

Biozones of Patagonia (Argentina)

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Abstract. *We present a classification of Patagonian ecosystems based on functional attributes derived from the seasonal curves of Normalized Difference Vegetation Index (NDVI), calculated from spectral data provided by the NOAA/AVHRR satellites. The attributes used were the annual integral, the relative range of NDVI, and the date of maximum NOW. These attributes capture critical aspects of the seasonal dynamics of carbon gains and allow for a good description of the spatial heterogeneity of ecosystem function in temperate areas. Our analysis defined 12 biozones that capture current ecosystem functioning. The units defined showed a good agreement with previously defined phytogeographical provinces. Mapping biozones based on attributes derived from satellite data does not require assumptions on the relationship between vegetation units and environmental features. This reduces the errors associated to the lack of correlation between the vegetation and environmental features.*

Introduction

Traditionally the description of the regional heterogeneity of ecosystem types was based on structural characteristics of vegetation. The main goal was to describe and map the potential vegetation of the region. The regional studies performed in Patagonia were not the exception. The attributes more frequently used to describe the vegetation were the relative abundance of plant functional types, species composition, and physiognomy (Hauman 1926, Soriano 1956, Boelcke et al. 1985, León et al. 1998). Maps were constructed by extrapolating point observations. The underlying hypothesis of this mapping strategy was the existence of a correlation between the structural characteristics recorded or observed and some environmental features easy to map (landscape units, geoforms, etc.). These relationships between the environment and the vegetation have not been tested formally.

Human activities have modified most of the Patagonian region. There are evidences that the introduction of domestic herbivores at the beginning of the century altered both the functioning and the structure of its ecosystems (Lean and Aguiar 1985, Borelli et al. 1988, Paruelo et al. 1993, Aguiar et al. 1996, Bisigato and Bertiller 1997, Perelman et al. 1997). To understand the impact of human-related disturbances (grazing, mining, and global change) on a regional basis it is necessary to characterize the present status of the vegetation. To base such characterization only on structural features (i.e. species composition, relative abundance of plant functional types) may have some problems. For example, the inertia of the vegetation structure may delay the perception of the response of the ecosystem to a disturbance (Pennington 1986, Malanson et al. 1992, Milchunas and Lauenroth 1995). Functioning, the exchange of energy and matter of the ecosystem, has in general a shorter response time than structure. This represents a clear advantage for the use of functional attributes to characterize ecosystems. An additional advantage is that functional attributes can be monitored using satellite data easier than structure (Malingreau 1986). It is difficult to extrapolate point observations of actual vegetation based on a description of the physical environment (soils, topography, geomorphology) because the relative importance of disturbances and the response of

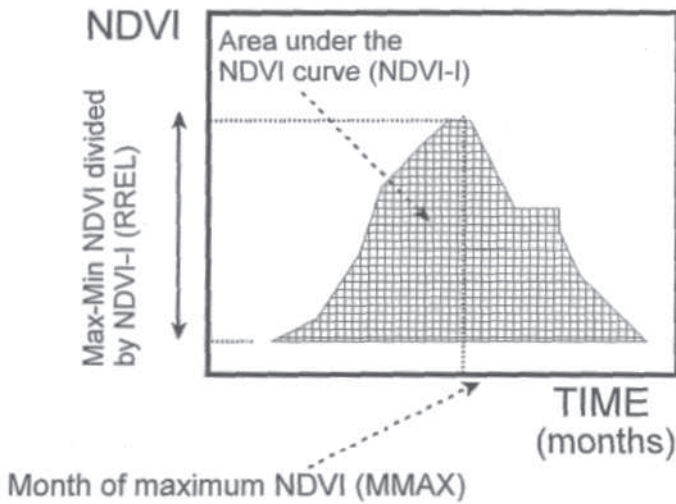


Figure 1. Idealized seasonal curve of the NDVI derived from the NOAA/AVHRR satellites and the functional attributes used in the definition of the biozones: the annual integral (NDVI-I), the relative range of NDVI (RREL) and the date of maximum NDVI (MMAX).

the vegetation to them may differ among landscape units. The use of remotely sensed data help to solve the problem of characterizing the spatial heterogeneity and mapping ecosystems types. In this article we used spectral data provided by the NOAA/AVHRR satellites to define biozones in the Patagonian region. We follow the idea stated by Paruelo et al. (1991) and Soriano and Paruelo (1992) of using functional attributes to define ecosystem types (biozones). The study area corresponds to the geographical and political definition of Patagonia. It includes the provinces of Neuquén, Río Negro, Chubut, Santa Cruz, and Tierra del Fuego. From a phytogeographical viewpoint the area included the Patagonian steppes, the Monte shrub-steppes and scrublands, and the Subantarctic forests (Cabrera 1976). A general description of the area can be found in León et al. (this issue) (vegetation physiognomy), del Valle (this issue) (soils) and Paruelo et al. (this issue) (climate).

The classification was performed on three attributes of the seasonal curves of the Normalized Difference Vegetation Index (NDVI): the annual NDVI integral (NDVI-I), the relative range of NDVI (RREL) and the date of maximum NDVI (MMAX). The use of only three attributes simplifies the interpretation of the classes and provides essentially the same pattern as the analysis of more complex NDVI data sets.

Methodology

We used 36 images of NDVI per year for the period 1982-1991 from the Pathfinder AVHRR Land database compiled by NASA (James and Kalluri 1994). The NDVI was calculated from the reflectance in the red band (channel 1, 540-680 nm) and in the near infrared band (channel 2, 725-1100 nm) provided by the AVHRR/NOAA satellites ($NDVI = (CH_2 - CH_1) / (CH_1 + CH_2)$). The spatial resolution of the images was 8x8 km; consequently each pixel represented 64 km².

Table 1. Codes, dominant physiognomic types and area of the biozones defined. Biozones were grouped based on the Phytogeographical Province that include most of each unit (Patagonia, Monte, Espinal, Subantarctic) or the degree of anthropic alteration of the landscape (agroecosystems).

Phytogeog. Prov.	Biozone Code	Dominant Physiognomic type	Area (km ²)
<i>Patagonia</i>	Kg11	Semideserts 1	95400
	Kf11	Semideserts 2	68800
	Jg11	Patagonian shrub steppes	134800
	Jf11	Shrub-grass steppes	99900
	Jd12	Grass-shrub steppes	43600
	Id12	Grass steppes	48600
<i>Monte</i>	Hg11	Scrub lands	48300
	Jh11	Monte shrub steppes 2	134500
	Ig4	Monte shrub steppes 1	54400
<i>Subantarctic</i>	Ha12	Ecotone forest-steppes and mesic grasslands	52400
	Ea2	Close deciduous forests	69100
<i>Agroecosystems</i>	Gd12	Irrigated valleys	22600

We calculated three functional attributes of the ecosystem from the seasonal curves of NDVI: the annual integral (NDVI-I), the relative range of NDVI (RREL) and the date of maximum NDVI (MMAX) (Figure 1, Paruelo and Lauenroth 1998). These attributes represent fundamental aspects of the carbon gain dynamics of the ecosystem (Tucker et al. 1985a, Loveland et al. 1991, Paruelo et al. 1991, Paruelo and Lauenroth 1995). Previous multivariate analysis of the seasonal curves of NDVI showed that these attributes are highly correlated to the main direction of variation and consequently they capture most (80-90%) of the regional variability of the data (Paruelo et al. 1991, Paruelo and Lauenroth 1995). The annual integral (NDVI-I), the area under the seasonal curve, is a good estimator of the fraction of the photosynthetic active radiation intercepted by the canopy (Sellers et al. 1992) and consequently of primary production (Tucker et al. 1985b, Prince 1991, Paruelo et al. 1997). The relative range (RREL) corresponds to the difference between the maximum and minimum NDVI throughout the year, divided by the NDVI-I (Figure 1). The date of maximum NDVI (MMAX) corresponds to the month with the highest frequency of NDVI peaks (mode) for the 10 year period (Figure 1). RREL and MMAX capture the main characteristics of the seasonality of carbon gains (Paruelo and Lauenroth 1998).

To characterize the heterogeneity of the Patagonian region, we performed a classification based on the three attributes of the NDVI curves. We performed an unsupervised classification to avoid the use of structural information on the definition of the spectral signatures of the classes. We used the ISODATA (Iterative Self Organizing Data Analysis technique) clustering technique (Tou and Gonzalez 1974) and the maximum likelihood method as the decision rule (Hord 1982). This iterative method uses minimum spectral distances to assign each individual pixel to a cluster. Based on the spectral location of the pixels included in a cluster, a new mean is defined in each iteration.

We assigned two different names to the biozones defined. The first one is a code based on the three attributes used in the classification. The first letter of the code (capital) corresponds to the NDVI-I value: A indicates a NDVI-I value higher than 0.45 and K a NDVI value lower than 0. The second letter of the code corresponds to the RREL value: *a* represents RREL greater than 0.45 and *i* a value lower than 0.1. In both cases the class intervals were 0.05 NDVI units. The third element of

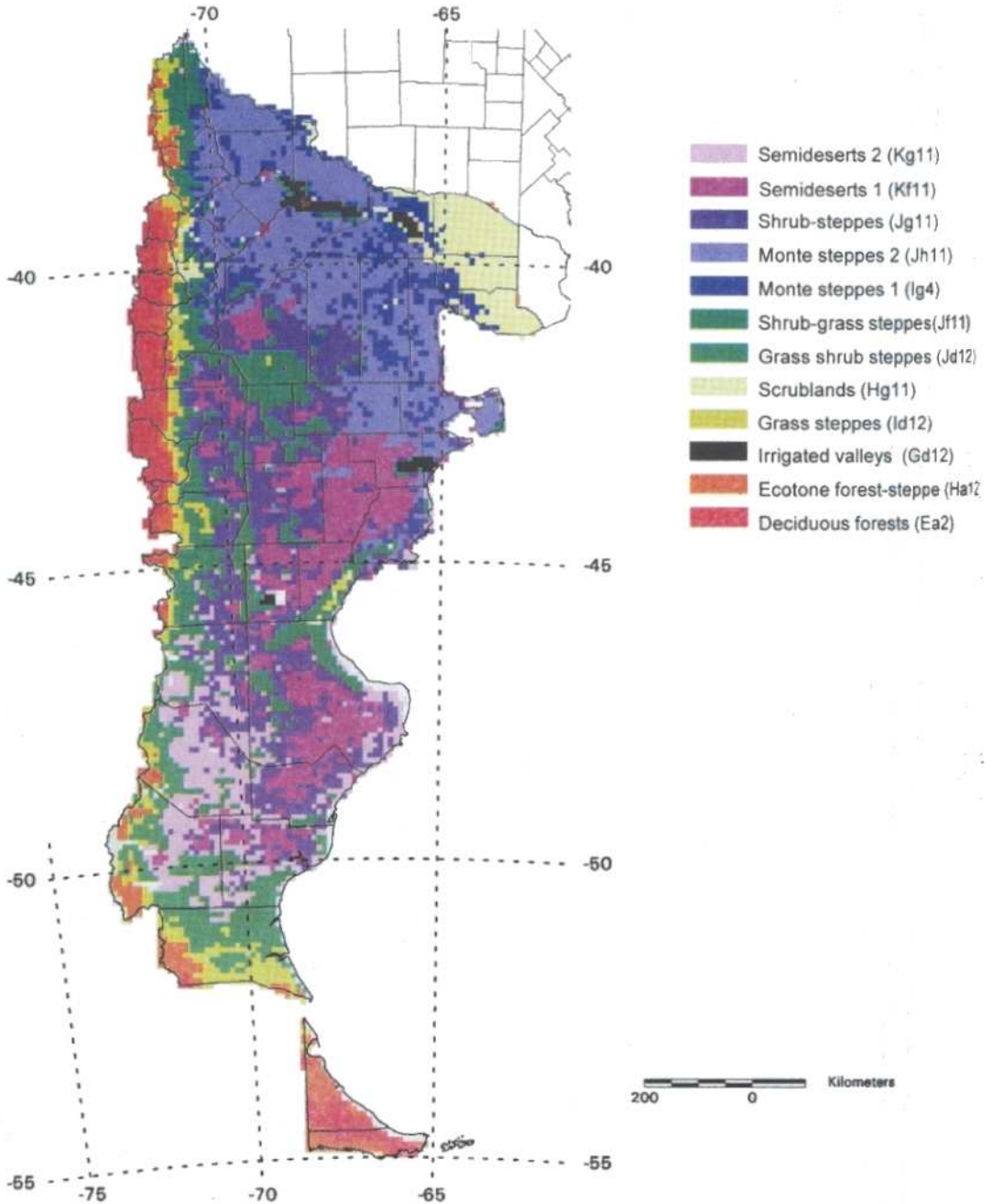


Figure 2. Functional biozones of Patagonia. See Table 1 for the definition of the units.

the code corresponds to the number of the month of maximum NDVI (MMAX, 1 January, 12 December). In addition to this code (based only on functional attributes), we also named the biozones based on the dominant physiognomy of the vegetation. NDVI-I was converted into aboveground net primary production (ANPP) using the equation presented by Paruelo et al. (1998)

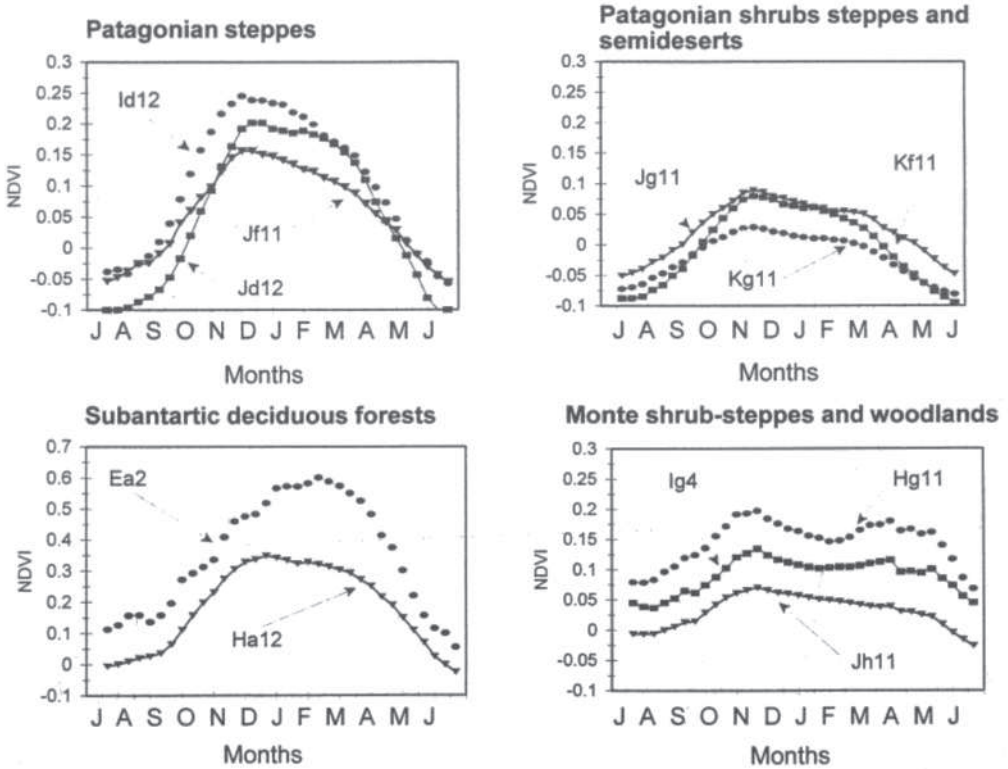


Figure 3. Average (1982-1991) seasonal curves of NDVI for the non-agricultural biozones of the Patagonian geographical region. Curves are the average of 10 pixels (8x8 km each) randomly selected within each

(to correct the NDVI-I values) and Paruelo et al. 1997 (to calculate ANPP). For each biozone we randomly sampled 10 pixels to construct the average seasonal curves of NDVI.

Results and Discussion

The Normalized Difference Vegetation Index data allowed us to identify 12 biozones in Patagonia (Figure 2, Table 1). Figure 3 summarizes the seasonal dynamics of NDVI for the non-agricultural biozones. Each curve corresponded to the 1982-1991 average NDVI. One of them (Irrigated Valleys, Gd12) corresponded to environments highly modified by agricultural activities such as the horticultural valleys of the Negro, Colorado, and Chubut river and the Sarmiento area (Chubut). The most extensive biozone of the region was the Jg 11 or Patagonian shrub steppes. This unit

showed low values of NDVI-I and RREL, and the NDVI peak occurred in November (Figure 3). It occupied a 15% of the region and, in general, corresponded to the transition between the semideserts and the shrub-grass steppes. This biozone is well distributed across Patagonia, from Rfo Negro to Santa Cruz province. Average ANPP, estimated from NDVI-I, was $490 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. The dominance of shrubs, many of them evergreen, would explain the low values of RREL, because the presence of green leaves in winter increases the minimum values of NDVI.

In the Patagonian semideserts (Kg 11 y Kf 11) the peak of NDVI occurred also in November (Figure 3). They had, however, lower values of NDVI-I than the shrub steppes. The Kf 11 semideserts occurred mainly in the central-west portion of Santa Cruz province and were the most productive semideserts ($450 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$). They also displayed the highest intra annual variability in NDVI (RREAL) (Figures 2 and 3). The Kg 11 unit had a broader latitudinal distribution than Kf 11: it extended from Rfo Negro to eastern Santa Cruz (Figure 2). The average ANPP of the semideserts Kg11 was $390.\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$.

The biozone Jf 11 (shrub-grass steppes) showed also a broad distribution in the region (Figure 2). In general, it occurred west from the shrub-steppes and the semideserts. ANPP is a 30% higher than in the shrub steppes ($650 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$). In the grass-shrub steppes (Jd12) average ANPP did not change much. However, the intra annual variability of carbon gains increased and the peak of production (MMAX) occurred later than in the previous biozone (Figure 3). This biozone (Kd12) can be considered as a transition toward the grass steppes. Species composition (León and Facelli 1981), plant functional types relative abundance (Jobbágy et al. 1996), and ecosystem functioning (Figure 3) gradually changes from semideserts to grass steppes.

Grass steppes (Id12) occupied a narrow belt along the Andes and in southern Santa Cruz (Figure 2). This biozone accounted for a small area of Patagonia (5%), but had a broad latitudinal distribution. It occurred also in high altitude plateaux of the San Jorge Gulf area in Chubut. Carbon gains showed an important seasonal variability and a peak in December (Figure 3). Average ANPP was around $900 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$.

The Subantartic deciduous forests (Ea2) and the forest-steppe ecotone (Ha12) covered 13% of the region (Figures 2 and 3, Table 1). The area named ecotone included also mesic grasslands without woody elements as in Northern Tierra del Fuego and Southwestern Santa Cruz (Figure 2). The NDVI-I and the intra-annual variability for forests is higher than for the steppe (Figure 3). The dominance of deciduous species of *Nothofagus* explains the ample relative difference between maximum and minimum NDVI values throughout the year. The area that corresponded to the denser forests had the NDVI peak in February (Figure 3). The greater water availability and the effect of low temperatures on the start of the growing season may explain the delay in the peak of production of forests respect to the extra-Andean biozones (Jobbágy et al. in press). The domain of the equation used to estimate ANPP from NDVI-I is restricted to grasslands and shrublands; consequently, we do not provide estimates of ANPP for forests.

The most abundant biozone in the Monte Phytogeographical Province (Jh11) occupied an area similar to the Patagonian shrub steppes (Figure 2, Table 1). Average ANPP was around $600 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. This biozone had the lowest intra annual variation of the NDVI (RREL) (Figure 3). This fact should be associated to the dominance of evergreen shrubs of the genus *Larrea*. The other biozone of the Monte region (Ig4), also dominated by *Larrea* sp., differed from the previous one in the timing of the productivity peak. For the unit Jh11, the maximum NDVI occurred in late spring while for unit Ig4 it occurred in fall (Figure 3). The seasonal curve of unit Ig4 shows two NDVI peaks (spring and fall). For the period analyzed the peak occurred more frequently in April (fall). The distribution of unit Ig4 corresponds to the southernmost zone of influence of the Atlantic air masses in South America. The influence of Atlantic air masses determines a more even distribution of precipitations throughout the year than in southern Patagonia where they are concentrated during winter. The estimated ANPP was higher than in the other Monte biozone ($730 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$). The biozone Hg 11 corresponded to the transition between the Monte and the Espinal phytogeographical Province (Cabrera 1976) (Figure

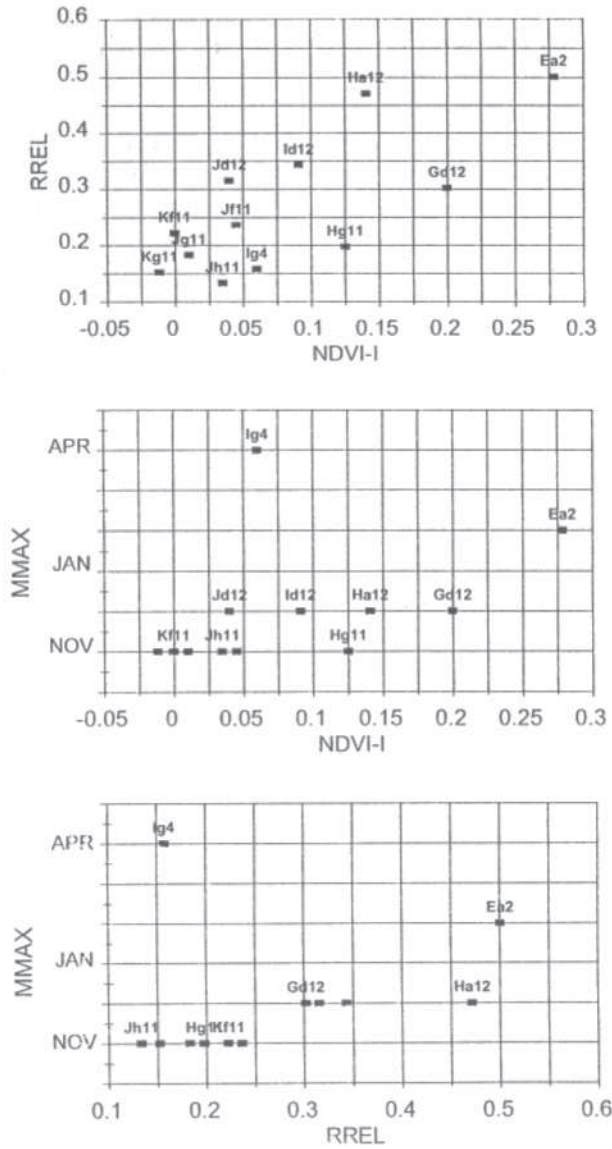


Figure 4. Relationship between the average values of the three attributes of NDVI curve used in the definition of the biozones (NDVI-I, RREL, MMAX). See table 1 for the definition of the units.

kg.ha⁻¹.y⁻¹) than the two other Monte biozones. The seasonal dynamics of NDVI was quite similar to the Monte unit Ig4.

In general, RREL increased with increments of the NDVI-I (Figure 4a). The rate of increase of RREL with NDVI-I was lower for the biozones corresponding to the Monte and the irrigated valleys. For the biozones of Patagonian Phytogeographical Province an increment of NDVI-I is associated with a delay in the month of maximum NDVI. This delay may be associated with an increase in water availability (Jobbágy et al. in press) (Figure 4b, c).

Concluding remarks

The use of functional attributes of the ecosystem derived from the seasonal curves of NDVI allowed us to identify units that represented the actual functioning of the ecosystem. One of the units

defined, for example, corresponded to a highly modified agro-ecosystem: irrigated valleys. This particular unit, originally a semidesert or a shrub steppe, presents now a functioning similar to a deciduous forest due to the irrigation and the agricultural practices.

An important advantage of a classification of ecosystems based on remote sensing data is that it does not require a model of the relationship between vegetation and environment to extrapolate point observations. Every single pixel is classified based on its spectral values. An additional advantage of a classification based on remotely sensed data is its dynamic nature. Classifications can be redo every year or for different periods to analyze trends. That will allow to analyze the variability of the area occupied for a biozone through time and the possible climatic or anthropic controls of the changes.

The analysis based on functional attributes allow us to define a clear boundary between the Monte and the Patagonian steppes. The location of this boundary is independent of the number of clusters used to define the classes. The limit between Patagonia and Monte steppes has a good correspondence with the southernmost area of influence of the Atlantic air masses.

We observed a gradual transition among the different biozones defined for the Patagonian phytogeographical province (Kg 11, Jill, Jg1 1, Jf11, Jd12 and Id12). The location of the boundaries among them are sensitive to the classification decision rule used, to the number of classes and to the area included (variability) in the analysis. This gradient in ecosystem functioning has been also described for structural attributes such as plant functional type relative abundance or floristic composition (León and Facelli 1981).

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