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NDVI Spatio-temporal Patterns and Climatic Controls Over Northern Patagonia

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Abstract

In this study, we identify the main modes of variability of the Normalized Difference Vegetation Index (NDVI) and their relationships with precipitation and temperature variations across northern Patagonia (36°–45° S). In this approach, we combined a recently developed high-resolution gridded dataset (20 × 20 km) for temperature and precipitation with a re-scaled NDVI grid to spatially match the climate database. Climate–vegetation relationships were analyzed taking into account a wide range of temporal variations (intra- to inter-annual) of both climate and NDVI. An Empirical Orthogonal Function analysis performed on NDVI delimits four regions that are spatially consistent with previous vegetation classifications for northern Patagonia. In addition, these coherent NDVI regions show similarities with the spatial precipitation patterns and the temporal evolution of precipitation over the common period 2001–2010. Both NDVI and precipitation show evident annual cycles over the Mediterranean climatic region in northwestern Patagonia. These annual cycles decrease in amplitude toward the eastern arid rangelands, and to the south on the evergreen all-year-round rainforests. Significant positive relationships between monthly precipitation and NDVI are recorded in the dry temperate rangelands in northeastern Patagonia. In contrast, direct associations between monthly NDVI and precipitation were absent in the Central Patagonia cold grasslands, where seasonal interactions between precipitation, temperature and NDVI appear to be more relevant. Relationships between NDVI and temperature are generally weaker east of the Andes, but significantly positive in late winter/spring over the temperate forests in western North Patagonia. Our results indicate that climate–NDVI relationships in northern Patagonia are biome specifics with the occurrence of temporal lags and precipitation–temperature interactions in the responses of vegetation to climate at some ecosystems.

Key words: Vegetation index; Climate variations; EOF; Climate–vegetation relationships; Northern Patagonia; Spatio-temporal analysis.

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Highlights

- Spatially delimited regions using EOF analysis on NDVI are consistent with most previous functional and structural vegetation classifications across northern Patagonia.

- EOF analyses reveal that both NDVI and precipitation share similar spatial and temporal patterns of variability across the region.
- Climate–NDVI relationships in northern Patagonia are specific to the regions delimited by the EOF analysis, and show temporal lags and precipitation–temperature interactions in the responses of vegetation to climate.

Introduction

Most studies relating large-scale climate fluctuations to regional ecosystem dynamics are focused on Normalized Difference Vegetation Index (NDVI) variations (Paruelo and others 1993; Braswell and others 1997; Buermann and others 2003; Mao and others 2012). NDVI is considered a proxy of the Aerial Net Primary Productivity (ANPP) (Monteith and Moss 1977; Paruelo and others 1997, 2000), a functional estimate of energy input into terrestrial ecosystems (Townsend and others 2003; Chapin and others 2011). Therefore, NDVI is a very useful tool for studying the integrated effect of the main climatic constrains (temperature and precipitation) on vegetation dynamics (Jobbágy and others 2002; Fabricante and others 2009).

NDVI responses to climatic variations are often complex and not straightforward (Jobbágy and Sala 2000; Jobbágy and others 2002; Fabricante and others 2009). The influence of temperature and/or precipitation on NDVI often depends on biome characteristics (Mohamed and others 2004; Los and others 2001; Knapp and Smith 2001), the functional types of dominant species (Ehleringer and others 1991) and the phenological stages of the vegetation (Buermann and others 2003; Mao and others 2012; Ichii and others 2002). In addition, changes in NDVI often lag behind climatic variations (Oesterheld and others 2001; Los and others 2001; Bao and others 2015). These temporal delays may be due to asynchronies between climatic variations and phenological cycles (Ehleringer and others 1991); but also to NDVI inertia (Colyvan and Ginzburg 2003); which means that this variable responds to the temporal integration of environmental variability (Fabricante and others 2009). The inertia commonly observed in NDVI responses is a distinctive feature of biological systems that tend to filter out high-frequency variability and follow longer environmental changes (Stenseth and others 2002; Drinkwater and others 2010; Mahecha and others 2010; Di Lorenzo and Ohman 2013). For example, some studies have noted that total annual precipitation in the dry Patagonian steppes explains a low percentage of inter-annual variations in primary productivity (Lauenroth and Sala 1992; Jobbágy and others 2002). Specifically, they recorded stronger relationships between NDVI and accumulated rainfall over different periods previous to the growing season (Jobbágy and Sala 2000; Fabricante and others 2009). Similar results have also been reported for other semiarid and arid rangelands elsewhere (Webb and others 1978; Oesterheld and others 2001).

Another source of complexity in the analysis of climate–NDVI relationships is related to differences in vegetation sensitivity to climatic variability, which in turn also varies at different temporal and spatial scales. For example, the weak response of NDVI to rainfall in arid and semiarid rangelands has been ascribed to changeable spatial and temporal relationships between temperature and vegetation. NDVI shows stronger relationships with temperature over areas and/or periods, where moisture is not the limiting factor for plant growth, as often occur at high latitudes and upper elevations (Knapp and Smith 2001; Los and others 2001; Ichii and others 2002; Nemani and others 2003) or at the beginning of the growing season in cold and temperate regions with a well-defined seasonal cycle in vegetation growth (Ichii and others 2002; Buermann and others 2003; Mao and others 2012; Bao and others 2015; Lavergne and others 2015). In this sense, Braswell and others (1997) suggested that global spatial correlation patterns between climate and NDVI integrate the individual responses from different ecosystems. For example, although vegetation growth is mostly controlled by soil moisture in warm and arid rangelands (Kemp 1983; Bao and others 2015), it may be also modulated by temperature in cold rangelands (Ram and others 1988; Braswell and others 1997) or during the beginning of the growing season in semiarid cold grasslands (Buermann and others 2003). Consistent with these observations, positive relationships between late winter-spring temperatures and vegetation productivity had also been reported over different sites in the arid Patagonian steppes (Paruelo and others 1993; Jobbágy and others 2002).

Because the correlation patterns between climate and NDVI are likely to depend on the biome (Braswell and others 1997), in this study we evaluated differences in sensitivity to climate variability using a dynamic classification of biomes. A vegetation classification based on the temporal variability of the NDVI provides a useful framework to explore the relationships between climate and vegetation indices. So far, the most commonly used methodologies to perform spatial classifications on vegetation had been based on the visual interpretation and/or digital classification of satellite or aerial imagery (Salinero and Salinero 2006). These methods are based mainly on structural attributes of the vegetation. Paruelo and others (1993, 1998) made an important progress by incorporating the temporal dimension to the classification process, allowing the identification of functional features of different vegetation units in the landscape. In addition, Paruelo (2008) proposed a method for vegetation classification through the description of ecosystem-scale biophysical processes, paying more attention to functional attributes than structural characteristics of the vegetation. Thus, this classification methodology is independent of the vegetation structure and focuses on matter and energy flows in the ecosystems (Paruelo and others 2001). This vegetation characterization, denominated ecosystem functional types (EFT), considers several functional attributes from the mean seasonal curve of NDVI (Pettorelli and others 2005), and provide information on the integration of the annual curve, the months of maximum and minimum NDVI values, the normalized NDVI according to its variation range and the rates of increase and/or decrease in NDVI.

Although EFT takes into account temporary changes in the NDVI that describe the dynamics of the energy and matter flows in an ecosystem, the EFT only considers the seasonal/annual variations as the main temporal scale at which these flows occur. This approach might be appropriate in some ecosystems in which annual variations dominate, but it is important to emphasize that intra- and inter-annual variations play important roles in many ecosystems. In arid and semiarid regions, for example, resources such as water, nutrients and plant biomass experience alternate cycles of high and low abundance (Reynolds and others 2004; Ogle and Reynolds 2004; Schwinning and Sala 2004). In these arid ecosystems, precipitation often occurs in isolated and irregular pulses (Westoby 1972; Noy-Meir 1973). Even in regions dominated by the annual/seasonal cycles, it is important to describe the contribution of intra- and inter-annual cycles to the overall dynamics of vegetation. In this context, Mahecha and others (2010) proposed the use of dimensionality reduction methods to determine the global spatial patterns of photosynthetic variation at annual, high-frequency (4.5 months) and low-frequency (> 1.25 years) scales to obtain the main patterns of geographical variability associated with each temporal scale. In this context, the goals of this paper are (1) to identify the spatio-temporal patterns of variability in NDVI at different timescales (annual, inter- and intra-annual) over northern Patagonia and (2) to analyze the temporal relationships between climatic variables (temperature and precipitation) and NDVI, considering the time lags and the different temporal scales at which these relationships occur.

Study Area

Located in the southern sector of South America, the extended North Patagonia (36°–45° S) region is under the influence of the semi-permanent anticyclones of the Atlantic and Pacific oceans to the north and the circum-Antarctic cyclonic belt to the south. The Westerlies, with the associated storm tracks, constantly drive humid air masses embedded in synoptic-scale perturbations from the Pacific Ocean along the region (Figure 1; Prohaska 1976; Hoskins and Valdes 1990; Garreaud and others 2009). The Cordillera de los Andes intercepts the air masses coming from the Pacific and determines

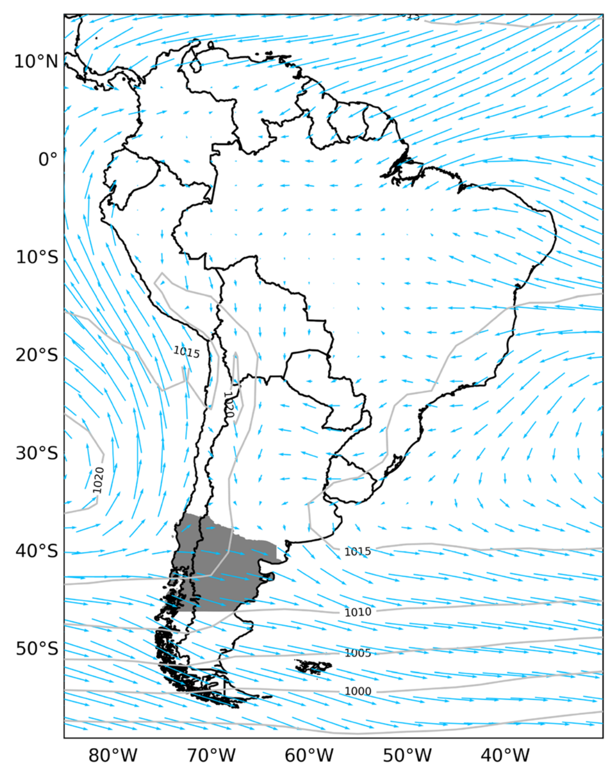

Figure 1. Geographical location of the study area (gray shaded). Mean wind direction (wind barbs) and sea level pressure derived from the NCEP–NCAR reanalysis during the 2001–2010 period are shown. Note the strong westerly winds crossing the study area from 40° S to the south.

a strong zonal asymmetry in precipitation, with humid and dry conditions west and east of the Andes, respectively (Villalba and others 2003; Garreaud 2009). The highest precipitation peaks occur along the Cordillera de la Costa and the Cordillera de los Andes (Falvey and Garreaud 2007; Viale and Nuñez 2011; Viale and Garreaud 2015). The spatial pattern of mean annual temperature variations in northern Patagonia is determined by the pole-equator temperature gradient, terrain elevation and zonal asymmetries related to the cold Humboldt current to the west and the interactions between the cold Malvinas and the warm Brazil ocean currents to the east (Villalba and others 2003; Garreaud and others 2009). Mean annual temperatures range from 12 °C in the northeast sector till 6 °C in southwestern Patagonia (Paruelo and others 1998).

The strong climatic gradients observed in northern Patagonia are clearly reflected in the vegetation distribution (Paruelo and others 1998). Figure 2 shows terrain elevation, mean annual temperature and total annual precipitation derived from the Northern Patagonia Climatic Grid (NPCG), together with mean annual NDVI. Broadly, the moister regions along and west of the Cordillera de los Andes coincide with the distribution of the humid Subantarctic temperate forests, while the dryer regions east of the Andes are dominated by arid and semiarid rangelands (Bianchi and others 2016).

A useful framework to describe the vegetation distribution in northern Patagonia is provided by classifications based one Homogeneous Ecological Regions (HERs) and Forest Types (FTs) (Figure 3). These classifications are not fully comparable, as they aim to describe forest formations (FT) and arid and semiarid grasslands (HER). Therefore, different methodologies are used to elaborate these classifications. The HER classification is based on the interaction between local abiotic factors (climate, soil, hydrology and topography) with the structure and function of the associated vegetation (Bran 2000; Maybury 1999). The FT classification is based on the presence and dominance within the upper-strata of different tree species in the forest (Donoso 1993). According to these classifications, most land-cover types over northern Patagonia correspond to non-managed environments; with the exception of the Chilean Central valley and the northeastern portion of the Chiloé Island in Chile, and the Rio Negro Valley in Argentina.

Along the western sector of the study area occurs the transition from the Mediterranean climate (dry summer and moist winter) of central Chile to the oceanic-subantarctic climate (humid conditions all year round) farther south (Villalba and others 2003; Peel and others 2007; Garreaud and others 2009). The Araucaria (*Araucaria araucana*) and Coihue (*Nothofagus dombeyi*)—Rauli (*Nothofagus procesa*)—Roble (*Nothofagus obliqua*) FTs between 37° and 40° S (Laclau 1997) give way to the Valdivian Evergreen (Siempreverde Valdiviano) FT (Pisano 1950; Donoso 1993) in the presence of Alerce (*Fitzroya cupressoides*) and Cohiue de Magallanes (*Nothofagus betuloides*). The Lenga (*Nothofagus pumilio*) FT shows a wider latitudinal range along the upper limit of the Patagonian forest in the Cordillera de los Andes from 35° to 55° S.

Due to the orographic effect, the Pacific air masses turn dry and warm on the lee side of the Andes. Precipitation decreases from total annuals of around 3000 or more on the Andes to less than 200 mm in the Central Patagonia (Jobbágy and others 1995). The narrow longitudinal band east of the Andes with total annual precipitations from approximately 1000–500 mm corresponds to the transition between different mesic FTs (*Araucaria araucana, Austrocedrus chilensis, Nothofagus sp.*) and the gramineous steppes (sub-Andean grasslands) and in the Sierras and Mesetas (Sierras and Plateaus) HERs (León and others 1998; Laclau 1997). The driest area (< 200 mm) is located in the transition between the gramineous steppes and the Monte (León and others 1998). Toward the northeast of the study area, total annual precipitation slightly increases up to 400 mm due to spo-

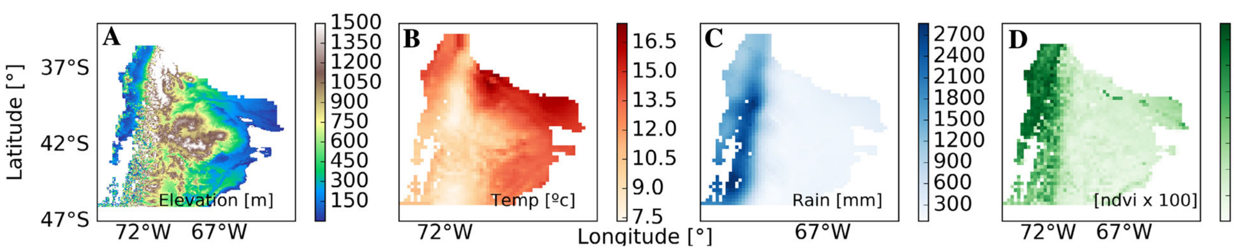

Figure 2. Terrain elevation (derived from ASTER-DEM) (**A**), mean annual temperature (**B**), total annual precipitation (**C**) and NDVI (**D**) averaged for the period 2001–2010.

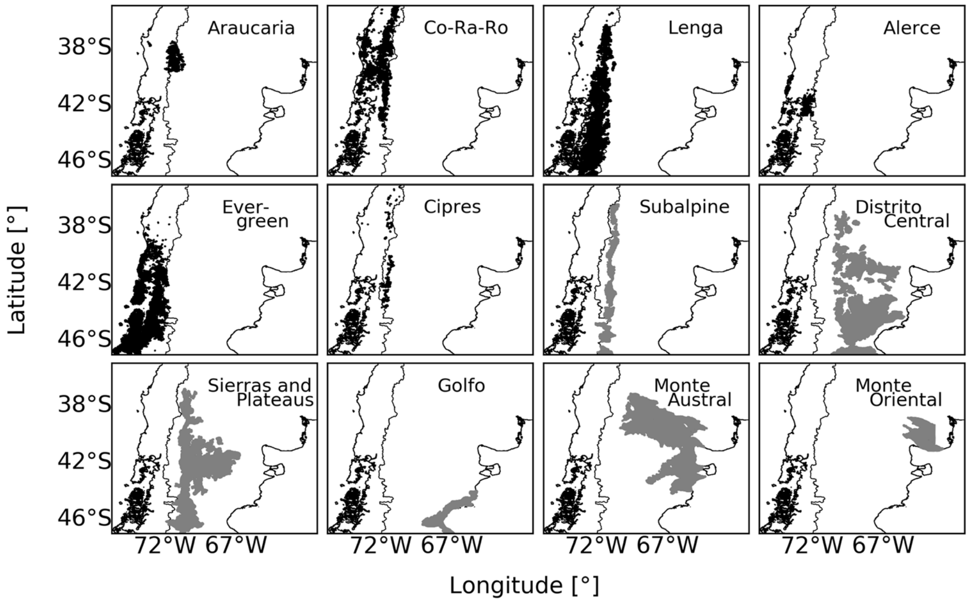

Figure 3. Forest types (FT) (black shaded) and homogeneous ecological regions (HER) (gray shaded) in northern Patagonia. The HERs refer to phytogeographical formations (Evergreen, Subalpine, Distrito Central, Sierras and Plateaus, Golfo, Monte Austral and Monte Oriental), while the FTs are related to dominant tree species (Araucaria, Coihue-Raulí-Roble (Co-Ra-Ro), Lenga, Alerce y Ciprés).

radic incursions of moist and warm air masses (mainly during summer) driven by the semi-permanent anticyclone over the South Atlantic Ocean (Labraga and Villalba 2009). This region is covered by the Monte Austral and Monte Oriental dominated by shrubby vegetation and C4 grasses.

Methodology

Monthly precipitation and temperature data were retrieved from the Northern Patagonia Climate Grid (NPCG; Bianchi and others 2016). NPCG was generated using monthly precipitation and temperature data from 218 and 114 locations, respectively, across northern Patagonia. This dataset covers the period 2001–2010. Its spatial resolution is 20 km × 20 km. NDVI data were derived from the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA-AVHRR) imagery. The rasters were degraded from their original resolution (approximately 1 km) to match the resolution of the NPCG (20 × 20 km; Bianchi and others 2016).

NDVI is defined as:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}} \quad (1)$$

where NIR and RED are the surface reflectance values from the infra-red and visible (red) portions of the electromagnetic spectrum, respectively (Chapin and others 2011; Fahey and Knapp 2007). This index enables to estimate the amount of photosynthetically active radiation (PAR) absorbed by vegetation (Ruimy and others 1994; Gamon and others 1995, Huete and others 2002), so it is an estimator of the Aerial Net Primary Productivity (ANPP) (Monteith and Moss 1977; Paruelo and others 1997, 2000).

We selected the 2001–2010 period to match the length of the NPCG dataset (Bianchi and others 2016). NOAA-AVHRR imagery does not show missing data over Patagonia during this period. The linear trends were removed from the original NDVI and the temperature and precipitation data derived from NPCG by subtracting the linear trends from the original series. The spatio-temporal variability of NDVI, rainfall and temperature was analyzed by conducting Empirical Orthogonal Function (EOF) analysis. This method enables the characterization of the temporal and spatial variability of the time series in the databases. EOF analysis has been widely used for identifying spatial and temporal patterns of climate variability (Barnston and Livezey 1987; Villalba and others 2003; Aravena and Luckman 2009) and satellite-derived data (Lasaponara 2006; Li and Kafatos 2000; Sarkar and Kafatos 2004; Tourre and others 2008). EOF analysis re-projects data matrices onto orthogonal axes called Empirical Orthogonal Functions (EOF) that capture the main modes of variability and reduce the dimensionality of the original data (Navarra and Simoncini 2010). Specifically, EOF transforms the original data matrix A_{orig} into a zero mean vector by subtracting the mean value to each corresponding row of A_{orig}, that is:

$$A = A_{\mathrm{orig}} - a * I \tag{2}$$

where I is a vector of ones ($I_j = 1$ for all j), while a is the vector of sample means. Then, the covariance matrix is computed in the following way:

$$S = 1/(n-1)A * A\ T \tag{3}$$

Finally, the eigenvectors v and the eigenvalues λ are computed from the covariance matrix:

$$Sv = \lambda v \tag{4}$$

It is demonstrated in Navarra and Simoncini (2010) and Hannachi and others (2007) that the number of independent maps (or vectors) in the original datasets is equal to the orthogonal set of eigenvectors of the covariance matrix. Finally, the variance explained by each eigenvector is proportional to the eigenvalues. The EOFs were rotated using the Varimax methodology. The rotation of the EOFs improves their physical and biological interpretations since it maximizes the correlation with the raw data (Richman 1986; Von Storch and Zwiers 1999).

To describe the temporal variability of the EOFs, the power spectra were calculated applying a fast Fourier transform (FFT) to the monthly time series:

$$\mathrm{X}[\mathrm{k}] = \sum_{n=0}^{N-1} x(n) e^{\frac{(-j2\Pi kn)}{N}}, \tag{5}$$

where $x(n)$ are the EOF monthly time series.

The variability of NDVI based on EOF was contrasted using the previously defined Homogeneous Ecological Regions (HER; Bran 2000) and Forest Types (FT; Donoso 1993). NDVI was averaged over each HER defined by Bran (2000) for the arid and semiarid regions of Patagonia, and over each FT proposed by Donoso (1993) for the temperate forests of Patagonia. The spatial Pearson correlation coefficients between the time series of NDVI, averaged over the HERs and FTs, and the EOFs were computed in order to assess the similarities between both classifications.

Because the vegetation responses to rainfall and/or temperature also depend on phenological phases (Ehleringer and others 1991; Paruelo and others 1998, 2001; Los and others 2001; Ichii and others 2002), we seasonally disaggregate the climate–NDVI relationships by computing three-month means for NDVI, temperature and precipitation. After that, the influence of climate on NDVI variability was estimated by computing correlation coefficients between both monthly and seasonal variations in climate and NDVI with lags from 1 to 12 months.

Results

Spatio-temporal Variability of the Normalized Difference Vegetation Index

The NDVI spatial patterns associated with the four main EOFs are depicted in Figure 4 together with the percentage of variance explained by each EOF. In addition, the temporal evolution of the four NDVI EOFs, along with the mean NDVI series estimated for the corresponding FTs or HERs, is shown in Figure 5. Finally, the power spectra of these time series are displayed in Figure 6. The first EOF is spatially related to the upper-elevation regions of the Cordillera de los Andes (between 70° and 73° W approximately), and the northern Patagonia Plateau. It explains 43.56% of the total variance, and the associated temporal evolution is dominated by a marked annual cycle, with minimum values during late winter and maximum values during late spring and summer (Figures 5 and 6). The mean NDVI for the Coihue-Rauli-Roble, Araucaria and the Lenga FTs shows similar annual oscillations (Figure 5). The correlation coefficients between the time series of this EOF and the mentioned FTs and HERs range between $r = 0.9$ and $r = 0.97$ (Table 1). Although the inter-annual variations in NDVI recorded for upper-elevation grasslands show less amplitude than those recorded for the forests, they are also strongly correlated with NDVI EOF 1. The spatial distribution of this EOF seems to be related to elevation and, hence, temperature (Figure 2). The spatial relationship between EOF 1 amplitudes and temperature is inverse ($r = -0.71$, $n = 1691$, $p < 0.01$), but positive with elevation ($r = 0.64$, $n = 1691$, $p < 0.01$).

The second EOF explains 17.17% of the total variance and is spatially weighted toward the southeastern sector of the study region coincident with the Patagonia phytogeographical province (León and others 1998), including the Central, Golfo, and the Sierras and Plateaus HERs. The temporal amplitudes of the EOF 2 are reduced in comparison with those of the EOF 1 and show large contributions of intra- and inter-annual cycles in the total variance (Figure 6). The annual cycle shows minimum and maximum values during fall

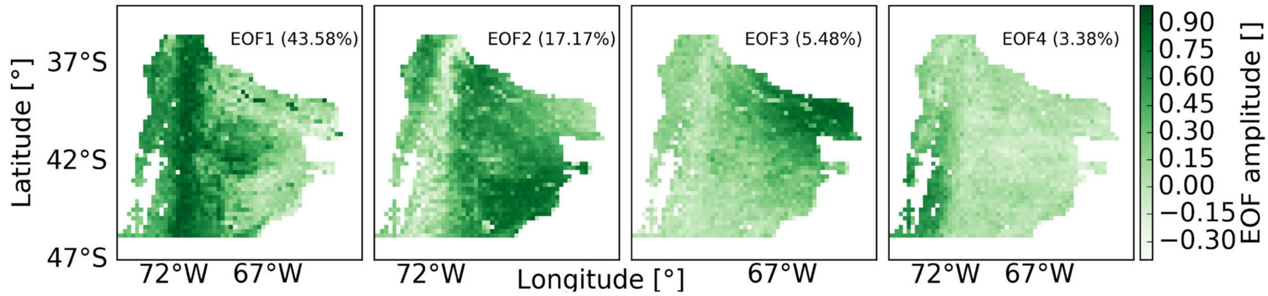

Figure 4. The four leading EOFs of NDVI (2001–2010) in northern Patagonia. The variance explained by each spatial pattern is indicated in the upper right corner.

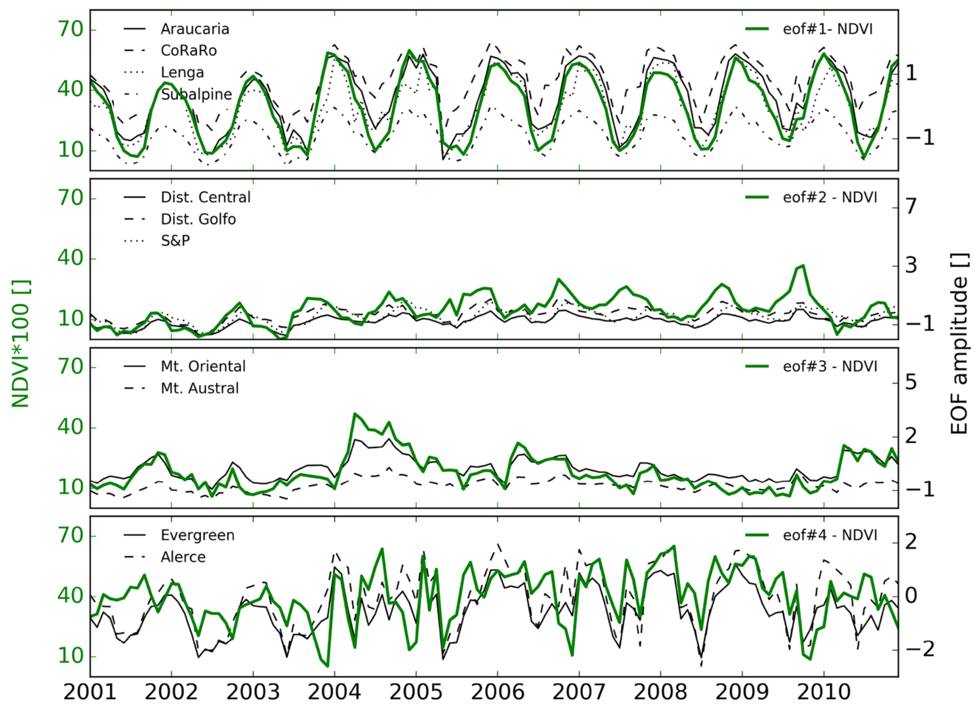

Figure 5. Monthly temporal variations of the four main NDVI EOFs, along with the NDVI variations averaged over the corresponding HERs and FTs regions shown in Figure 3.

and spring, respectively. Similar temporal patterns are observed for NDVI averaged over the Central, Golfo, and the Sierras and Plateaus HERs. The correlation coefficients over the period 2001–2010 between NDVI EOF 2 and the above-mentioned HERS are $r = 0.85$, $r = 0.83$ and $r = 0.54$, respectively (Table 1).

The third EOF, which explains 5.48% of the total variance in NDVI (Figure 4), matches the HERs for the Monte Austral and the Monte Oriental. The annual cycle has no relevance in the temporal pattern of the EOF 3 (Figures 5 and 6). The variance is largely explained by low-frequency oscillations (in the range between 2 and 5 years (Figure 6). Over the period 2001–2010, the NDVI averaged over the Monte Austral and Oriental shows similar oscillations, which are highly correlated with EOF 3 ($r = 0.73$ and $r = 0.94$, respectively Table 1).

The fourth EOF (3.38% of the total variance) is expressed toward the southwest of the study region and coincides with the Alerce and Evergreen FTs. The temporal behavior of this EOF is characterized by the lack of an annual cycle and high intra-annual variability (Figures 5 and 6). The 6- and 17-month oscillations are the most important modes of variability in the NDVI EOF 4.

The spatial patterns associated with the four main EOFs of precipitation are depicted in Figure 7. Overall, the EOF analysis performed on precipitation delimits similar regions as the NDVI—derived EOFs. Furthermore, NDVI and precipitation EOFs

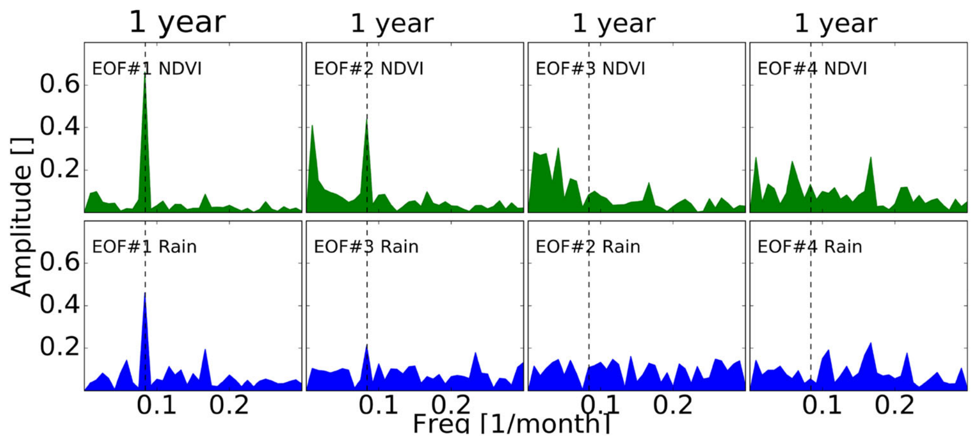

Figure 6. Power spectra of NDVI-derived EOFs (upper) and rainfall-derived EOFs (lower) estimated over the interval 2001–2010.

Table 1. Correlation Coefficients Between the Time Series of the NDVI-Derived EOFs and the NDVI Averaged Over the Corresponding FTs and HERs

	EOF 1		EOF 2		EOF 3		EOF 4
Araucaria	0.97	Dist. Central	0.83	Mt. Oriental	0.94	Evergreen	0.64
CoRaRo	0.90	Dist. Golfo	0.85	Mt. Austral	0.73	Alerce	0.55
Lenga	0.91	S&P	0.54				
Subalpine	0.97						

All values are statistically significant at the 99% confidence level.

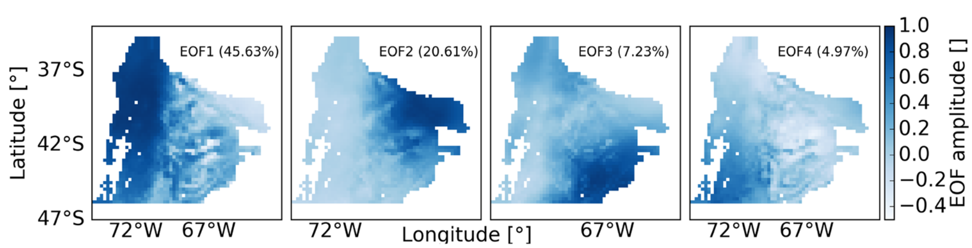

Figure 7. The four leading EOFs of annual precipitation (2001–2010) across northern Patagonia. The variance explained by each spatial pattern is indicated in the upper right corner.

also share similar temporal features. For example, the annual cycle reaches its maximum amplitude in both NDVI and precipitation EOFs located west in the study area, but decreases in amplitude for the EOFs located in the central and southeastern sectors; and the amplitude associated with the annual cycle is lowest in the NDVI and precipitation EOFs located in the northeastern and southwestern sectors (Figure 6).

In contrast to precipitation and NDVI, the dominant temperature pattern shows a much more homogeneous spatio-temporal behavior over northern Patagonia. The first EOF (not shown) shows a single common pattern over the region, which represents 95% of the total variance dominated by a strong annual cycle.

Precipitation and Temperature Influences Over NDVI Dynamics

The EOF analysis performed on both precipitation and NDVI datasets shows similar spatial patterns that coincide with the spatial distribution of the Monte Oriental HER (EOFs 2 and 3, respectively). Over the period 2001–2010, both precipitation and NDVI series lack a consistent annual cycle. However, we observed a significant relationship

($r = 0.65$, $n = 120$, $p < 0.01$) between the 12-month-integrated series of the precipitation EOF and the raw time series of the NDVI EOF (Figure 8).

We found two seasonal-locked relationships between climate and NDVI. The first consists of positive correlations between precipitation during late spring, summer and fall, and all-year-round NDVI over the Monte Oriental HER but also in some sectors of the Monte Austral HER (Figure 9). The relationships between precipitation and NDVI are statistically more robust when the series are temporarily displaced. Therefore, the relationships are stronger when comparing precipitation variations in late spring/summer rainfall with those of the NDVI in autumn and winter. The second pattern consists of positive relationships between spring temperature and NDVI over the Andean temperate forests of northern Patagonia (Figure 10). For the same region, inverse relationships between precipitation and NDVI occur during spring. However, this negative relationship may be spurious because temperature and precipitation are negatively related over the region during spring (not shown).

Discussion

In the first part of this study, we assessed the spatio-temporal relationships between climate and NDVI variability in northern Patagonia. Although temporal and spatial patterns of climate and NDVI variability have independently been estimated (Aravena and Luckman 2009; Paruelo and others 1998, 2001; Fabricante and others 2009), their variations have not been simultaneously considered for northern Patagonia. Different spatio-temporal variations of NDVI and climate were recorded across the region reflecting differences in phase and amplitude of their annual cycles. Larger amplitudes in the annual cycles of precipitation and NDVI occur in the northwest area of northern Patagonia with marked Mediterranean climate, but they are absent for precipitation and NDVI in many sectors east of the Andes. Despite these geographical differences, we observed similar reductions in the amplitudes of the NDVI and precipitation annual cycles from the Mediterranean region to the humid throughout-year evergreen forests in the southwest and to the arid sectors in the eastern Patagonia plateaus and plains. The reduced contribution of the annual cycle and the relatively larger importance of inter- and intra-annual cycles in NDVI variations outside the Mediterranean sector are consistent with similar patterns in temporal precipitation variations. Indeed, the annual NDVI and precipitation spatial fields are significantly correlated ($r = 0.75$, Figure 2) and the NDVI-derived EOFs discriminate similar geographical regions as those resulting from the EOF analysis on precipitation (Figure 7). Similarities in the spectral signatures of precipitation and NDVI at local–spatial scale also support our findings (Figure 6). For example, the existence of a well-defined annual cycle in the precipitation over the northern portion of the Andean Cordillera, consistent with the dominant Mediterranean climate, is clearly reflected in the temporal evolution of the NDVI in the Araucaria, Coihue–Raulí–Roble, and Lenga FTs, and in the Subalpine Grasslands and Sierras y Plateaus HERs. Consequently, our results support the existence of geographical differences in NDVI variations across northern Patagonia but similarities in the relationships between climate and vegetation changes at the FT and HER spatial scales. However, this general pattern was not always recorded for all ecosystems, reflecting the complex interactions between variations in climate and vegetation. Thus, our analyses do not support a direct temporal relationship between rainfall and NDVI across the dry Distrito del Golfo and Distrito Central HERs, both in the Patagonian phytogeographical province (León and others 1998). Several authors have already reported a lack of consistent relationships between vegetation productivity (or NDVI) and precipitation across different grasslands in central-eastern Patagonia (Knapp and Smith

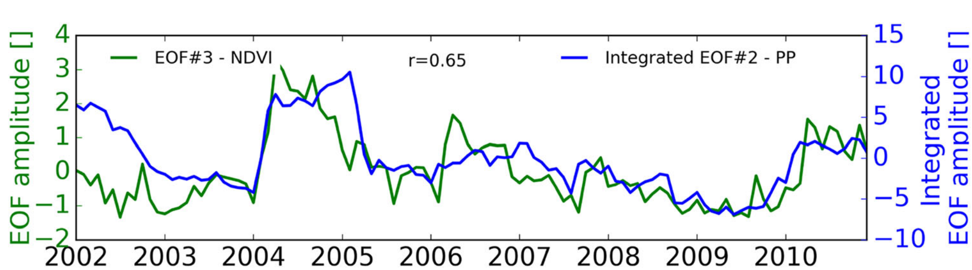

Figure 8. Twelve-month-integrated series of precipitation-derived EOF 2 (blue line) and NDVI-derived EOF 3 (green line). The correlation coefficient (r) is also indicated (Color figure online).

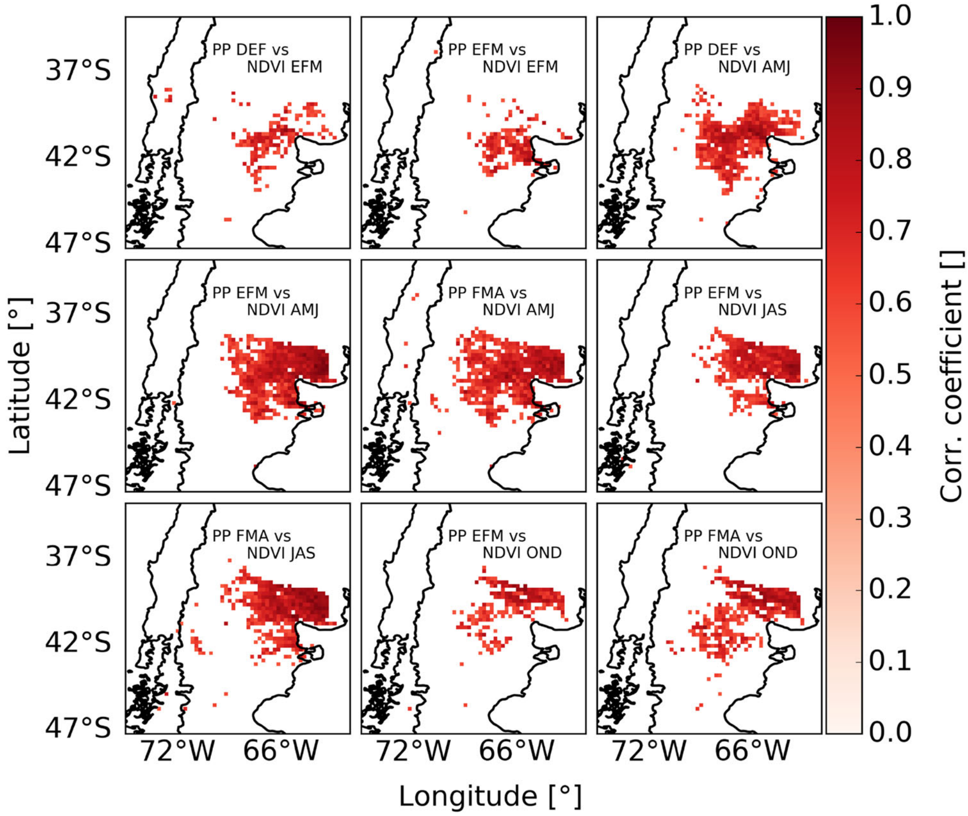

Figure 9. Spatial correlation patterns between seasonal precipitation and NDVI composites. Seasonal NDVI and precipitation (PP) are indicated in each panel. Colored grids represent statistically significant correlation coefficients at the 95% confidence level.

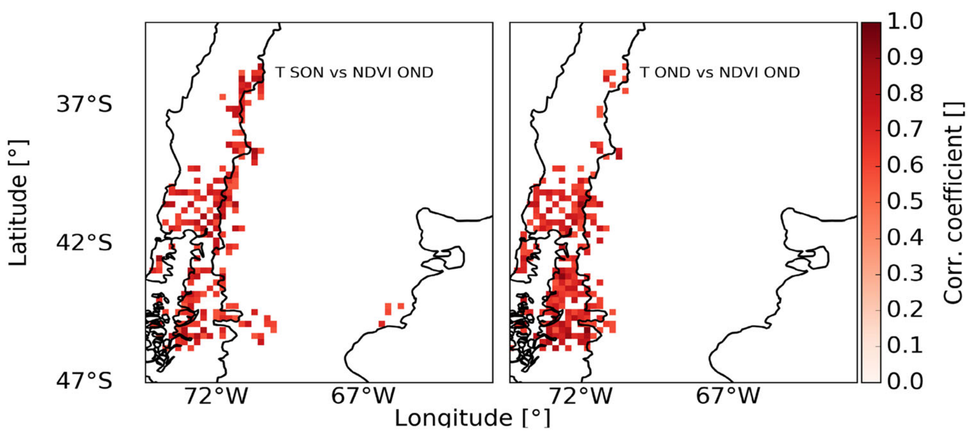

Figure 10. Spatial correlation patterns between seasonal temperature (*T*) and NDVI composites. Colored grids represent statistically significant correlation coefficients at the 95% confidence level.

2001; Jobbágy and others 2002). Sala and others (2012) suggest that the weak precipitation–NDVI relationship may be due to phase shifts between rain pulses and plant responses. In northern Patagonia, Fabricante and others (2009) also documented poor relationships between inter-annual variations in NDVI and seasonal precipitation. In these cold regions, the relationships between NDVI and precipitation may be lagged and occur over longer time scales (Sala and others, 2012). Previous studies indicate that lags in the responses of primary productivity to precipitation may be associated with structural changes in plant communities or ecosystems (Yahdjian and Sala 2006; Reichmann and others 2013). Yahdjian and Sala (2006) reported a decrease in the density of *Stipa speciosa, Stipa humilis* and *Poa ligularis* grass species in response to drought in the Subalpine grassland HER, which in turn, negatively affected the ecosystem productivity in the following growing season. Reichmann and others (2013) reported a positive relationship between precipitation and density of grass-tiller pasture. These authors recorded an increase (decrease) in productivity after a wet (dry) year. On inter-annual to decadal scales, changes in precipitation could trigger important structural changes in these ecosystems. For example, a sequence of wet years may increase the productivity and establishment of grass species and therefore, grasses dominance over shrubs (Peters and others 2012). An increase in the intensity and frequency of droughts, instead, may facilitate the invasion of shrubby species (Verstraete and others 2009). Grasses that use water from the upper layers of the soil show small lags in relation to rainfall events, whereas shrubs that extract water from the deeper layers of the soil tend to show longer lags to precipitation variations (Wang and others 2003; Sepúlveda and others 2018). Another possible cause of the weak precipitation–NDVI relationships over the cold grasslands may be due to the varying responses of vegetation to precipitation between environments or even between different functional types within an ecosystem (Verstraete and others 2009; Peters and others 2012). Other authors attribute the non-response of NDVI to precipitation variations to the indirect role of temperature in cold grasslands (Ram and others 1988; Braswell and others 1997). Although soil moisture is generally the limiting factor for vegetation growth in warm-dry grasslands (Kemp 1983; Bao and others 2015), cold grasslands can also be influenced by temperature. Like in temperate forests, late winter and spring temperatures determine the beginning of the growing season and therefore modulate variations in NDVI (Buermann and others 2003). This positive relationship between above-average winter-spring temperatures and the length of the growing season, which in turn modulate the variations in total annual productivity, had already been described for the Patagonian steppes (Paruelo and others 1998; Jobbágy and others 2002).

In contrast to the cold grasslands, the warmer temperatures prevailing in the Monte Oriental HER during the growing season induce strong positive relationships between annual (12-month-integrated) precipitation and NDVI. When seasonally disaggregated, the strongest relationship occurs when annual NDVI is compared with summer precipitation, concurrent with the warmer period with the most abundant rainfalls over the Monte Oriental. Negative temperature–NDVI relationships suggest that moisture availability is the limiting factor for vegetation growth in these temperate xeric environments (Mao and others 2012; Los and others 2001; Mohamed and others 2004). Another important factor to be considered when analyzing the sensitivity of NDVI to precipitation in the Monte Oriental HER is the larger relative abundance of C4 grasses (León and others 1998). The growth of C4 species is usually triggered by rainfall events whenever temperature is suitable for plant growth (Noam and others 1992). Hence, these species are capable of rapidly capitalizing sporadic summer rainfall events into growth and seed production (Ehleringer and others 1991; Pucheta and others 2011; Pol and others 2010).

In the northwestern Patagonian temperate forests, NDVI is positively related to temperature at the beginning of the growing season. Previous studies indicate that NDVI tends to show stronger relationships with temperature in areas where moisture is not the limiting factor for tree growth (Knapp and Smith 2001; Los and others 2001; Ichii and others 2002; Nemani and others 2003). Following the wet winters in the northern Patagonian Andes, soil moisture is not the limiting factor for plant growth at the beginning of the growing season (Buermann and others 2003; Mao and others 2012; Bao and others 2015; Lavergne and others 2015). According to Knapp and Smith (2001), water accumulated in the soil in humid temperate forests during winter is adequate to satisfy the evaporative demand even during dry years. In the Patagonian Andes, Villalba and others (1997, 2003) documented a positive relationship between *Nothofagus pumilio* radial growth and temperature during the onset of the growing season. Indeed, the growth of *N. pumilio*, the dominant subalpine tree in the Andes, is particularly sensitive to temperature variations (Donoso 1993). The negative relationship between NDVI and precipitation reflects the reduction in solar radiation due to higher cloud cover and the lower temperatures recorded in the temperate forests during precipitation events (Mao and others 2012; Knapp and Smith 2001; Lavergne and others 2015).

NDVI is a tool commonly used to advance in our understanding of vegetation dynamics. Gaitán and others (2014) compared several satellite-derived vegetation indices over the arid/semiarid Patagonian steppes and found that NDVI is a good predictor of functional and structural ecosystem attributes such as vegetation basal cover, species richness, infiltration and nutrient cycling. It is important to note that other indices such as EVI (enhanced vegetation index) have proven to be advantageous over NDVI in regions with large biomass, where NDVI tends to saturate (Huete and others 2002). On the Chilean sector of Chiloé (42°–43° S), Lara and others (2018) have observed that EVI better captures seasonal vegetation cycles than NDVI. However, Olivares-Contreras and others (2019) show that the NDVI is able to recognize subtle differences in forest greening, observing positive trends in greening at maritime-influenced forests and negative at the continental part of the Chilean Aysén region between 45° and 48° S. These findings indicate that future studies of the relationships between climate and large-scale plant productivity should be based on more than one vegetation index derived from satellite imagery.

CONCLUSIONS

The recent development of a high-spatial-resolution climate data grid (Bianchi and others, 2016) offers for the first time, the possibility of exploring the spatial–temporal relationships between the patterns of variations in climate and NDVI over northern Patagonia. Our study reveals direct relationships between variations in climate and NDVI at some ecosystems in northern Patagonia, but complex interactions at others with less marked or absent annual cycle in precipitation. Both precipitation and NDVI show their maximum annual amplitudes over the Mediterranean region in the northwest. In these biomes, NDVI is positively related to spring temperatures. On the contrary, in the arid and semiarid biomes east of the Andes, both precipitation and NDVI show weaker annual cycles and less-consistent relationships. However, in the relatively warmer and drier Monte biomes, seasonal variations in NDVI and precipitation are closely connected.

Our results provide insights on NDVI's intricate responses to regional and subcontinental climate variations. For some biomes, the specificities of the relationships between climatic variations and the functional properties of each ecosystem open the possibility of using this information as predictive tools of vegetation productivity. In steppe ecosystems, plant productivity is preceded by variations in rainfall a few months earlier, which is a valuable information for anticipating livestock management in these landscapes.

The climatic changes predicted for North Patagonia in relation to Global Warming are going to introduce important variations in the relationships here documented (see Lara and others 2018), so high-resolution spatial studies between variations climatic and NDVI should be continued, incorporating, as far as possible, the occurrence of extreme climatic events and their particular impacts on different Patagonian biomes.

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