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A test of the use of NDVI data to predict secondary productivity

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Abstract

Question: How well does the use of NDVI predict secondary productivity at landscape scales? What is the influence of vegetation quality and phenology over secondary productivity?
Location: Magellanic steppe in Tierra del Fuego, Argentina. (52°45' to 54° S, 68°15' to 67°30' W).
Methods: Monthly and yearly integrated NDVI (NDVI-I) were calculated from AVHRR/NOAA 14, as estimators of phenology and aerial net primary productivity respectively. From a vegetation map we obtained the proportional cover of different physiognomic types and calculated the palatable fraction (forage) productivity that were used as estimators of vegetation quality. Data were analysed through correlations and regressions.
Results: NDVI-I was not related with secondary productivity indices, while December and annual maximum NDVI, proportion of lawns and tussock grasslands and forage productivity were positively related with secondary productivity. A negative relationship was found between the proportion of heathlands and secondary productivity, but a positive relationship between heathland's proportion and NDVI-I was found.
Conclusions: NDVI-I is not a good predictor of secondary productivity at the scale of our study. These results could be due to: (1) NDVI-I is not related to primary productivity and (2) primary productivity is not related to secondary productivity.

Keywords: Argentina; Heathland; Landscape scale; Lawn; Magellanic steppe; NOAA/AVHRR; Palatability; Sheep; Tussock.

Abbreviations: ANPP = Above-ground net primary productivity; aPAR = Absorbed photosynthetic active radiation; AVHRR = Advanced very high resolution radiometer; NDVI = Normalized difference vegetation index; NDVI-I = Integrated normalized difference vegetation index; NOAA = National Oceanic and Atmospheric Administration.

Introduction

An adequate assessment of the potential secondary productivity of different areas within a landscape or region is a valuable tool for improved rangeland management. Secondary productivity is partially determined by total primary productivity, the seasonal dynamics of primary productivity and vegetation quality (McNaughton et al. 1991; Larter & Nagi 2001) but measurement of these variables is difficult, especially at a scale suitable for management. A possible approach is to search for empirical relationships between secondary productivity parameters and one or more variables that are easy to measure (e.g. vegetation data derived from satellite images) and are surrogates for the determinants of secondary productivity (i.e. quality, phenology and primary productivity). These relationships can also be used to calculate the potential secondary productivity of different zones (e.g. Oesterheld et al. 1992; Oliva et al. 1995; Cingolani et al. 1998). In a regional analysis, Oesterheld et al. (1998) found that livestock stocking rate and mean annual integrated Normalized Difference Vegetation Index (NDVI) were strongly related ($r^2 = 0.90$). The authors suggested that smaller areas, such as landscape units, could be mapped with annual integrated NDVI (NDVI-I) and translated into stocking rates. However, the relative importance of vegetation quality and phenology may increase at smaller scales, and should be taken into account in studies at the landscape or community scales. In this paper we address the use of NDVI to predict secondary productivity at landscape scales and incorporate data on vegetation quality and phenology.

The NDVI, a parameter derived from red and near-infrared reflectance, has proven to be a good indicator of the absorbed photosynthetic active radiation (aPAR) (Gamon et al. 1995). Primary productivity is a function of aPAR and radiation use efficiency, allowing NDVI to be a suitable estimation of primary productivity. This fact has already been determined at the regional scale, for a wide range of vegetation types (Taylor et al. 1985; Goward et al. 1985; Burke et al. 1991; Paruelo et al. 1997). The NDVI obtained from a NOAA/AVHRR (Advanced very high resolution radiometer) sensor is a potential tool for monitoring the seasonal dynamics of the world's vegetation at a wide range of scales (Justice et al. 1985; Danaher et al. 1992; Turcotte et al. 1993; Anyamba & Eastman 1996). The NDVI may also reflect forage quality, but this relationship has not been clearly demonstrated (Oesterheld et al. 1998). Some advances have been made in improving the knowledge on the relationship between nutrient content, phenology and NDVI (Guillon et al. 1999; Wessman et al. 1988).

In the Magellanic steppe of Tierra del Fuego (Argentina) vegetation structure and composition are related to a soil fertility gradient resulting from mineral composition and texture of the underlying rock (Collantes et al. 1999). Animal productivity is also strongly associated with this spatial fertility gradient (Cingolani et al. 1998). Previous results (Posse & Cingolani 2000) showed that landscapes with large differences in animal productivity did not show differences in their NDVI-I. This lack of relationship may be, at least partially, because the fraction preferred by livestock (short graminoids and forbs) is responsible only for a low proportion of the above-ground net primary productivity (ANPP) (Posse et al. 1996; Cingolani et al. 2002). Most productive items of vegetation (Posse 1997) are little consumed by sheep due to their low quality (Posse et al. 1996; Anchorena et al. 2001). Additionally, inter-annual variation of animal productivity appeared to be more related to phenological aspects, estimated through the NDVI changes over time, than to annual NDVI-I (Posse & Cingolani 2000). These previous results suggest that in the Magellanic steppe vegetation quality and phenology exert more influence on the spatial and temporal variation of secondary productivity than the total annual ANPP.

In this study we focused on the spatial relationship between NDVI and secondary productivity, at a finer scale than previous studies (Posse & Cingolani 2000). The objectives were to analyse the relationship at the paddock level (the minimum productive unit) between different secondary productivity indexes and (1) the NDVI-I, as estimator of primary productivity, (2) some aspects of NDVI dynamics as estimators of phenology and (3) vegetation quality estimated through the proportion of different physiognomic types and the production of high quality vegetation (palatable fraction)**.** The hypothesis was that, at the paddock level, phenology and quality were more important than primary productivity in their influence on secondary productivity.

Study area

The Magellanic steppe occupies the northern extreme of Tierra del Fuego Island (52°45' - 54° S, 68°15' - 67°30' W). The climate is semi-arid to sub-humid, with oceanic characteristics (Walter & Box 1983; Koremblit & Forte Lay 1991). Mean annual precipitation is 371 mm, evenly distributed throughout the year. A high water deficit occurs during summers (Koremblit & Forte Lay 1991) due to evaporation driven by strong winds (Walter & Box 1983). Mean annual temperature is only 5.4 °C in Rio Grande city, and there is no frost-free period. Snowfall is frequent in winter.

Land use for sheep has been extensive since colonization in the early 1900s (Belza 1975). Ewes usually remain in the same paddock for their reproductive lives and 95% of births occur in October. There are three large farms, close to Rio Grande city i our 106 028 ha study area. These farms are divided in paddocks of ca. 2000 - 4000 ha with different long-term secondary productivity (Cingolani et al. 1998). Animal production data per paddock were obtained from long-term records of two farms. Data available were lamb marking, winter mortality and stocking rate. Lamb marking is the number of lambs as a percentage of the total number of mothers counted in November, one month after birth. Winter mortality is the percentage of dead ewes between June and November. Stocking rate is the number of ewe equivalent/ha in June. Mean values for 10 to 30 yr were used.

Upland vegetation is dominated by tussock grasslands of *Festuca gracillima*, with variable cover of the mid-size shrub *Chiliotrichum diffusum*. Both species have relatively low palatability (Posse et al. 1996). Inter tussock vegetation is mainly composed of short graminoids and forbs, the most consumed (Posse et al. 1996) and nutritious food items (Posse 1997; Anchorena et al. 2001). Only the short graminoids and forbs were considered as forage (Cingolani et al. 2002). There is a soil fertility gradient, which strongly determines the growth form distribution in the landscape (Collantes et al. 1999). The cover of short graminoids and forbs increases with increasing soil fertility (Cingolani et al. 1998, 2002). In contrast, as soil fertility decreases, these growth forms decrease and grasslands shift towards open cushion heathlands dominated by *Empetrum rubrum*, a strongly avoided acidophilic species (Posse et al. 1996). The foliar characteristics of *E. rubrum* (Cingolani et al. unpubl.) indicate its low nutrient content (Berendse & Elberse 1990; Cebrián & Duarte 1994; Diaz et al. 1999). Lowland vegetation (meadows and marshes) have high quality forage (Anchorena et al. 2001) which is mainly available in summer, because flooding and freezing limits its use by animals in other seasons, especially during cold and snowy years (Anchorena et al. 2001).

Methods

Estimation of NDVI-I and its seasonal dynamics

We used images from the AVHRR/NOAA 14 satellite, with 1 km^2 resolution at nadir. The processing included geometrical and panoramic corrections. NDVI was computed as (channel 2 - channel 1) / (channel 2 + channel 1), where channel 1 is the red waveband (580 to 680 nm) and channel 2 the near infrared band (725 to 1100 nm). Monthly NDVI data were used as an estimate of the seasonal course of primary production. Monthly cloud free images were obtained applying the maximum value composite technique to the NDVI daily data. This technique minimises atmospheric and other degrading effects (Holben 1986). Data were processed by ERDAS imagine 8.3 (ERDAS Inc., Atlanta, GA, US).

The growing season was assumed to extend from August to March. Data from April to July were excluded because there was too much noise associated with latitude, solar angle and cloudiness effects. Data from the 1997-1998 and 1998-1999 growing seasons were analysed. For each pixel, a unique value per month was obtained as the mean of both growing seasons, and a new image series was constructed.

We clumped groups of contiguous paddocks with similar landscape, vegetation and animal production (Cingolani et al. 1998) to provide samples with a higher number of pixels. Each sample area was located at least one pixel from the limit between samples to minimise spatial errors due to co-registration problems. Mean values for pixels per sample and date were calculated. The total number of samples was 15, representing 12 to 40 km^2. Length of the growing season was estimated by calculating maximum, minimum and annual NDVI amplitude. NDVI-I (time weighted annual mean of monthly NDVI) was calculated, as a primary productivity estimator.

Estimation of vegetation quality

Since vegetation quality is related to dominant growth forms, as was mentioned on the study area section, we used a vegetation map to obtain vegetation quality information for each sample. The map was obtained previously from mid-resolution images (Landsat TM and SPOT) and extensive field sampling (Cingolani 1999).

The map reflects dominant growth forms, in turn associated with overall floristic composition. The original number of vegetation units was 16, but we merged structurally similar vegetation types into eight physiognomic units (seven upland and one lowland units). Accuracy of the eight units classification was estimated as 82% (Cingolani 1999). According to an increase in high quality fraction (short graminoids and forbs) and a corresponding decrease in low quality fraction (dwarf shrubs), the seven upland units were ranked as follows: degraded heathlands, non degraded heathlands, shrubby grasslands, degraded tussock-lawns, tussock grasslands, tussock-lawn grasslands and lawns. Lowlands have the highest vegetation quality, but forage is available only in summer.

For each sample, we calculated two overall estimators of high quality vegetation productivity (i.e. the productivity of short graminoids and forbs which forms the intertussock vegetation, hereafter ‘forage productivity’ after Cingolani et al. 2002): (1) total annual forage productivity and (2) annual forage productivity excluding lowlands. The latter was calculated because winter and spring, when lowlands generally remain inaccessible, are the limiting seasons for animal production (Cingolani et al. 1998; Anchorena et al. 2001). Both calculations resulted from a model developed by Cingolani et al. (2002) for upland types and from data in Anchorena et al. (2001) for lowlands. We first calculated the annual productivity for each of the eight physiognomic types. Then, we calculated an area-weighted mean taking into account the percentage of each physiognomic type present in each sample.

Data analysis

As estimators of secondary productivity, we considered stocking rate, with data available for 13 of the 15 samples, winter mortality and marking percentage, with data available for nine of the 15 samples. To obtain data per sample, mean values of individual data for each paddock in a group were calculated, weighted by the area of the paddock. The relationship between secondary productivity indices and NDVI-I, NDVI seasonal dynamics (monthly data and maximum, minimum and amplitude) and indicators of vegetation quality (proportion of each physiognomic unit and both forage productivity estimators) were analysed through simple regression and Pearson correlations.

To better interpret our results by understanding the relationships among physiognomy and NDVI, we correlated the proportion of physiognomic types in the samples with NDVI-I, amplitude, maximum and minimum NDVI. Additionally, to illustrate the seasonal dynamics of the main physiognomic types (or combinations of them) we selected some paddocks that had nearly 50% total cover of selected physiognomy units and calculated monthly NDVI along the growing season. We selected degraded heathland, non-degraded heathlands, tussock grasslands plus lawns and acidophilic shrubby grasslands, since these were the largest units.

Results

Annual NDVI-I was not related with lamb marking, stocking rate or mortality (Fig. 1). Since the sample with lowest NDVI-I and stocking rate (corresponding to a group of paddocks with high cover of the worst quality physiognomic type, the degraded heathland) appeared to be an outlier (Fig. 1b), we performed the regression without it. The same result was found ($P > 0.05$). When monthly and timing variables were analysed, stocking rate was positively related to December NDVI, annual maximum (Fig. 2a) and annual amplitude (Fig. 2b). In fact, annual maximum and December NDVI values were identical, because all maximum values occurred in this month. In these cases we also performed the regressions eliminating the same outlier sample (i.e. that with the highest degraded heathland proportion), and they were not significant ($P > 0.05$). Monthly data were not related with productivity indices, except November NDVI, which was negatively related with lamb marking (Fig. 2c). In this case, no outlier was observed, since the sample with high degraded heathland proportion was not analysed due to the lack of lamb marking data.

Proportions of physiognomic types, reflecting differences in vegetation quality, showed significant correlation with stocking rate and lamb marking percentage, but not with mortality. Secondary productivity indices were positively correlated to proportion of lawns and tussock grasslands, whereas degraded and non-degraded cushion heathland had negative effects (Table 1). Additionally, we found that stocking rate had a significant positive relationship with total and upland forage productivity (Fig. 3a, b). Lamb marking percentage was significantly and positively related only to upland forage productivity (Fig. 3c), while mortality was not related with any of both variables. If we removed both

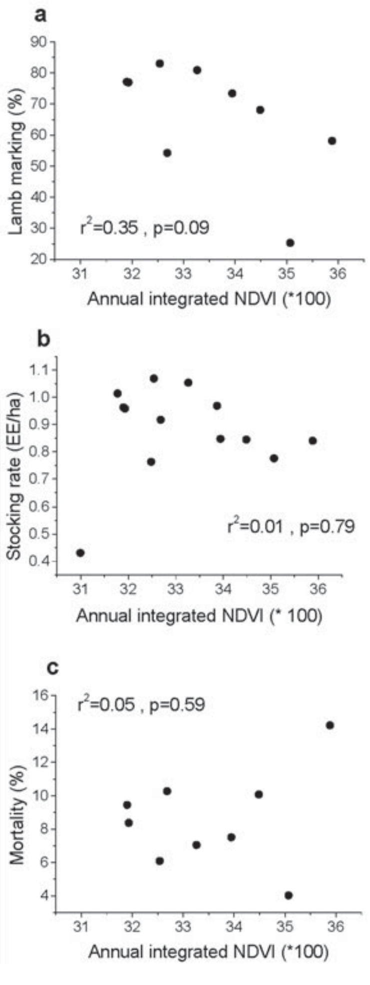

Fig. 1. Relationship between annual integrated NDVI (× 100) as an estimator of primary productivity; **a.** Lamb marking; **b.** Stocking rate; **c.** Mortality.

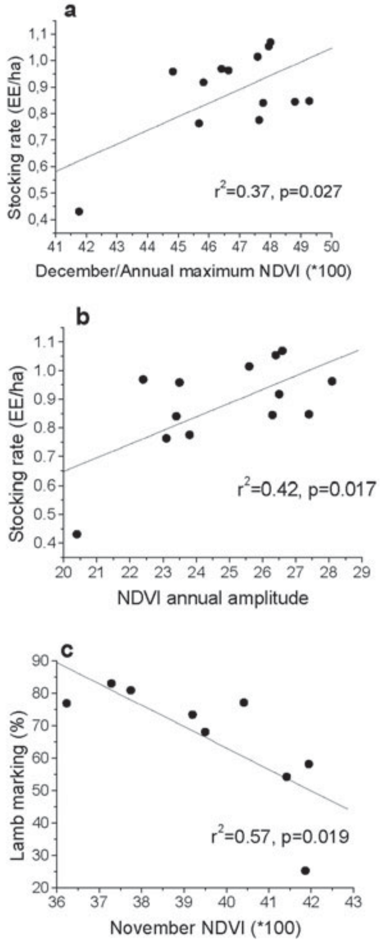

Fig. 2. Relationship between secondary productivity indexes and monthly NDVI and timing growth season variables values that have significant determination coefficients: **a.** Stocking rate vs December NDVI/ Annual maximum; **b.** Stocking rate vs annual NDVI amplitude; **c.** Lamb marking vs November NDVI.

Table 1. Pearson correlation coefficients (*R*) indicating the significant ($P < 0.05$) relationships between proportion of physiognomic vegetation units and secondary productivity indexes. ns = not significant.

	Lawn	Closed tussock grassland	Degraded heathland	Non-degraded heathland
Lamb marking ($n = 9$)	0.69	ns	ns	– 0.79
Stocking rate ($n = 13$)	0.64	0.65	– 0.79	ns
Mortality ($n = 9$)	ns	ns	ns	ns

Table 2. Pearson correlation coefficients (*R*) indicating the significant ($P < 0.05$) relationships between the proportion of each physiognomic type in the samples and the NDVI-I, amplitude, maximum and minimum NDVI. Only significant coefficients ($P < 0.05$) were present. ns = not significant.

	NDVI-I	Amplitude	Min	Max
Tussock grasslands	ns	0.58	ns	ns
Non degraded heathlands	0.64	ns	0.64	ns
Degraded heathlands	ns	– 0.52	ns	– 0.56

samples with the lowest forage productivity values (the poorest forage quality paddocks) the regression of Fig. 3a (stocking rate vs total forage availability) remains significant ($r^2 = 0.37$), but stocking rate vs winter forage productivity became non-significant ($P = 0.075$). So the relationship between stocking rate and total forage availability seems to be stronger. This highlights the importance of summer offer over carrying capacity, in spite of their restricted availability, since the relationship between stoking rate and forage availability is stronger when the summer offer is taking in account to calculate annual forage availability.

Closed tussock grasslands and both types of heathlands were the variables that most influenced NDVI dynamics, indicated by the variables that characterized the NDVI annual dynamic (amplitude, minimum and maximum NDVI) (Table 2). Non-degraded heathland contributed to increase integrated and minimum NDVI, while degraded heathland contributed to decrease the maximum NDVI. The higher proportion of closed tussock grasslands produced more amplitude. These patterns are also illustrated in Fig. 4. The seasonal dynamics of the main physiognomic types shows that NDVI values of degraded and non-degraded heathlands were greater

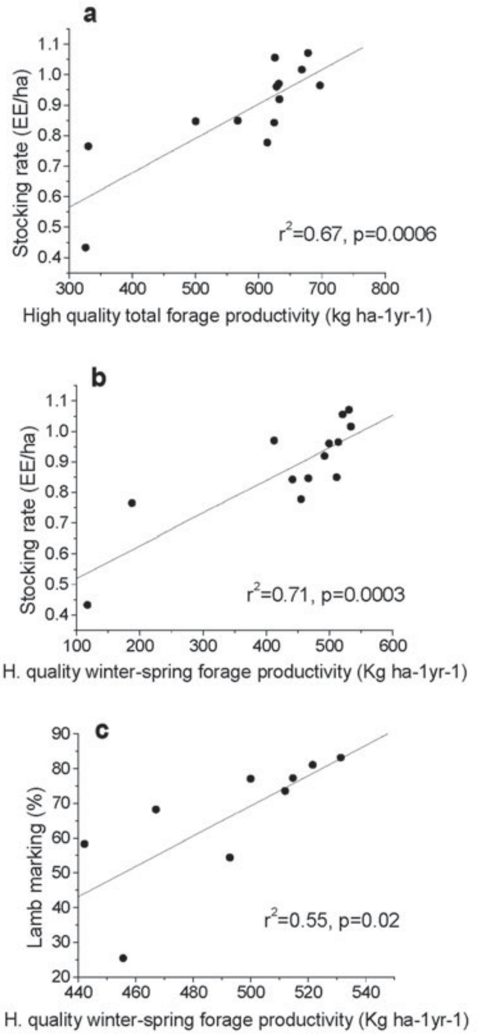

Fig. 3. Relationship between (**a**) Stocking rate vs high quality total forage productivity; (**b**) Stocking rate vs high quality upland forage productivity and (**c**) Lamb marking vs high quality upland forage productivity.

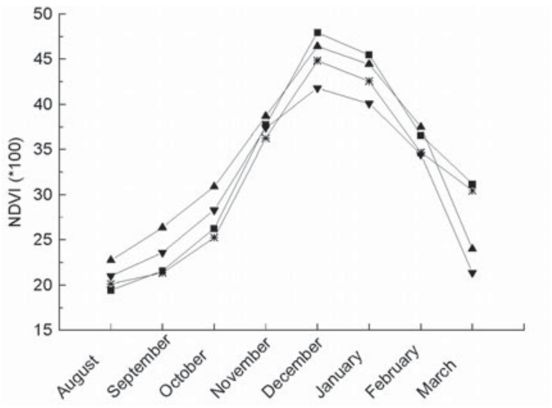

Fig. 4. Seasonal NDVI curves for four representative samples (groups of paddocks): —▼— sample dominated by degraded heathland (56%), —▲— sample dominated by non-degraded heathlands (41%), —■— sample dominated by tussock grasslands and lawns (56%), —*—sample dominated by acidophilic shrubby grassland (42%). In all cases, the remaining area of the sample is occupied by similar proportions of lowlands (20 - 30%) and small patches of the other physiognomic units.

than other physiognomic types between August and October, while between December and February heathlands (especially degraded ones) have lower values than tussock grasslands. In March heathlands differed most from the other units.

Discussion

At the spatial scale of this study, NDVI-I was not a good predictor of secondary productivity. Two possible explanations are: (1) NDVI-I is not a good surrogate of primary productivity or, (2) primary productivity is not related to secondary productivity. We think that both explanations are likely to be valid. The first explanation arises because the non-degraded heathland, an evergreen and low productive vegetation type, showed the highest NDVI-I. The second explanation was suggested by the strong control exerted by vegetation structure and forage productivity on secondary productivity. These factors are not directly related with total ANPP or integrated NDVI. For example, lawns have the highest forage productivity (Cingolani et al. 2002) but lower total productivity than tussock grasslands (Posse 1997; Anchorena et al. 2001).

Interpretation problems of satellite indices working with evergreen vegetation were predicted and reported elsewhere (Box et al. 1989; Paruelo et al. 1997). In spite of this, the NDVI and its integral were used with apparent success on various grasslands and shrubby grasslands to assess range cover types (Paruelo & Golluscio 1994), to estimate stocking rates in a regional approach (Oesterheld et al. 1998) and to characterize primary productivity patterns (Paruelo et al. 1993; Paruelo & Lauenroth 1995). However, the NDVI-I is not an adequate estimator of the spatial variation of primary or secondary productivity in our study. The evergreen nature of the dominant species of heathlands (*Empetrum rubrum*) and its lower dry matter conversion efficiency compared with grasslands (Webb et al. 1978; Berendse & Elberse 1990; Paruelo & Lauenroth 1995) are important reasons that probably preclude the use of NDVI-I to these objectives. Although there were no samples completely dominated by non-degraded heathlands (samples varied from 1 - 40%) this physiognomic type had a major influence on overall NDVI values.

The positive relationship between lawn and tussock cover and the negative relationship between heathland cover and secondary productivity indices highlight the importance of the quality factor on secondary productivity. Lawns and tussock physiognomic types are the upland units with the highest quality, because of their high cover and productivity of intertussock species (Cingolani et al. 1998, 2002), while heathlands have the lowest quality due the opposite reasons. The fact that animal productivity indices were not related to NDVI-I indicates that this index does not reflect the vegetation quality or forage productivity, at least in our study area.

Stocking rate showed a direct relationship with forage productivity, both total and winter-spring offer. The total productivity had a stronger effect, indicating that the proportion of lowlands in a paddock is taken into account by producers when deciding stocking rates. However, lamb marking percentage was positively related only to upland forage productivity indicating that summer forage productivity (from lowlands) does not influence breeding success. This is in line with previous results (Cingolani et al. 1998) and highlights the importance of uplands for lamb production. The critical period for lamb survival is during the final weeks of gestation and first weeks of lactation (Wilkinson & Chestnutt 1988). In our study, this occurs from October to December when lowlands are not yet fully available, at least in most years. Our results suggest that lowland proportion should not be considered as a criterion to determine stocking rates in the different paddocks, at least those used for lamb production.

Seasonal dynamics also appears to have an influence on secondary production, since maximum NDVI values and annual amplitude were directly related with stocking rate. However, when eliminating the outlier, no relationship was found. Unfortunately, we only have one sample with a high proportion of degraded heathland thus it is difficult to decide which of the results reflect the real pattern. The NDVI and stocking rate values of this sample are in line with the high proportion of bare soil present in degraded heathlands, which contributes to decrease annual amplitude (since bare soil does not change its reflectance with season) and stocking rate. Thus, we infer that there is a relationship between amplitude and stocking rate, but this is an indirect relationship caused by the high proportion of bare soil in degraded heathlands. The negative relationship between lamb marking and November NDVI was surprising. It would be expected that spring and early summer values had a positive correlation with lamb marking, as was found for the temporal analysis (Posse & Cingolani 2000). Our result, which was opposite to our expectations, seems to be an indirect effect of vegetation structure. November NDVI values are highly correlated by NDVI-I ($R = 0.68$, $p = 0.005$), and both values are positively correlated with proportion of non-degraded heathland. As already stated, this low-quality physiognomic type strongly hampers the lamb production of a paddock.

The spatial heterogeneity of tussock grasslands (a mosaic of tussocks and intertussock species) and the higher biomass of tussock probably obscures, at our working scale, the influence of the earlier regrowth of the forage fraction (Anchorena et al. 2001), a key resource for lamb production (Cingolani et al. 1998). In conclusion, vegetation structure exerts strong effects on NDVI seasonal dynamics and it also exerts a strong effect on secondary productivity. The relationships we found between dynamics and secondary productivity are consequence of this. The strong effects of dominant growth forms mask the dynamic of the forage fraction, which is the important determinant of the secondary productivity. The lack of a precipitation gradient in the study area was probably another factor that contributed to the lack of relationship between NDVI-I and secondary productivity indexes. Findings on the relationship of primary production patterns to NDVI and secondary productivity is based mainly on regional analysis over wide precipitation gradients (Oesterheld et al. 1992, 1998; Paruelo & Golluscio 1994; Paruelo et al. 1997). On small areas some previous results showed that summer NDVI varies among different cover types but no data were presented on productivity (Phulpin & Jullien 1988; Paruelo &d Golluscio 1994). In our work, the influence of factors other than ANPP, such as the dominant growth forms, with associated differences in energy conversion efficiency, quality and phenology, are likely to be important. Satellites can give information about the dynamics of the systems and allow the acquisition of high amounts of inexpensive data, but these data are strongly correlated with the dominant vegetation and other components are more difficult to assess. In sites such as our study area, where secondary productivity depends mostly on the productivity and seasonal dynamics of a small fraction of vegetation (intertussock biomass), NDVI is less useful than in areas where the main proportion of vegetation is palatable and can be considered as forage. Moreover, in our study area the low quality in a low productivity community was not correlated with NDVI as expected. The perennial character masked their low productivity resulting in a large annual NDVI-I value. Results obtained here point out the importance of knowledge of the system in the field, and highlight the importance of the scale and the hierarchical structure of the systems in the study of ecological processes (Wu & Loucks 1995).

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