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The climate of Patagonia: general patterns and controls on biotic processes

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Abstract. *In this article we review the main characteristics of the Patagonian climate, the spatial and temporal patterns of the most important climatic variables, and the influence of climate on ecosystem processes. The winter distribution of precipitation determines an asynchrony between the wet and the growing season in Patagonia. The amount of water that can be transferred from the wet season to the growing season depends mainly on the physical characteristics of the soil. In the semiarid steppe of Chubut, drainage accounted for 10% of annual precipitation. Winter distribution of precipitation determines also an asynchronic dynamics of evaporation and transpiration fluxes. The ENSO phenomenon have a significant impact on regional precipitation. In central-west Patagonia, spring precipitation (September to November) was lower than normal during La Niña events and greater than normal during El Niño events. From December to February the opposite pattern can be observed: higher than normal precipitation during La Niña events and lower than normal precipitation during El Niño events. The impact of this phenomenon on the seasonal temperature was not as clear as for precipitation. We did not detect any temporal trends in annual precipitation for the period 1961-1996. The phenology of carbon gains is quite homogeneous in Patagonia. Most of the region showed a peak of production in November, when, simultaneously, water availability and temperature are high. Toward the west, production peaked later (December). Deciduous forests showed the peak in January and February.*

Introduction

Previous attempt to describe the climate of Patagonia focused in a particular climatic factor (i.e., precipitation, Barros et al. 1979) or provided a general overview of atmospheric processes and patterns (Prohaska 1976, Soriano 1983). In this article we took a more comprehensive approach. We described the general characteristics of the Patagonian climate and the spatial and temporal patterns of the main climatic variables (precipitation, temperature, wind, humidity and radiation). We devoted special attention to the influence of climate on ecosystem processes.

Characterizing the climate of Patagonia from an ecological perspective has a major shortcoming: the availability of data. The density of official meteorological stations is extremely low (aprox. 30000 km^2/station before 1950 and 40000 km^2 in 1997) and they are mainly concentrated in coastal areas. In addition to the official data we compiled climatic data (mainly precipitation) from different sources (private ranches, experimental stations, global databases, provincial networks) reaching an aproximate density of one station every 12000 km^2 and a better spatial coverage.

The article is divided in two sections, the first is devoted to the general characteristics of the Patagonian climate. We summarized most of the published information on Patagonian climate at different spatial scales. Special attention was devoted to the analysis of temporal trends of annual

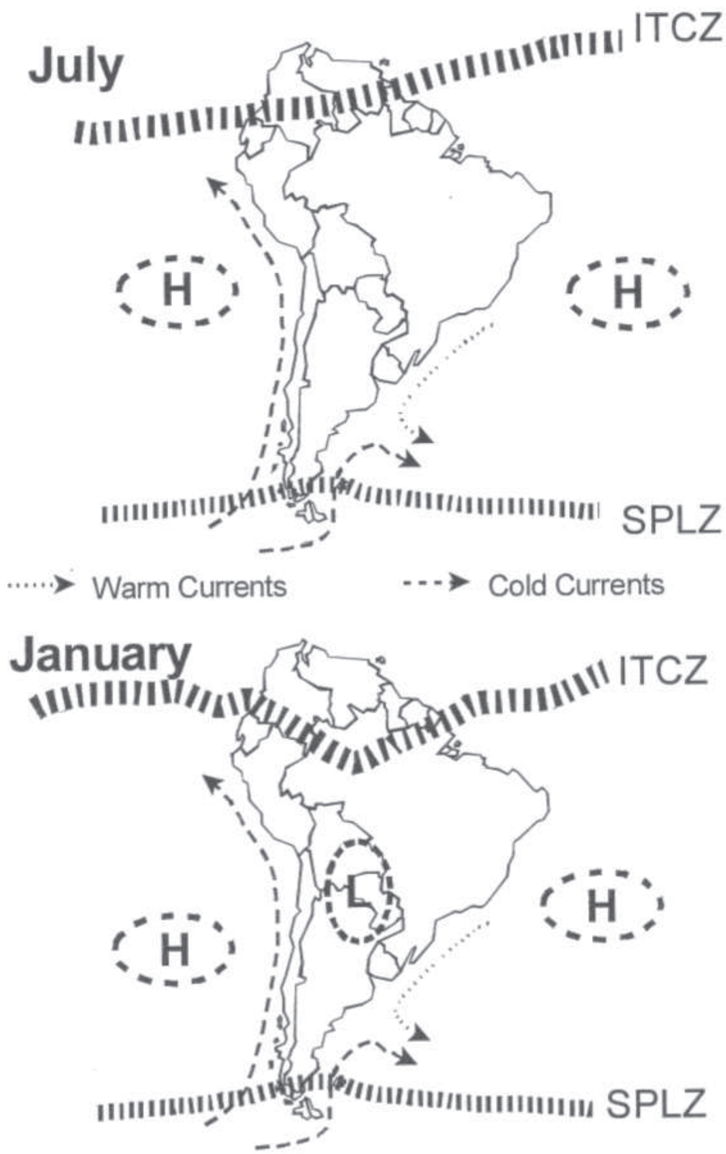

Figure 1. Schematic location of the high and low presssure centers over the oceans and the continent, the Intertropical Convergence Zone (ITCZ) and the Subpolar Low Pressure Zone (SPLZ) in the southern part of the Southamerican continent in July and January. The lines over the ocean indicate the main ocean currents.

precipitation and the influence of El Niño - Southern Oscillation phenomenon on the seasonal patterns of precipitation. In the second section we focused on the influence of the atmosphere on ecosystem processes such as water dynamics, phenology, primary production and the distribution of plant functional types.

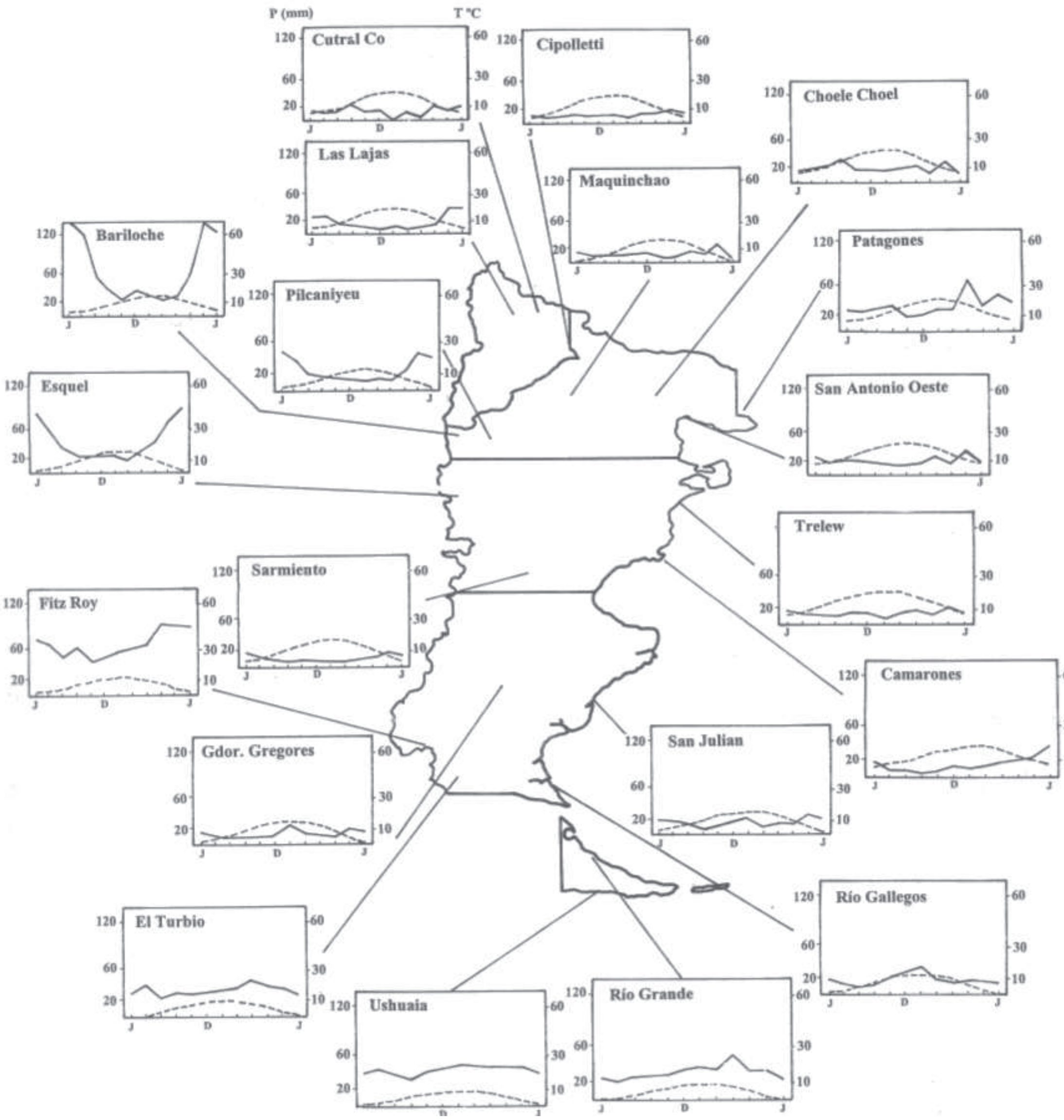

Figure 2. Seasonal distribution of precipitation and temperature for different sites in Patagonia. The solid line corresponded to monthly precipitation and the broken line to temperature.

The climate of Patagonia

General characteristics

Most of Patagonia is dominated by air masses coming from the Pacific Ocean. The patagonian region is between the semipermanent anticyclones of the Pacific and the Atlantic oceans at aproximately 30°S and the subpolar low pressure belt at approximately 60°S (Prohaska 1976). The strong, constant west winds (westerlies) are dominant across the region (Figure 1). The seasonal movement of the low and high pressure systems and the equatorward ocean currents determine the precipitation pattern. During winter, the subpolar low is more intense. This situation, combined with the equatorial displacement of the Pacific high and with ocean temperatures that are higher

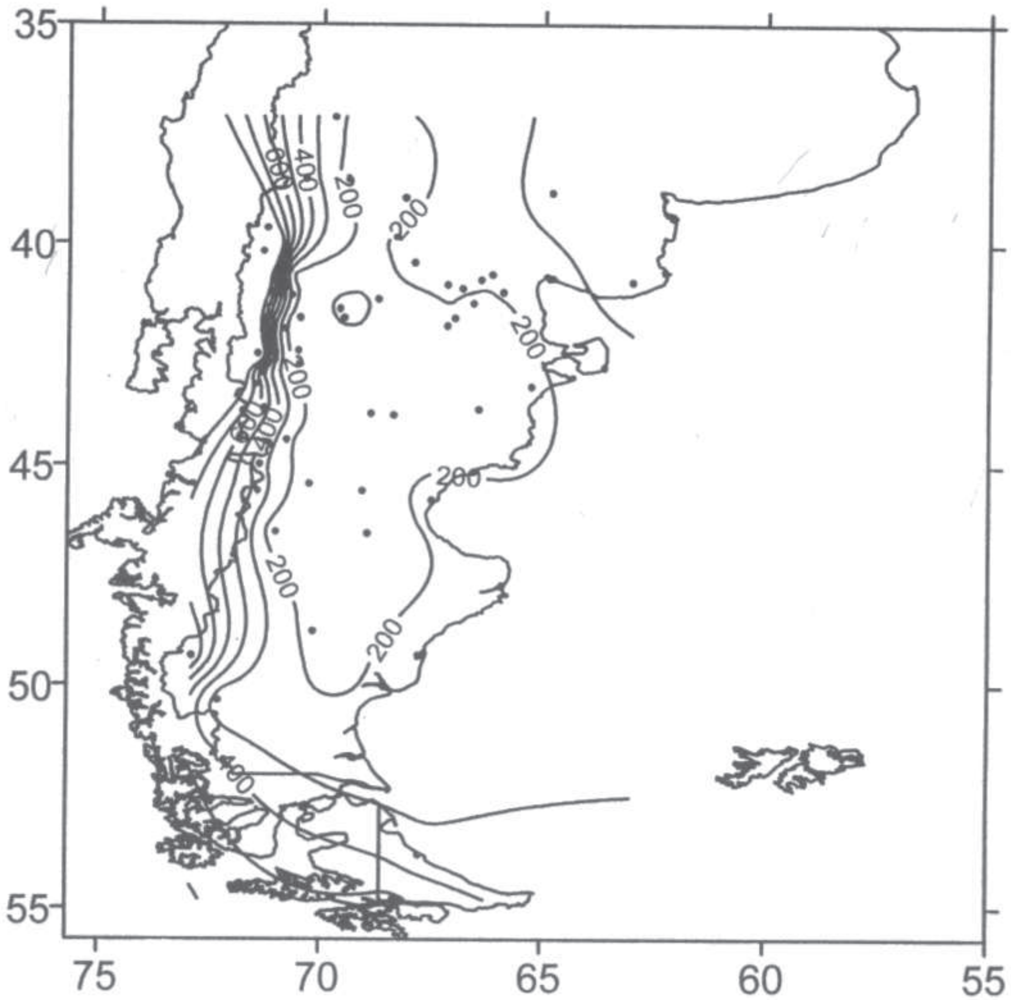

Figure 3. Mean annual precipitation (MAP) of Patagonia. Isolines were generated from 62 sites spread across the region. A list of the weather station is available at www.ifeva.edu.ar/coiron.

than the continental temperatures, leads to an increase in precipitation during this season. The northeastern (NE of Chubut, N and E of Río Negro and E of Neuquén) and the southern (S of Santa Cruz and Tierra del Fuego) parts of the region are additionally affected by air masses coming from the Atlantic ocean. This Atlantic influence results in a more even seasonal distribution of precipitation in this part of Patagonia.

The Andes play a crucial role in determining the climate of Patagonia. The north-south distribution of the mountains imposes an important barrier for humid air masses coming from the Pacific Ocean. Most of the water in these maritime air masses is dropped on the Chilean side, and the air becomes hotter and drier through adiabatic warming as it descends on the Argentine side of the Andes.

Precipitation and temperature patterns

General circulation patterns, the influence of the Pacific air masses and the topographic barrier parallel to the Pacific coast together result in a strong west-east gradient of precipitation across the region (Barros et al. 1979). Orographic precipitation is dominant on the Chilean side. Rising air cools faster on the west side of the Andes, where the amount of annual rainfall exceeds 2000 mm.

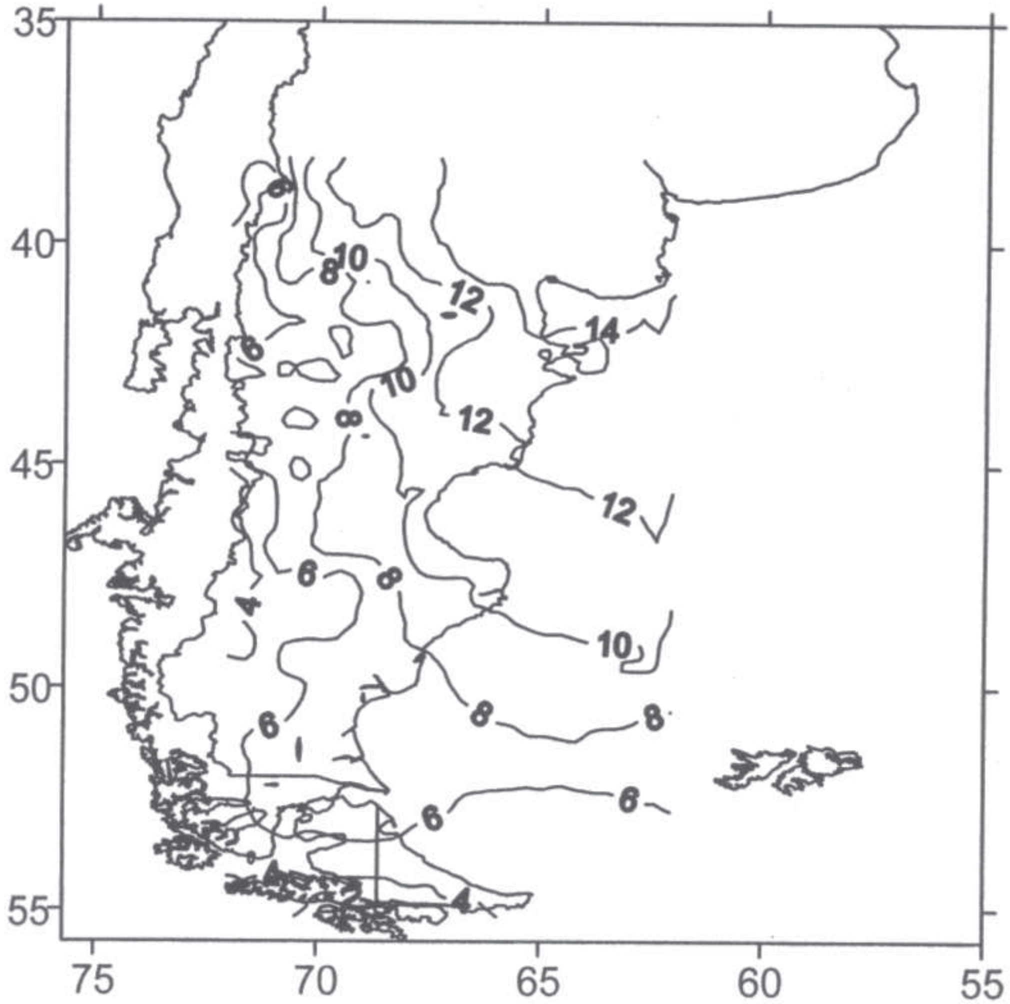

Figure 4. Mean annual temperature (MAT) of Patagonia. Data corresponded to the Leemans y Cramer (1991) database. This database has a spatial resolution 0.50.5 of latitud and longitude. (See Paruelo et al. 1995 for a description of the database).

On the eastern side of the Andes and as in most semiarid areas of the world, frontal precipitations are more important (Bell 1981). From the Andes and eastward total annual precipitation decreases exponentially. Most of the central portion of Patagonia receives less than 200 mm per year (Figure 3). The distance from the Andes explained 94% of the spatial variability of the mean annual precipitation (Jobbágy et al. 1995). In the northwest part of the region, annual precipitation decreased almost 7 mm per km, for the first 60 km eastward from the Andes (Soriano 1983).

In Patagonia, precipitation is mainly concentrated in winter. In the center and western part of the region, 46 % of annual precipitation occurred in winter, 27 % in fall, 16 % in spring and 11 % in summer (Jobbágy et al. 1995). Most of the precipitation events resulted in less than 5 mm (Beltrdn 1997). The total amount of water falling in these small events remained constant over the years. The difference between wet and dry years was related to the occurrence of precipitation events greater than 10 mm (Golluscio et al. 1998).

Except for the sites located in the Monte phytogeographical province (NE of the region), the winter precipitation maximum results in a strong summer deficit (Figure 2). An increase in total annual precipitation not only decreases the magnitude of the water deficit but also delays its start. This delay has a great impact on the phenology of the different vegetation units (Jobbágy et al. in press).

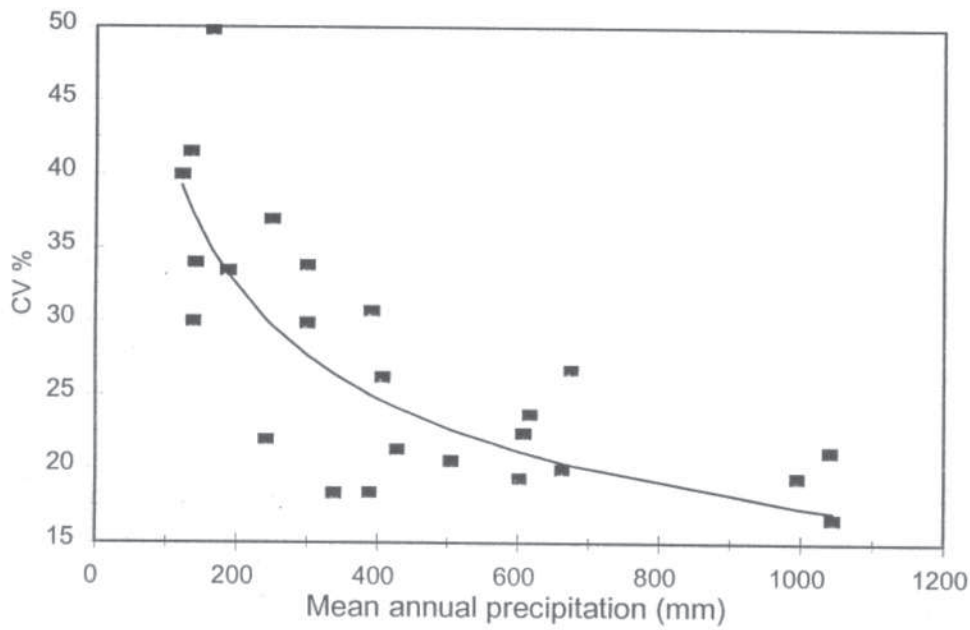

Figure 5. Coefficient of variation (%) of mean annual precipitation as a function of the mean annual precipitation for 19 sites in Chubut and Rio Negro (from Jobbágy et al. 1995).

The interannual variability of precipitation increased exponentially along the west-east gradient (Jobbágy et al. 1995). The coefficient of variation (standard deviation/mean) of annual precipitation varied between 15 % at the humid end of the gradient and 50 %, in the driest area (Figure 5).

Patagonia can be defined as a temperate or cool-temperate region. A characteristic of the temperature pattern is the NW-SE distribution of the isotherms, determined mainly by the presence of the Andes. Mean annual temperature ranges from 12°C in the northeastern part to 3°C toward the south (Figure 4). The mean temperature of the coldest month (July) is greater than 0°C in all the extra Andean Patagonia. However, toward the southwest absolute minimum temperatures are lower than -20°C. The annual range of monthly temperature is lower in Patagonia than in similar areas of the Northern Hemisphere. In Patagonia, thermal amplitude varies between 16°C in the center-north of Río Negro and *5°C* in the southern extreme of the region. In North America, at the same latitude, corresponding values are greater than 20°C, due to the much larger land mass of North America above 50° (Paruelo et al. 1995). Local factors such as topography and wind affect air temperature. The strong westerly winds that blow in Patagonia decrease the perception of the mean annual temperature (wind chill) by 4.2°C over the whole region (Coronato 1993). Wind chill effects are more pronounced in summer (Coronato 1993). Toward the west the decrease in the perceived temperature ranges between 3 to 6°C (Beltrdn et al. 1996). This wind chill factor could have unfavorable effects on sheep production.

Wind and humidity

A characteristic of the Patagonian climate is the predominance of winds from the west. In the center-west of the region, westerly winds represent between 65 and 75 % of the daily observations in

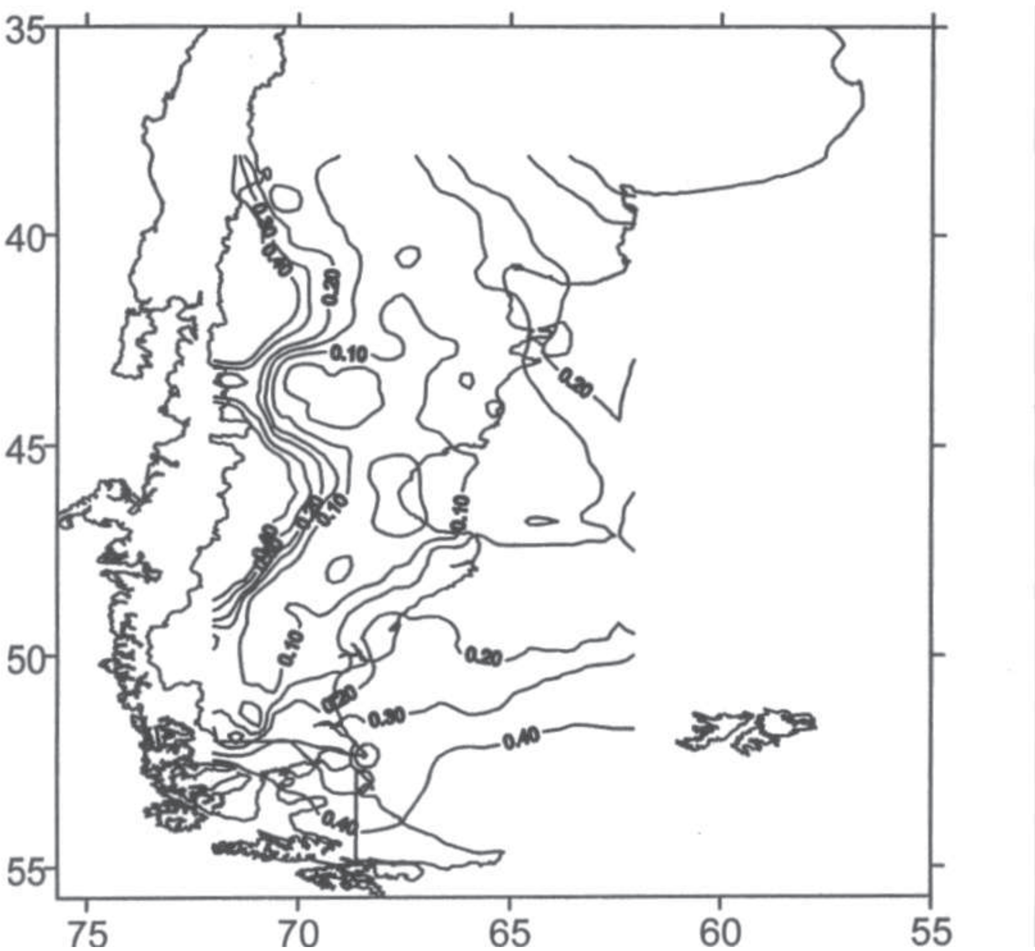

Figure 6. Aridity Index (MAP/PET) for Patagonia. MAP data corresponded to the Leemans and Cramer (1991) database. PET was calculated from mean annual temperature (Shaw et al. 1995).

the year. Because of the seasonal displacement of the pressure systems, winter has a more uniform distribution of winds from the west, whereas in summer a southerly component is evident (Beltrán 1997).

Westerly winds are characterized not only by their persistence during the year but also by their intensity. Mean annual values of wind speed varied between 15 and 22 km h^{-1} in the center-west part of the region. The annual distribution of the wind speed shows a maximum between September and January and a minimum in winter. The frequency of calms was greater during winter and may account for up to 25% of the bihourly observations. Calm events seldom occurred during spring and summer (Beltrán 1997).

Low humidity content characterizes both polar and westerly winds. Vapor pressure values for the whole region ranged from 8 to 12 hPa in January and from 4 to 7 hPa in July. A slight oceanic influence may be observed in eastern Patagonia. Relative humidity has a seasonal variation opposite to that of temperature, with greater humidity in winter (greater than 70%) than in summer (between 50 and 60%) (Beltrán 1997).

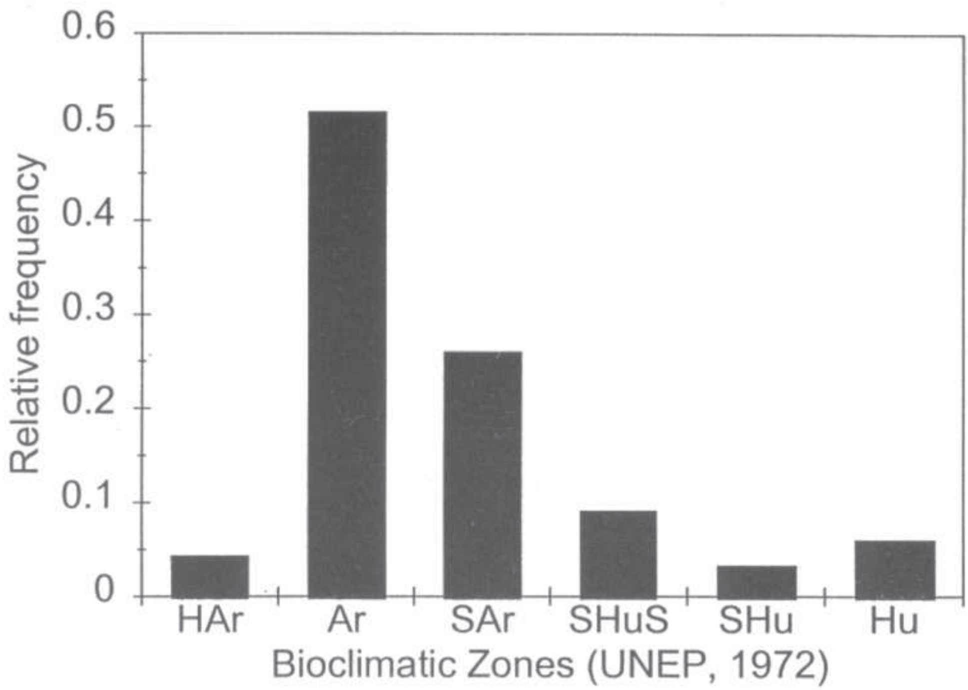

Figure 7. Proportion of Patagonia correponding to the different bioclimatic zones defined Le Houérou (1996), on the basis of the MAP/PET: ratio Hyperarid (HAr) <0.05, Arid (Ar) 0.05-0.20, Semiarid (SAr) 0.20-0.45, Dry subhumid (SHus) 0.45-0.65, Subhumid (SHu) 0.65-0.75 and Humid (Hu) >0.75. Mean annual precipitation and temperature data corresponded to the Leemans and Cramer (1991) database. PET was calculated from mean annual temperature (Shaw et al. 1995).

Radiation and cloudiness

Latitude and cloud cover are the main determinants of the spatial and temporal distribution of radiation. The broad latitudinal range of Patagonia results in a marked spatial variation in solar radiation and photoperiod. The annual average solar radiation decrease from 376 cal cm^2 day^{-1} in the north (Cipolletti) to 209 cal cm^2 day^{-1} in the south (Río Grande) (FAO 1985). Patagonia has one of the highest percentage of cloud cover in the whole country. However, it has the lowest number of rainy days (Prohaska 1976). The northern part of the region has the greatest proportion of sunshine hours (50%) whereas western Santa Cruz and Tierra del Fuego have less than 40% (FAO 1985).

Soil water dynamics in Patagonia

Aridity is another important characteristic of Patagonia. Although in some areas precipitation is greater than atmospheric demand, most of the region has a marked water deficits in spring and summer (Figure 2). The diagrams of Figure *2* show that water deficit (estimated from air temperature and precipitation course) increases since spring. The ratio of mean annual precipitation (MAP) and potential evapotranspiration (PET) for the steppe ranges between 0.46 for areas dominated by *Festuca pallescens* grass steppes (Esquel) and 0.11 for the semideserts of central Chubut (Sarmiento) (Figure 6). According to the bioclimatic characterization proposed by Le Houérou (1996) (based in the MAP/PET ratio), 4.2% of Patagonia is hyperarid (Figure 7). Most of the region belongs to the arid category and only 9 % of the area corresponds to the subhumid or humid bioclimatic zones.

The ratio MAP/PET varies not only in space but also in time, both within and among years. For a typical area of the Occidental District (Rfo Mayo), the MAP/PET ratio ranged among years

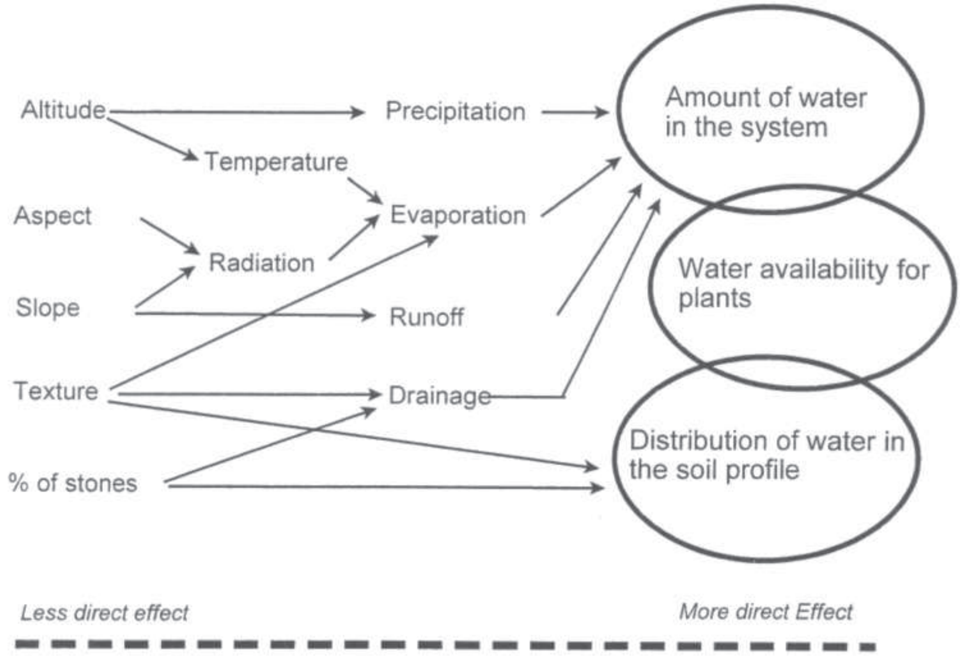

Figure 8. Influences of environmental variables on plant water availability

from 0.06 to 0.2 (Paruelo and Sala 1995). An analysis on a weekly scale showed that for more than 5 weeks this ratio was higher than 0.8. This suggests the existence of a period of the year in which water is not the limiting factor in the steppe, despite the fact the mean annual precipitation is lower than 150 mm.

Local factors such as soil texture, % of stones, aspect, slope and leaf area index, also exert an important influence on water dynamics (Paruelo 1991, Jobbágy 1993, Coronato and Bertiller 1996). These factors and their interactions determine the amount of water in the system, its vertical distribution in the soil profile and its availability for the vegetation (Figure 8).

Winter distribution of precipitation and cold temperatures determine that the wet season and the growing season in Patagonia do not coincide. The amount of water that can be transferred to the growing season depends mainly on the physical characteristics of the soil (texture, % of stones, effective depth). Drainage losses will begin once the difference between cumulative precipitation and evapotranspiration becomes greater than the storage capacity of the soil. In the semiarid steppe of Chubut, drainage accounted for about 10% of annual precipitation (Paruelo and Sala 1995). Winter distribution of precipitation also causes an asynchronic dynamics of evaporation and transpiration fluxes. Even though atmospheric demand is low, evaporation is high in winter because the upper layer of the soil is wet. Transpiration losses peak in spring and early summer when the availability of water and energy is high. In the Patagonian steppe transpiration losses accounted for about 34% of annual precipitation (Paruelo and Sala 1995).

Figure 9 shows the effects of some water balance controls (Figure 8) on transpiration, evaporation, drainage and runoff fluxes. These are the results obtained using a soil water model (DINAQUA, Paruelo and Sala 1995) across a precipitation gradient in western Patagonia (Jobbágy

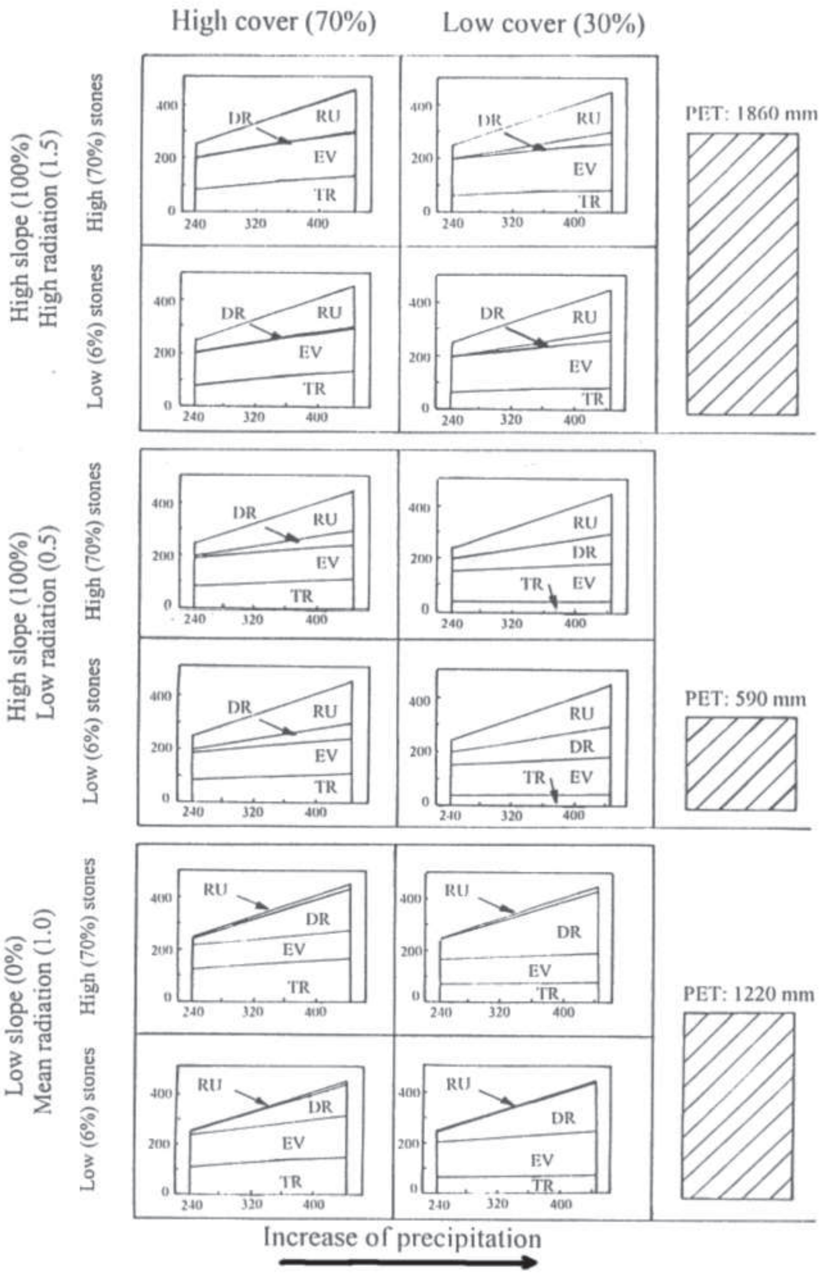

Figure 9. Transpiration (TR), Evaporation (EV), Drainaje (DR), Runoff (RU) and Potential Evapotranspiration (PET) simulated by DINAQUA (Paruelo and Sala 1995) for environmental conditions representatives of western Chubut. Each graph represent different combinations of plant cover, % stones, radiation, and slope levels.

1993). The simulations considered two levels of vegetation cover, two levels of slope and aspect (radiation level) and soil with different physical characteristics (% of stones). Precipitation and radiation (modified by the slope and aspect of the terrain) were the factors that affected water dynamics the most. Transpired water varied between 19 and 123 mm for the range of conditions

Table 1. Temporal trends in mean annual precipitation. N corresponded to the number of years, b is the slope of the relationship between mean annual precipitation and years and r the correlation coefficient of the relationship. * indicates significant correlation (p < 0.05).

	Period 1931-1960				Period 1961-1996			
Stations	N	b	r		N	b	r	
Neuquén	19	3,054	0,576	*	35	2,213	0,294	
San Antonio Oeste	30	2,185	0,195		28	2,468	0,351	
Maquinchao	23	0,844	0,164		25	3,530	0,494	*
Esquel	29	-6,653	-0,419	*	31	-4,809	-0,451	*
Trelew	30	1,682	0,262		31	2,494	0,365	*
Comodoro Rivadavia	30	-0,145	-0,015		33	1,084	0,129	
Santa Cruz	29	-2,153	-0,306		25	2,387	0,307	
Río Gallegos	28	-2,124	-0,330		35	1,978	0,346	*
Ea Leleque	30	1,583	0,105		34	-0,455	-0,046	
Paso de Indios (Neuquén)					34	0,438	0,067	
Bariloche					33	-0,953	-0,055	
Paso de Indios (Chubut)					23	2,354	0,235	
El Maitén					33	-0,925	-0,089	
Ea La Elena					34	-0,907	-0,069	
Ea Fofocahuel					33	-0,287	-0,060	
Ea Montoso					34	0,759	0,101	
Ea Lepa					35	-2,795	-0,244	
Cholila					33	-0,874	-0,039	
Puerto Deseado					30	-1,986	-0,286	
San Julián					26	-3,657	-0,323	

Table 2. Step-wise regression models of the cover of the dominant species of the Occidental district and environmental variables. Every model is statistically significant (p<0.001). TR/PET: transpiration-potential evapotranspiration ratio, ALT: altitude (meters above sea level 100, a surrogate for temperature), MAP: mean annual precipitation (mm x 100), %S: percentage of stones in the soil.

Species	Model	r^2
Festuca pallescens	225 x TR/PET + 2.3 x ALT -31	0.72
Mulinum spinosum	6 x MAP - 8 x PET -6.8	0.28
Nassauvia glomerulosa	-6.6 x MAP + 0.1 x %S + 24.4	0.28
Stipa humilis	-3 x PMA + 5.2 x PET + 9.3	0.22

considered. The aridity index (transpiration/potential evapotranspiration) varied over almost one order of magnitude (0.02 to 0.19) between extreme conditions.

Climatic trends

Many authors reported increases in precipitation over time in different areas of southern South America (Barros and Mattio 1977-78, Hoffman et al. 1987, Barros et al. 1996). For the Patagonia region the positive tendencies are only significant in small areas (Castañeda and Barros 1994).

An analysis of 20 sites in the region showed no temporal trends in annual precipitation during the period 1961-1996 (Table 1). Only Esquel showed a statistically significant decreasing trend in annual precipitation during this period. For some sites (Maquinchao, Trelew and Rio Gallegos) a statistically significant positive trend was detected (Table 1).

The ENSO (El Niño-Southern Oscillation) phenomenon is one of the main sources of interannual variability of meteorological variables, particularly of precipitation. In central-west Patagonia, spring precipitation (September to November) tend to be lower than normal during La

Niña events and greater than normal during El Niño events. From December to February, in the summer period, the opposite pattern can be observed: higher than normal precipitation during La Niña events and lower than normal precipitation during El Niño events (Beltrán et al. 1998). The impact of this phenomenon on the seasonal temperature was not as clear as for precipitation. However, during El Nifio events, summer temperatures tended to be higher than normal (Aceituno 1988, Kiladis and Díaz 1989, Beltrán 1997).

Climatic similarities with other regions

Only in the Northern hemisphere is it possible to find temperate continental semiarid and arid areas: the deserts of Turkestan and Gobi in Asia, and the Great Basin in North America. Patagonia and the Great Basin are particularly similar from a climatic viewpoint. Both regions are located leeward of a north-south oriented mountain range, and close to the Pacific Ocean. They are also under the influence of the westerlies and the maritime air masses of the Pacific Ocean. Both regions can be characterized as cool-temperate with precipitation maxima in the cold season. The Monte phytogeographic region, located in the NE of Rio Negro and Chubut, is climatically similar to creosote bush steppe in SW United States. Both are temperate regions with mean annual temperature greater than 12°C, and mean annual precipitation between 200 and 250 mm not concentrated in a particular season (Paruelo et al. 1995).

Climatic controls of ecosystem structure and functioning in Patagonia

Climate has an important influence on the structure and functioning of patagonian ecosystems, mainly through its impact on the water dynamics. At a continental scale, the total amount of precipitation is the main control of the differences between Patagonia and the Subantarctic forests. At the regional scale changes in the seasonality of precipitation would account for the differences between the Monte and the Patagonian phytogeographical provinces (Leon et al. 1998). At the local scale, factors such as the structure of the landscape, edaphic characteristics or landuse become more relevant than climate in shaping the ecosystem structure and functioning.

Climatic controls of ecosystem structure

The relative abundance of the main plant functional types in Patagonia, grasses and shrubs, showed a clear response to climatic factors (León and Facelli 1981, Bertiller et al. 1995, Jobbágy et al. 1996). This behaviour is similar to that observed in other regions (Paruelo et al. 1998): shrubs increase as mean annual precipitation decreases and the proportion of winter precipitation increases. By contrast, grasses increased as precipitation increased (Paruelo and Lauenroth 1996). Another important functional type, forbs, did not respond to regional climatic factors (Jobbágy et al. 1996). Their abundance would be controlled by factors that operate at local scale. The thermal characteristics of Patagonia and the winter distribution of precipitation preclude another important functional type in temperate regions: C_4 grasses (Paruelo et al. 1998).

Climatic variables affect not only the relative abundance of functional types but also species distribution. Leon and Facelli (1981) described the changes in cover of the most important species of west Patagonia as a function of mean annual precipitation. Jobbágy et al. (1996) found that the main floristic gradient in W Chubut was strongly correlated with total annual precipitation. The cover of *Festuca pallescens*, the dominant grass in the western steppes, increased linearly with water availability (Jobbágy 1993, Bertiller et al. 1995). The aridity index and the altitude explained 72% of the variation in the cover of *Festuca pallescens* in a complex landscape of western Chubut. Variables that control water availability at the local scale accounted for from 22 to 56% of the variability in the cover of the main species of the Patagonian steppe (Table 2) (Jobbágy 1993).

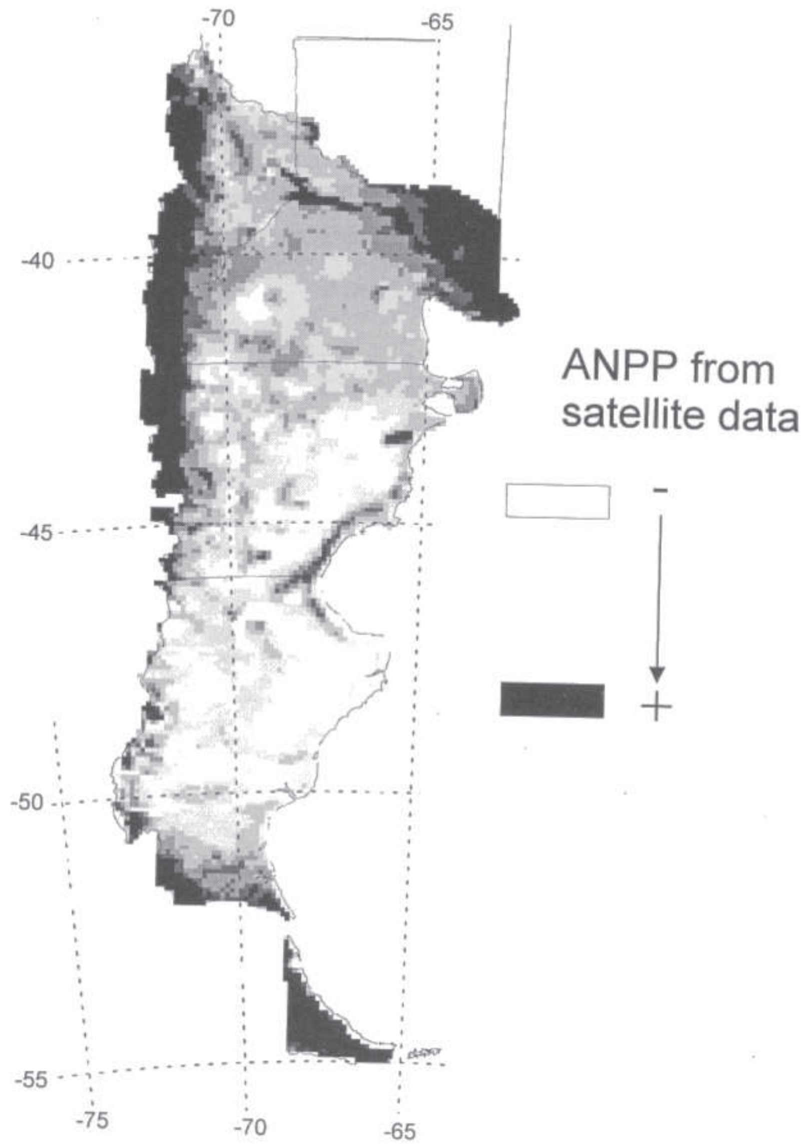

Figure 10. Average Aboveground Net Primary production (ANPP) for the period 1982-1991 estimated from the NOAA/AVHRR NDVI integral (Paruelo et al. 1997). Satellite data corresponded to the Pathfinder AVHRR Land database (NASA) with a spatial resolution of 8x8 km.

Climatic controls of ecosystem functioning

McNaughton et al. (1989) showed that aboveground net primary production (ANPP) is an attribute that integrates important aspects of ecosystem functioning. One of the most important generalizations in ecology is the linear positive relationship between ANPP and the mean annual precipitation in arid to subhumid regions (Sala et al. 1988). In western Patagonia, mean annual

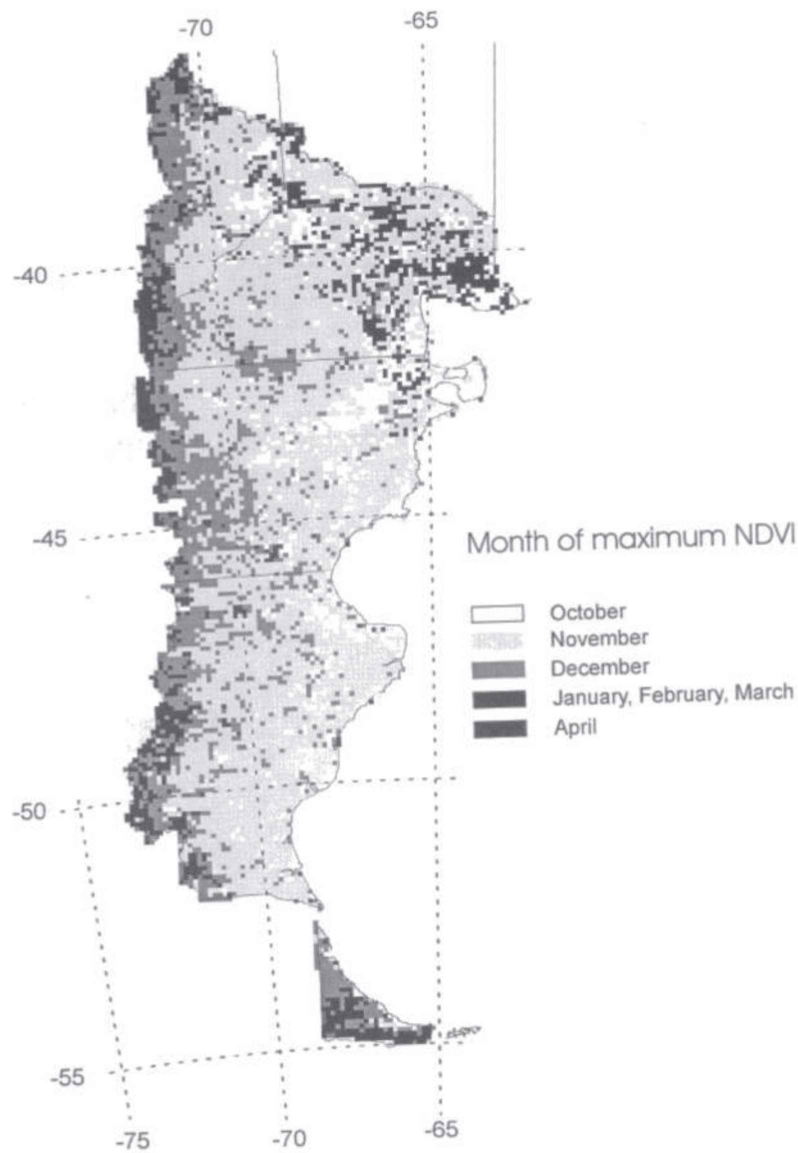

Figure 11. Month of NDVI peak (an estimator of ANPP) across Patagonia for the period 1982-1991. Satellite data corresponded to the Pathfinder AVHRR Land database (NASA) with a spatial resolution of 8x8 km.

precipitation explained more than 60% of the spatial variability of ANPP, based on satellite data (Paruelo et al. 1993, Jobbágy et al. in press). The residuals of the model were highly correlated with the distance to the Atlantic Ocean, a surrogate for the vapor pressure deficit during summer. Temperature also affects ANPP estimates derived from satellites data (Jobbágy et al. in press). ANPP showed a peak between 4 and 5.5 °C and decreased towards the cooler and warmest end of a temperature gradient (Jobbágy et al. in press). Mean ANPP estimated from satellite data (Figure 10) showed a good agreement with the spatial patterns of mean annual precipitation and aridity index (Figures 3 and 6).

Climatic controls of phenology

Soriano et al. (1976) studied the phenology of the dominant species of the steppe the Occidental District of Patagonia. Except for annual ephemeral forbs that bloom in September, most of the species of the steppe concentrate their reproduction between December and January. Grasses showed green leaves all year round, without a clear dormant period. Among the shrubs, *Mulinum spinosum, Acantholipia seriphiodes* and *Adesmia campestris* have a well-defined dormant period. In contrast, *Senecio filaginoides* showed branches with full expanded leaves the whole year. Based on phenology, Soriano and Sala (1983) divided the species of the steppe into two groups: opportunistic (grasses and evergreen shrubs) and periodic (deciduous shrubs). The phenology of the dominant species of the Subandean District, *Festuca pallescens,* showed a strong correlation with the sum of the maximum temperatures (Bertiller et al. 1990).

The seasonal variation of the Normalized Difference Vegetation Index (NDVI), an index calculated from spectral data from the NOAA/AVHRR series of satellite sensors, can be used to follow the dynamics of carbon gains throughout the year (Lloyd 1990, Paruelo et al. 1998) and to identify the spatial variation of production peaks across the region (Figure 11). On average, for the, period 1982-1991, most of the region showed a peak of production in November, when water availability and temperature are simultaneously high (Paruelo and Sala 1995). Toward the west, production peaked later (December). Deciduous forests showed the peak in January and February. The delay in the timing of the production maximum can be related to an increase in water availability that extends the growing season. Some areas of the Monte shrub steppe region had production peaks in early spring (October) and in fall (April). This would be related to the even distribution of precipitation during the year in this area.

The use of satellite imagery allowed one to identify the main environmental controls of ecosystem phenology. Mean annual temperature was the main control of the spatial and temporal variation of the beginning of the growing season (Jobbágy et al. in press). Growing season started 8.1 days earlier per °C of increase in monthly temperature. The beginning of the growing season was not related to precipitation. Both the time of maximum productivity and the end of the growing season had a positive relationship with mean annual precipitation and a negative relationship with mean annual temperature (Jobbágy et al. in press). These relationships offer the possibility of monitoring the phenology of the vegetation by using remote sensing.

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