Chepes	406	−0.09	−0.16	−0.09	0.14
Catamarca	352	0.13	−0.29	0.18	0.64
Mean ± 1 S.E.		−0.003 ± 0.189	0.09 ± 0.25	0.10 ± 0.14	0.510 ± 0.221

Temporal variability of precipitation for the study region was estimated by using the relative difference between each growing season precipitation and its respective growing season mean precipitation for seven sites. Growing season mean precipitation was calculated using long-term data (1980–2000).

NDVI-Igs average values (1996/97, 1997/98, 1998/99 and 1999/2000) for each county. Finally, we estimated stoking rate for each paddock (Table 1).

To answer the questions stated above, we fit straight-line regression models for the relationship (1) between grazing effects on ANPP (the slope of NDVI-Igs vs. distance to the watering point) and MAP, and (2) between grazing effects of annual variability of ANPP (the slope of the NDVI-Igs CV vs. distance to the watering point) and MAP (the independent variable in both cases).

To evaluate biases related to the particular sites included in the analyses, we randomly selected 20% of the paddocks, removed them from the data set, and recalculated the regression model between grazing effects on ANPP and MAP, and between grazing effects of annual variability of ANPP and MAP. We repeated this procedure five times. We compared the coefficient of determination (R^2), the slope, the y-intercept and the p-value of the models generated using the incomplete data sets.

3. Results

Grazing effects on NDVI-Igs were different between sites and years (Fig. 2). We defined grazing gradients following Pickup and Chewings (1994) classification. Gradients were defined following Pickup and Chewings (1994) classification (normal: gradual increasing; inverse: gradual decreasing; and composite: gradual increasing at first and decreasing at final).

Thus, normal, inverse and composite gradients were observed, as well as cases of non-gradients. However, normal gradients and non-gradients were the most frequent cases. Grazing gradients were different between years. Also following Pickup and Chewings (1994) classification, permanent gradients (maintained after major growth periods) and temporary gradients (with full recovery after a major rainfall) were observed (Fig. 2). Temporary gradients were the most common. Taking into account the spatial and temporal grazing gradient classification of Pickup and Chewings (1994) most of the paddocks showed normal-temporary grazing gradients (San Vicente, El Quicho, El Chañar, Miraflores and Pinas II). Some paddocks such as Pampa Blanca, La Chilca and San Javier showed normal-permanent grazing gradients. Other paddocks such as Virgen del Rosario and Santa Josefa presented alternatively normal, inverse and non-gradients. Finally, Pinas I, El Resuello and La Viña only presented gradients one of 4 years. We did not analyze the presence or absence of composite gradient because we only used a simple linear regression model. This type of model was selected to facilitate the analysis of grazing effects at regional scale.

Grazing effects on the NDVI-Igs also varied across the precipitation gradient (Fig. 3). The average effect of grazing on NDVI-Igs, described by the slope of NDVI-Igs vs. distance to the watering point, was significantly higher in the driest extreme of the MAP gradient compared to the wettest extreme (Fig. 3E). The effect of grazing varied among growing seasons (Fig. 3A–D). For the 1996/97 growing season (Fig. 3A), 92% of the grazing gradients (paddocks) showed a significant ($p < 0.05$) change in NDVI-Igs with distance from the watering point. Contrarily, for the 1997/98 (Fig. 3B) and 1998/99 growing seasons (Fig. 3C), NDVI-Igs

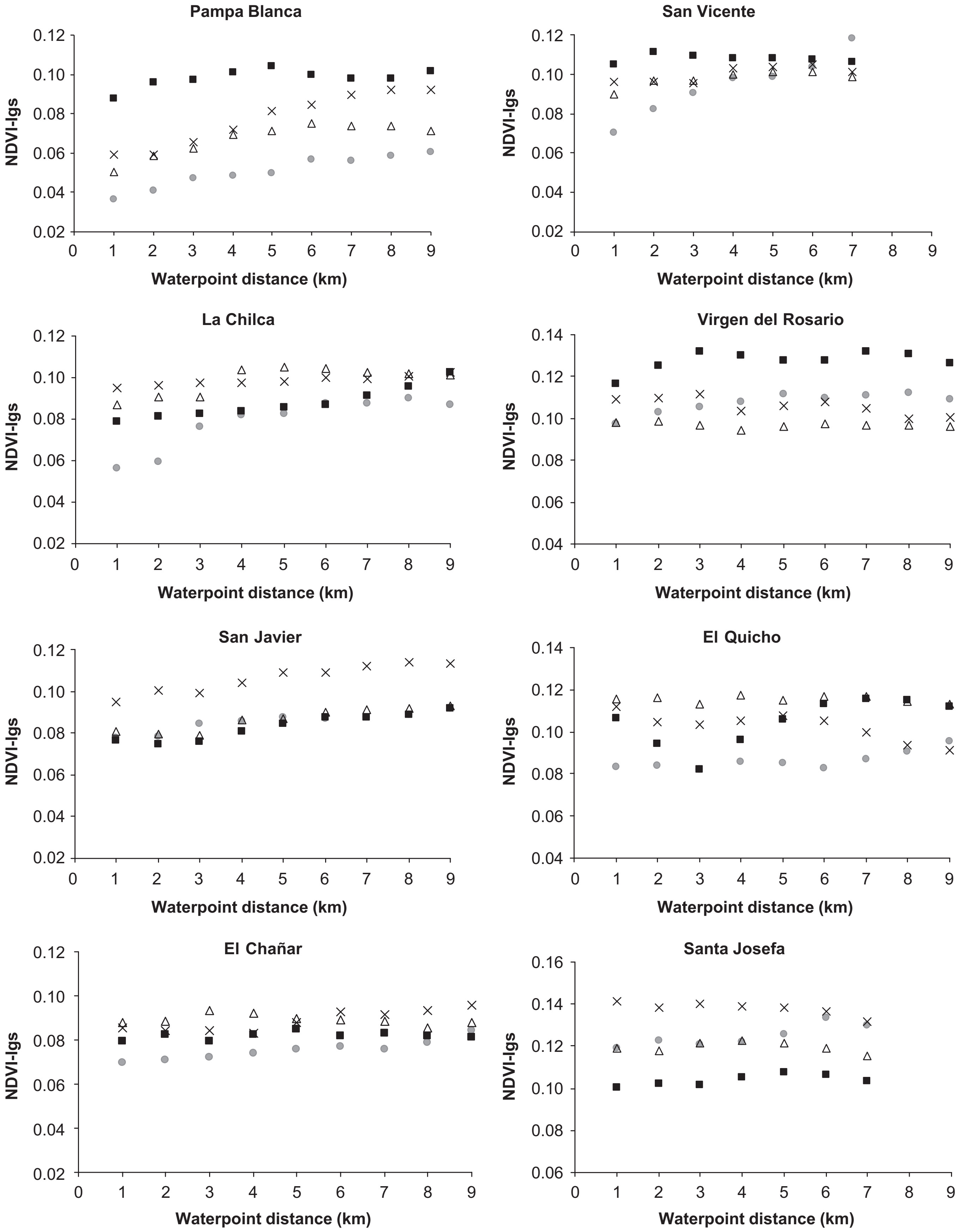

Fig. 2. Growing season NDVI integral (NDVI-Igs) gradients for each paddock during 1996/97 (gray circles), 1997/98 (black squares), 1998/99 (triangles) and 1999/2000 (crosses).

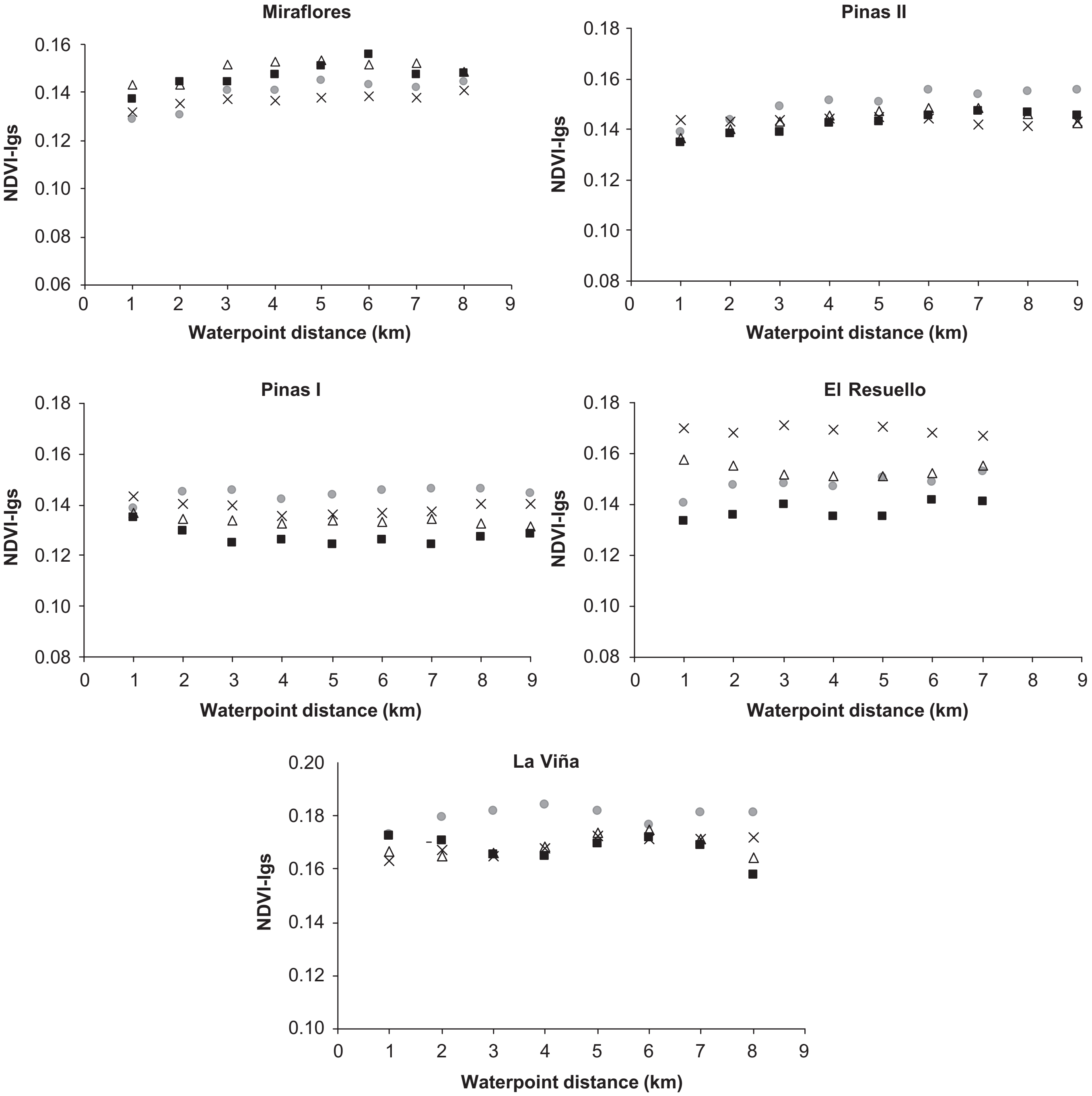

Fig. 2. (*Continued*)

changed significantly with distance to the watering point ($p<0.05$) in only 46% of the grazing gradients. For the 1999/2000 season (Fig. 3D), 54% of the sites showed a significant change of NDVI-Igs across the grazing gradient, but two paddocks showed inverse gradients (negative slope, $p<0.05$) meaning that NDVI-Igs decreased away from the watering point. NDVI-Igs changed significantly from the watering point ($p<0.05$) for all four growing seasons analyzed in only two paddocks (MAP = 281 and 387 mm). For most of the sites, the grazing gradients were significant ($p<0.05$) during two or three growing seasons. For the paddocks located in the wettest portion of the area (MAP = 541 and 625 mm), the grazing gradients were significant ($p<0.05$) in only one season. These patterns suggest the existence of strong interactions between grazing history, current-year grazing and water availability in determining ANPP.

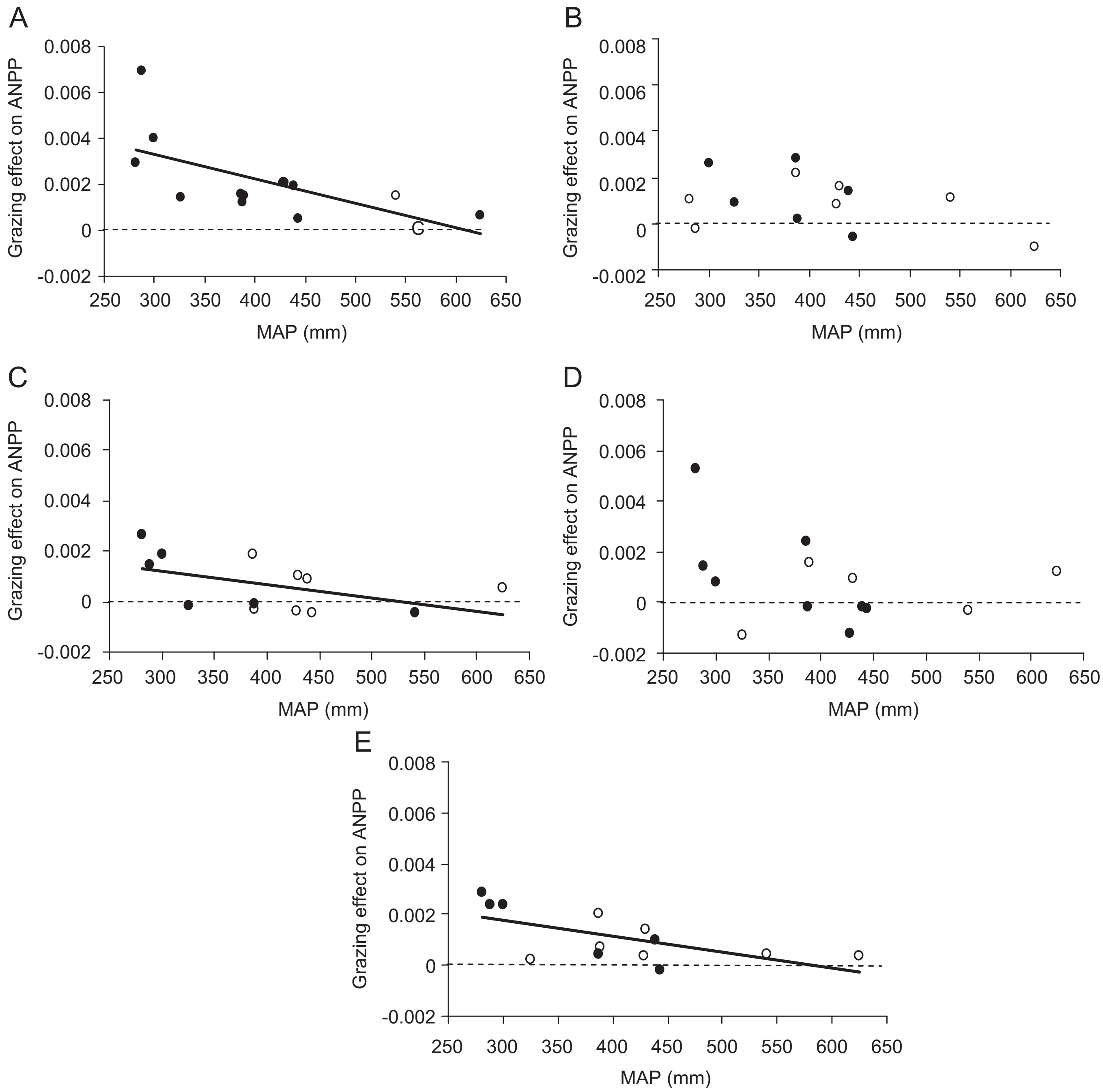

Fig. 3. Grazing effect on Normalized Difference Vegetation Index (NDVI) across a regional gradient of mean annual precipitation (MAP): (A) 1996/97 ($R^2 = 0.3883$, $p = 0.0229$); (B) 1997/98 ($R^2 = 0.1431$, $p = 0.2024$); (C) 1998/99 ($R^2 = 0.2359$, $p = 0.0924$); (D) 1999/2000 ($R^2 = 0.1000$, $p = 0.2818$); and (E) average growing season data ($R^2 = 0.3653$, $p = 0.0189$). Grazing effect was estimated using the slopes of linear regression models of the seasonal integral of NDVI (NDVI-Igs) and watering point distance (grazing gradient). Significant grazing gradients ($p<0.05$) are indicated by using black circles, and non-significant grazing gradients are indicated by using open circles.

Grazing effects on annual variability of NDVI-Igs (relationship between annual CV of NDVI-Is and watering point distance) were significant for seven paddocks (Fig. 4, dark circles). This relationship was negative in six paddocks, and was positive in only one paddock. These results indicate that annual changes of NDVI-Igs were greater near the watering points. Grazing effects on annual variability of NDVI-Igs decreased ($p<0.05$) along the MAP gradient (Fig. 4).

Grazing effects on ANPP decreased along the regional MAP gradient (Fig. 3). However, in wet years, the effect of grazing on NDVI-Igs was similar across the regional gradient of MAP (Fig. 3B and D). Regional

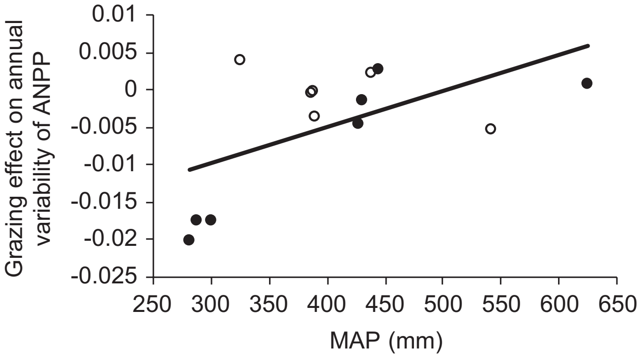

Fig. 4. Grazing effect on inter-annual variability of Normalized Difference Vegetation Index (NDVI) across a regional gradient of mean annual precipitation (MAP; $R^2 = 0.3313$, $p = 0.0395$). Inter-annual variability of NDVI was estimated as growing season integral of NDVI (NDVI-Igs) coefficient of variation by using 1996/97, 1997/98, 1998/99 and 1999/2000 NDVI-Igs data for watering point distance of each paddock. Grazing effect was estimated as the slopes of the linear regression models between annual variability of NDVI-Igs and watering point distance for each paddock. Significant models ($p < 0.05$) are indicated by using black circles, and non-significant models are indicated by using open circles.

Table 3
Sensibility analysis for regression models between grazing effect on NDVI (Fig. 3E) and inter-annual variability of NDVI (Fig. 4) and MAP

Dependent variable	Data subsets				
	1	2	3	4	5
Grazing effect on NDVI					
Slope	−0.000006	−0.000007	−0.000005	−0.000008	−0.000006
R^2	0.40	0.60	0.34	0.35	0.35
y-intercept	0.003633	0.004166	0.003035	0.004130	0.003340
Significance level	$p<0.05$	$p<0.05$	$p<0.10$	$p<0.10$	$p<0.10$
Grazing effect on inter-annual variability of NDVI					
Slope	0.000041	0.000059	0.000033	0.000056	0.000051
R^2	0.28	0.54	0.22	0.28	0.36
y-intercept	−0.021261	−0.030257	−0.017975	−0.026017	−0.024330
Significance level	$p<0.15$	$p<0.05$	$p<0.15$	$p<0.15$	$p<0.10$

NDVI, Normalized Difference Vegetation Index; MAP, mean annual precipitation; R^2, coefficient of determination. Subsets were produced by randomly deleting 20% of the points of the original data set.

patterns changed among years because NDVI-Igs had high inter-annual variability nearby the watering points of paddocks with low MAP (Fig. 4).

The regional models of the grazing effect on NDVI-Igs (Fig. 3E) and on the inter-annual variability of NDVI-Igs (Fig. 4) were not sensitive to the set of paddocks included in the analyses (Table 3). The parameters, coefficients of determination and probability level of the models were similar for all the subsets of data analyzed.

4. Discussion

Our results showed that grazing effects on NDVI-Igs were greater in arid than in wet sites. The patterns of grazing effect on NDVI-Igs identified (Fig. 3E) are consistent with Sims and Singh's (1978) findings. They showed that the effect of grazing on ANPP varied across six North American grassland types. Under mesic conditions, grazing appears to stimulate ANPP. Contrarily, in dry conditions they found that grazing decreased ANPP. Milchunas and Lauenroth (1993) observed a similar pattern at a broader scale that encompasses a wide range of ecosystems. Our results disagreed with Oesterheld et al. (1999) results for grasslands and savannas. They observed that the effect of grazing on ANPP was similar across an MAP gradient. Even though we tested a hypothesis similar to the mentioned meta-analyses (Milchunas and Lauenroth, 1993; Oesterheld et al., 1999), our analyses went a step further because they were based on a common methodology for every site, and they were performed for the same growing seasons and for a structurally homogeneous region. Instead of restricting the analyses to grazed–ungrazed treatment, we evaluated the response of the NDVI-Igs across a grazing gradient defined by the distance to the watering point. Because of the characteristics of the region, we were not able to cover sub-humid sites (more than 700 mm of MAP).

Grazing effects on NDVI-Igs varied between growing seasons (Fig. 3A–D), being greater in dry than in wet years. Pickup and Chewings (1994) observed that some grazing gradients disappear after a sequence of high rainfalls. They classified these gradients as temporary. In sites affected by different long-term grazing intensity, NDVI-Igs may vary among years because of plant composition changes. For example, annual grasses and ephemeral dicots are opportunistic species groups that increase their abundance in favorable years (O'Connor and Roux, 1995). Heavily grazed sites (nearby watering points) offer the suitable sites to opportunistic species because of the local release in plant competition (Bullock et al., 1995; Lavorel et al., 1994).

Holmgren et al. (2001) listed some population and community level processes that occur in arid and semi-arid region in wet years, i.e. during an ''El Niño'' event. Such phenomena have short-term and long-term consequences for the ecosystem. Some examples include increases in growth, flowering and fruit production of perennial herbs, shrubs and trees; recruitment of shrubs, trees and cacti; and profusion of annual species. Moreover, Holmgren and Scheffer (2001) suggested that events like El Niño could open a window of opportunity for the restoration of degraded semi-arid vegetation by means of grazer control. In our case, it is likely that during a wet year (for example, 1997/98 to 1999/2000 in our study; see Table 2) some of the mentioned processes (for example, a high recruitment and growth of annual species) were higher nearby than far from the watering point. As a consequence, some grazing gradients may be temporary (see Fig. 3A–3D).

The existence of temporary grazing gradients (see Figs. 2 and 3A–D) was consistent with the significant reduction in the NDVI-Igs CV away from the watering point in six paddocks (see Fig. 4). O'Connor et al. (2001) observed that annual variability of ANPP was higher in plant communities grazed heavily than in those grazed lightly. Increases in ANPP inter-annual variability of poor condition states of a rangeland may be due to different factors. For example, rangelands in poor condition often have a greater proportion of annual species whose germination varied among years (Kelly and Walker, 1976). In addition, communities in good condition, with greater species richness, stabilize their production over time because of an increased efficiency of transforming water into growth during wet or dry years (O'Connor et al., 2001).

Oesterheld et al. (1999) presented a conceptual model on the relative effects of fire, grazing and climate on ANPP. Such a model is based on cases that do not allow evaluating the effects of the interactions among the disturbances. Our data allow us to improve such model (Fig. 5). Grazing has a neutral or negative effect on ANPP according to the particular conditions of the year and the position of the site in the regional MAP gradient. During normal growing seasons, regarding precipitation (for example, 1996/97; see Fig. 3A and Table 2) the negative effect of grazing on ANPP is greater than in wet years. However, it becomes evident only at the driest extreme of the MAP gradient (Fig. 4). During wet years, grazing would not have a negative effect on ANPP at the driest extreme of the MAP gradient (for example, 1997/98 and 1999/2000; see Fig. 3B and 3D and Table 2). Thus, the grazing effect on ANPP is null under humid conditions. We did not include the grazing effects on ANPP during extremely dry years into the conceptual model because our data set was limited to normal and wet years (Table 2).

Only MAP was included as a regional control of grazing effects on NDVI-Igs (and hence on ANPP) in our conceptual model. However, other factors may control the effect of grazing on ANPP. Milchunas and Lauenroth (1993) showed that consumption level can modulate the effect of grazing on ANPP. No data on the consumption level were available for the paddocks included in our study. However, we estimated the stocking rate of 13 paddocks (Table 1) from counties data of the Arid Chaco region. This relationship between stocking rate and NDVI-Igs was linear on a log–log scale with slope >1, which indicates an exponential form, similar to those reported in other regions (Coe et al., 1976; East, 1984; McNaugthon et al., 1989; Oesterheld et al., 1992, 1998). Taking into account that there is a strong correlation between NDVI and ANPP (Box et al., 1989; Burke et al., 1991; Goward et al., 1985; Hobbs, 1995; Paruelo et al., 1997; Tucker et al., 1985) and that the

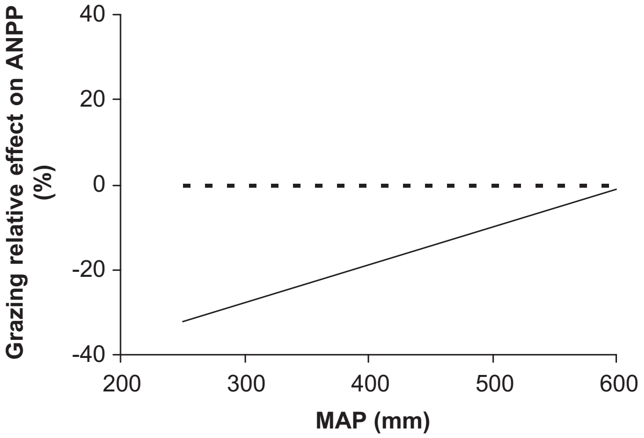

Fig. 5. A conceptual model of the relative effects of grazing on Normalized Difference Vegetation Index (NDVI) across a regional gradient of mean annual precipitation (MAP). The relative effects of grazing were calculated according to seasonal integral of NDVI as (NDVI-Igs$_{\text{grazed}}$−NDVI-Igs$_{\text{ungrazed}}$)/NDVI-Igs$_{\text{ungrazed}}$. The solid and dashed lines correspond to the grazing effects on NDVI during normal and wet growing seasons, respectively (see Table 2). The lines enclosing the response area for grazing represent the approximate boundaries of variation of NDVI according to Fig. 3A–D.

livestock production systems in the Arid Chaco region are strongly based on the direct utilization of native vegetation (Anderson et al., 1980, Ferrando et al., 2001), our NDVI-Igs–stocking rate relationship indicates that herbivore load per unit of ANPP increases as primary production increases.

Milchunas and Lauenroth (1993) showed that level of consumption contributed significantly to explain the grazing effect on ANPP. They observed the most negative grazing effect on ANPP where greater levels of consumption were applied. We observed in our MAP regional gradient that the herbivore load per unit of NDVI-Igs was greater in mesic sites (Table 1), and the grazing effect on ANPP was lower in the mesic sites (Fig. 3E). However, our study differs from Milchunas and Lauenroth's analysis in important aspects.

First, the consumption data used by Milchunas and Lauenroth (1993) were recorded in controlled experiments. Our estimates of stock density are derived from censi data, and they have a coarser spatial resolution. We were able only to describe regional patterns and not the internal variability of a paddock (e.g., changes associated to watering point distance).

Second, Milchunas and Lauenroth (1993) did not analyze the effect of the level of consumption on the ANPP difference between grazed and ungrazed sites. Contrarily, we described grazing gradients nested in a regional MAP gradient. Thus, we analyzed the interaction of grazing and MAP gradients on ANPP.

We did not analyze grazing effect on plant composition. However, is well known that grazing affects botanical composition and functional type's proportion on plant communities (Noy-Meir et al., 1989). Grazing impact on plant composition affects our results directly and indirectly. On one hand, some authors (Chase et al., 2000, Milchunas and Lauenroth, 1993) suggest that plant species changes reduce grazing effects on the ANPP, and grazing effects on plant composition are higher on the mesic than on the arid sites (Milchunas and Lauenroth, 1993). On the other hand, changes in plant composition and functional type's proportion affect light use efficient of vegetation (Goetz and Prince, 1999) and consequently NDVI–ANPP relationship (Monteith, 1972). Thus, we should know more on grazing effects on plant composition and NDVI–ANPP relationships.

5. Conclusions

Our findings contribute a conceptual framework to grazing management in semi-arid rangeland. Considering that grazing effects on NDVI-Igs were higher in arid than in wet sites suggests that appropriate grazing management strategies would be different in sites with different precipitation levels.

Our stocking rate data (Table 1) suggest that forage consumption is lower in the most xeric extreme of the MAP gradient, however, grazing impact on ANPP was higher in paddocks with lower MAP (Fig. 3E). These results suggest that plant communities localized at the driest extreme of the MAP gradient would be more susceptible to grazing with domestic herbivores. Consequently, grazing management strategies across MAP gradients should consider not only stocking density but also other practices such as rest periods, rest frequency or grazing systems.

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