DYNAMIC VEGETATION ANALYSIS: PHENOLOGICAL BEHAVIOUR AND PHENOLOGICAL PATTERN

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ABSTRACT

The concepts of phenological behaviour (mapping vegetation dynamics), and phenological pattern (actual foliar phenology), both obtained from the time-series analysis of monthly NOAA-AVHRR NDVI GAC images, are illustrated for the vegetation of Mendoza province (Central Western Argentina). A Fast Fourier Transform algorithm was used to decompose the series into dynamic parameters: mean NDVI, amplitude (maximum NDVI variability) and phase (time from start of cycle to maximum NDVI) for different periods. Mean NDVI, amplitude for 9, 3 and 1 year and phase for 1 year were selected. A classification was made based on these five bands with larger information (inter- and intra-annual variability), achieving a map of 18 areas of phenological behaviour. This map is related to ecosystems and vegetation units. The phenological pattern is a modelled monthly NDVI curve that describes the functioning of vegetation (at a pixel level), month by month during an average growth cycle and allows understanding its geographic variations; it is modelled with 11 FFT parameters, five of which are common to classification bands. The phenological pattern was modelled for 17 vegetation units in four extensive ecosystems. The map contributes dynamic elements to the regional study of vegetation, generating a new zonation explained by variables that determine vegetative growth. The overall phenological pattern of Mendoza vegetation responds to an annual cycle with localized weak bimodal patterns. Patterns of low winter-summer contrast correspond to xeric climate conditions, expressing the vegetative peak at the end of the summer; water availability enhances this contrast, shortening the time of maximum vegetative expression.

INTRODUCTION

Plant phenology analyzes the timing of vegetation activity as an answer to meteorological conditions. At regional scale, the duration and intensity of leaf display (foliar phenology) is important because it provides an overview of vegetation whose temporal changes may be detected and measured by NOAA-AVHRR NDVI images (1). The relation between the normalized difference vegetation index (NDVI) and the fraction of photosynthetic active radiation (PAR) (2) explains the relationship between NDVI images and photosynthetic activity of vegetation (foliar phenology) (3). Therefore, variations in foliar phenology along several growth cycles may be recorded and studied through time series of NDVI images (4). A synthesis of the temporal series, incorporating inter-annual and intra-annual variability, allows a description in dynamic terms. In this relation,(5) define the functional ecosystem types for temperate South America using attributes derived from the seasonal dynamics of NDVI: the annual integral (primary production), and two attributes to detect the seasonality of primary production: relative annual range of NDVI, and date of maximum NDVI. Other authors simplify the information through use of the Fast Fourier Transform (FFT) (6,7), where the attributes describing the series are mean NDVI, and amplitude and phase for each period (Fourier parameters). This method was developed to map “isogrowth” zones of Africa and South America (8). The information summarized by Fourier parameters gives a measure of vegetation ‘quality’ in dynamic terms, explains foliar seasonality (9) and allows identification of units with different phenological features called vegetation-soil-climate complexes (10).

The objective is illustrating the concepts of phenological behaviour, vegetation dynamics mapping, and phenological pattern, the rhythm of foliar phenology along the growing cycle. Both attributes obtained from the time-series analysis of monthly NOAA-AVHRR NDVI GAC images (11).

METHODS

Fast Fourier Transform

Satellite data is a series of 9-year monthly NOAA-AVHRR NDVI GAC images (7.6 x 7.6 km) from July 1982 to June 1991 (108 images). The time series analysis was performed applying the special so-called Mixed Radix Fast Fourier Transform algorithm developed at the National Aerospace Laboratory (NLR) in the Netherlands (6, 7). The FFT algorithm allows decomposing, for every pixel, the complex NDVI series into simpler periodic signals: an average signal plus the N/2 sinusoidal components with N being the time series length expressed as number of images (6, 8). The resulting 108 new images were: mean NDVI for the whole series (amplitude at frequency = 0) and the periodic components, amplitude (54 images) and phase (53 images) both associated with a period ranging from 9 years to 2 months; i.e. for 9; 4.5; 3; 2.25; 1.8; ..... ; 0.167 years. The amplitude represents a measure of the maximum NDVI variability at a given period, and phase is the time lag between this maximum and the initial point of the series.

Selection of the most relevant FFT parameters was made according to the amplitude variance contribution of each period to total amplitude variance. Total variance of the time series was calculated as the sum of variances of the individual terms as follows (12):

$$\text{Total variance} = \sum_{l=1}^{n} \frac{amplitude_j^2}{2}$$

where *j* is each term (period) in the series and *n* is the total number of terms. The relative contribution of each term is computed by dividing individual variance by the total variance.

Map of phenological behaviour

Classification was made of the most relevant FFT parameters that explain together at least 80% of the total variance, these bands were: mean NDVI, amplitude for 9, 3 and one-year periods, and phase for a one-year period. The classification was unsupervised, because of the lack of phenological information at regional level, by applying the iterative self-organising data analysis technique (ISODATA/ERDAS). An 18-class map was built, clusters were assessed through statistics, histogram, euclidean distance, and geographical distribution. Considering that Fourier parameters provide a new approach to the study of phenological behaviour at regional scale (9) and that the classification is based on temporal vegetation dynamics, over nine vegetative cycles the resulting map was called phenological behaviour map. Phenological behaviour is described by average values of FFT parameters for each class, within the heterogeneity inherent to each class, and expresses the level of vegetation activity and its intra- and inter-annual variability.

Map of ecosystems and its comparison with the map of phenological behaviour

The magnitudes of the ecosystems of Mendoza determine the homogeneity of biotic and abiotic factors (13). First-order ecosystems (ecobiomes) are Andean, Puna, Patagonia and Monte systems. Subordinate to them are second-order ecosystems or mesoecosystems (regional scale), to which third-order ecosystems (subregional scale) are subordinate. The description of vegetation units (14) corresponds to these two ecosystem levels, and the factors with which they are identified and designated are geomorphological (13). For this reason, a geomorphological map (15) was digitalized, identifying the basic units (geoforms) of second- and third-order ecosystems. To analyze the relationship between classes of phenological behaviour and ecosystems, the corresponding maps were crosschecked to detect percent coincidences of classes (SUMMARY-ERDAS).

Association of classes of phenological behaviour with vegetation units

The relationship between the phenological behaviour and the vegetation maps (14) was analyzed by sampling both maps, every 10 minutes in latitude and longitude; results guide the selection of vegetation units to be characterized by their phenological patterns.

Phenological pattern (monthly NDVI curve)

Decomposition of the complex time series of NDVI images into simpler periodic signals allows performing the inverse process and modelling the monthly NDVI for one year with only those periodic components conveying the most biological information disregarding noise. The resulting modelled curve shows the rhythm of phenology and we call it phenological pattern (11). The modelled annual NDVI curve, I(*t*), was calculated using the following equation (10):

$I(t) = \sum_{n=1}^{N} \left[A_n * \cos(\omega_n t + \varphi_n) \right]$ where: *I(t)* = reconstructed time series (with t= 1,…12 as first year of the series); A_n = amplitude value; φ_n = phase value *in radians*; *n* = index indicating periods; ω = $2\pi/n$ = frequency; we have considered the frequencies corresponding to periods: 9, 4.5, 3, 1 and 0.5 years, in addition to frequency 0 whose amplitude is the mean NDVI value; *t* = time, 1 to 12 months (from July till June).

The contribution of the six-month period was also considered despite one cycle a year is dominant in Mendoza. Thus, the phenological pattern was modelled with 11 FFT parameters, five of them common to classification bands. Phenological pattern of best represented vegetation units in four extensive ecosystems was modelled. In 19 representative sites the FFT parameters were extracted; each curve corresponding to one pixel.

RESULTS

Map of phenological behaviour

The most relevant FFT images were selected for classification: mean NDVI, amplitude for 9, 3 and one-year periods and phase for a one-year period (Figure 1).

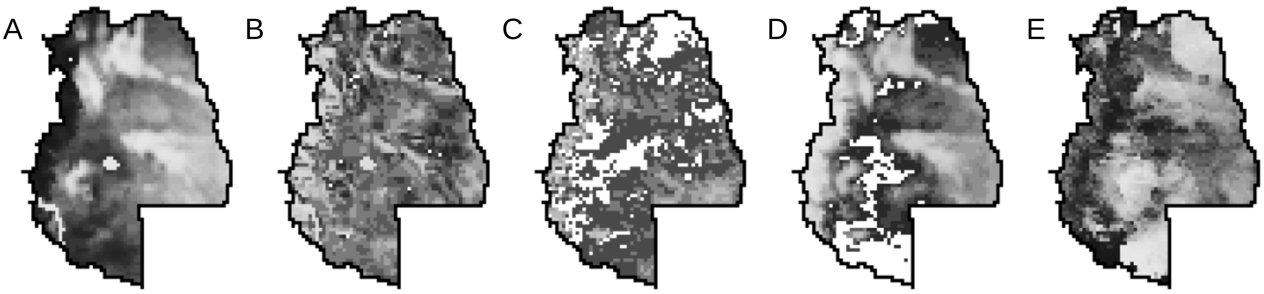

Figure 1: The Fourier images selected for the classification: A- Mean NDVI, B- Amplitude for 9 years, C- Amplitude for 3 years, D- Amplitude for 1 year, E- Phase for one year. Gray values represent DN values, i.e. darker gray corresponds to low DN values and lighter gray stands for higher Fourier parameter values. Where the variable takes a 0 (≤ 0.5) value, it gets confused with the background and looks like being "perforated".

The phenological behaviour map is presented along with the map of second- and third-order ecosystems (Figure 2). Each class of phenological behaviour is described by the mean value for each parameter (11).

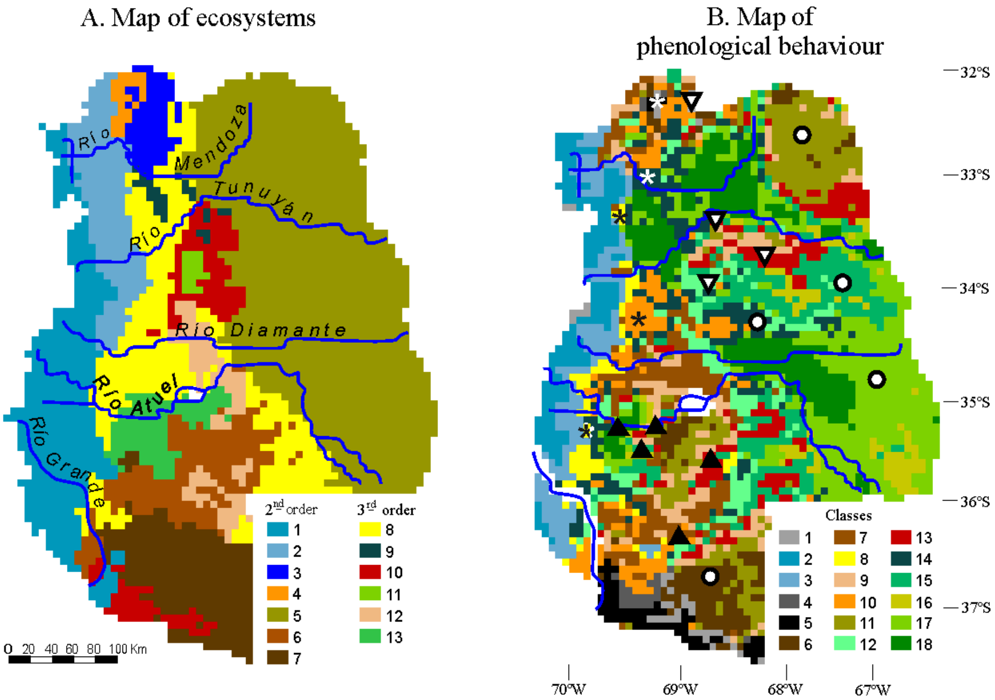

Figure 2: Maps of ecosystems and of phenological behaviour for Mendoza Province. A. Map of ecosystems. Second-order ecosistemas: 1- Cordillera Principal, 2- Cordillera Frontal, 3- Precordillera, 4- Uspallata Valley, 5- Plain, 6- N Payunia, 7- S Payunia. Third-order ecosystems: 8- Piedmonts, 9- Hillocks, 10- Badlans, 11- Guadal Plateau, 12- Bloque de San Rafael, 13- Bolsón de Llancanelo and marshes. B. Map of phenological behaviour with sites sampled for modelling phenological pattern of vegetation units of: mountains (*), bolsones and badlands (▽), Travesías (○) and Payunia (▲).

Phenological behaviour and ecosystems

The percent distribution of each class of phenological behaviour in the ecosystems shows ecosystems with many to few classes; this is illustrated for two classes (Table1) (11).

Table 1: Percent distribution of geographic correspondence of two classes of phenological behaviour with each ecosystem (Adapted from 1).

Class	Second-order ecosystems							Third-order ecosystems					
	1	2	3	4	5	6	7	8	9	10	11	12	13
10	13.9	18.2	14.6	3	2.4	3.6	12.7	22.4	0	3	0.6	5.5	0
17	1.2	1.6	0.8	0.4	78.1	1.4	0	12.6	1.2	0.8	0	0.8	1

Phenological pattern for diverse vegetation units

Phenological patterns are presented according to the grouping of 17 vegetation units (14) (Figure 3); each group is identified with different symbol in the map (Figure 2), where the place of the symbols marks the pixel selected for modelling (19 sites).

Mountain vegetation: Develops in the west region of Mendoza on two great natural systems: Andean and Puna systems; vegetation units occupy different altitudinal belts whose differences are reflected in a varying phenological pattern ranging from vegetation covered with snow (June-September, to evergreen vegetation without snow cover that increases its activity in summer, and to vegetation with an almost constant foliar phenology (Figure 3A). Detailed description in (11).

Vegetation of "Bolsones"(closed valleys) and Badlands: Occurs in the great Monte natural ecosystem (13); vegetation exhibits particular features, but the common denominator is the aridity shown by phenological curves (Figure 3B). The winter NDVI is similar for all; differences occur between October and March (showing the maximum vegetative growth in different months) and are determined by the ecosystem and by water availability.

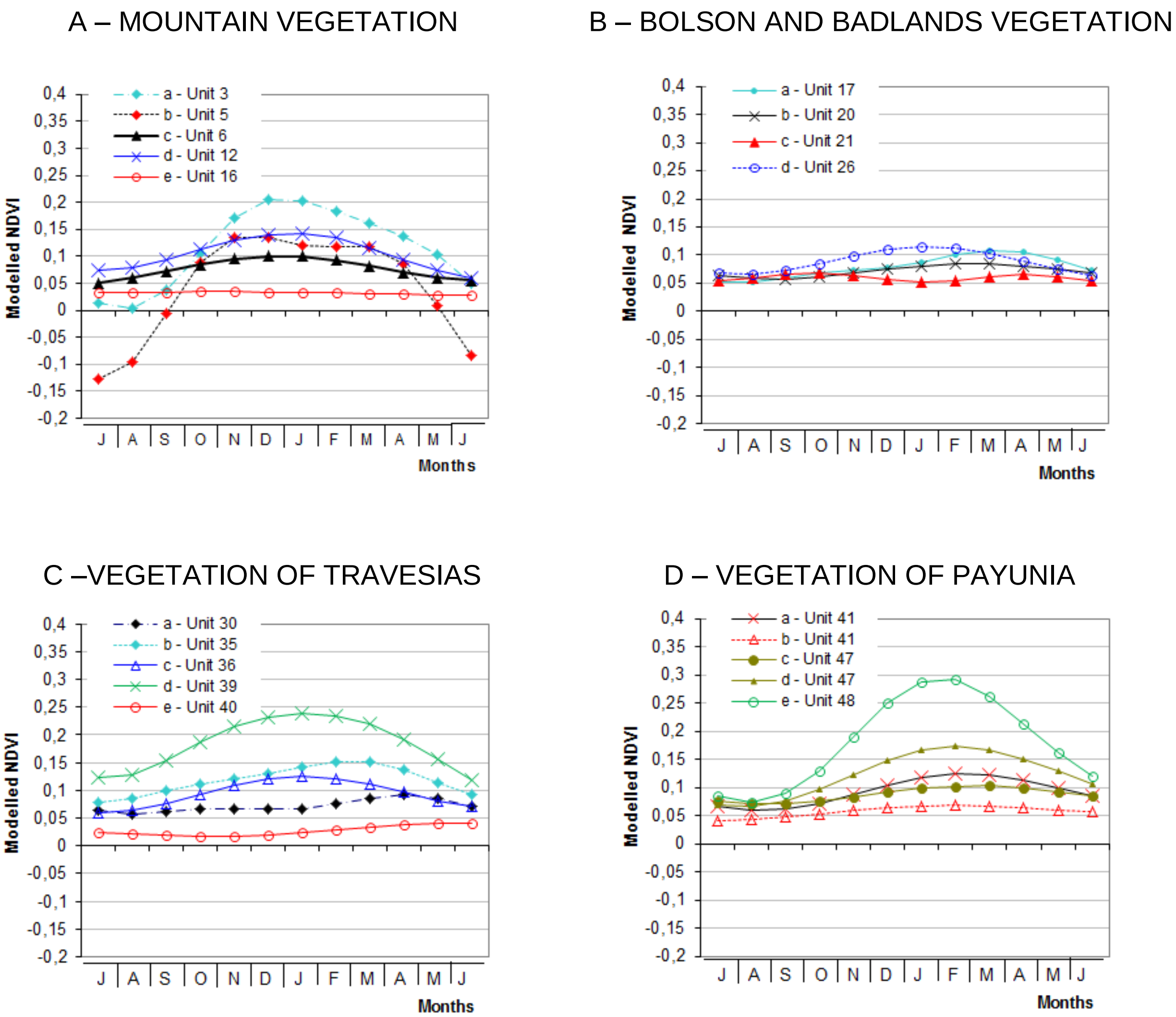

Figure 3: Phenological pattern of 17 vegetation units in Mendoza Province.

Vegetation of Travesías: Travesías are extensive plains lying in the east of the province, which are crossed by the Tunuyán and Diamante rivers that divide the region into three travesías: Guanacache, Tunuyán and La Varita (16) (Figure 2A). Chachahuén Travesía is the southernmost one and is located on a volcanic tableland. Each of these areas has different environmental conditions, which is reflected in the contrasting phenological pattern (Figure 3C).

Vegetation of Payunia Volcanic Region: Payunia is encompassed within the great Patagonia Ecosystem and is covered by an open shrubland (13). The vegetation of two ecosystems related to water availability is also analyzed, Llancanelo Watershed and Atuel Marshes (Figure 3D).

CONCLUSIONS

Fourier Parameters

The Fourier images selected for the classification (Figure 1) contributed the most to total amplitude variance and reflected behaviours that were coherent with current vegetation. Amplitude for 9 and 3 years (Figure 1B, C) reflects inter-annual variability of rainfall or river flow giving supplementary information for arid areas. Instead, the most humid areas focused the information on the one-year period that reflects intra-annual variability or seasonality. For Africa, amplitude for 9- and 4.5-year periods reflect inter-annual variability (8) and it is suggested (9) that areas with high amplitude for 9 years (Kalahari) could denote higher resilience against climate variations. FFT parameters are statistically independent and convey complementary information (17).

Phenological behaviour and phenological pattern

The objective of phenological behaviour is a map based on temporal vegetation dynamics, whose classes express (in spatial manner, within the heterogeneity inherent to each class) the level of vegetation growth and its intra- and inter-annual variability. In areas with two cycles per year, also amplitude for 6 months should be included (8).

The objective of the phenological pattern is modelling monthly NDVI rhythm without noise and comprising intra- and inter-annual variability; the result is a curve modelled with 11 FFT parameters, five of them are common to the classification bands applied in the phenological behaviour map. The phenological pattern describes the functioning of vegetation at regional scale and shows the way in which vegetative activity varies, month by month, through changes in foliar phenology, throughout a year, for a certain site.

The classes of phenological behaviour are conceptually equivalent to the classes of isogrowth zones of Africa and South America (8) and to vegetation-soil-climate complexes (10) and the phenologycal pattern was named as modelled yearly NDVI curve or simulated NDVI (8).

Phenological behaviour map

Spatial continuity of classes is important because changes in foliar phenology are gradual and respond to climate, unless very outstanding topographic (hills) or edaphic (wetland, irrigation) conditions determine a rapid change. In comparing, by sampling, the classes of phenological behaviour with the vegetation units (14), there is no univocal relationship at regional level, a vegetation unit has several corresponding classes of phenological behaviour because both maps were made with different criteria: temporal dynamics of vegetative growth for the first and regional-scale physiognomic-floristic traits and ecosystem features for the second (13). Also, in these images, each pixel represents 57.8 km^2 and involves different communities, and the NDVI signal responds to the foliage features of the spatially dominant vegetation. Consequently, the difference in the generation of each map explains the dynamic variations that the same vegetation unit exhibits for different climates and ecosystems, such as unit 41 (Figure 3D_a, b). Similar results were found (10, 5).

Phenological behaviour and ecosystems

The diversity of Mendoza ecosystems determines a varied response from regional foliar phenology (Table 1). The largest ecosystems, although having a higher number of classes sometimes show strong concentration (>40%) of a phenological class (Cordillera Principal, plain and S Payunia). Ecosystems determine the dynamic features of vegetation, with low vegetative growth in ecosystems with pronounced relief and dry soils where to low rainfall is added strong runoff (S Payunia and badlands); the highest photosynthetic activity develops in plain and piedmonts, ecosystems with lower slopes that favour infiltration.

Phenological patterns

The diverse phenological patterns characterizing Mendoza reflect the contrast between vegetation of arid areas where the dynamics of plant cover, despite being very low, show different nuances depending on the ecosystem (Figure 3: A_e; B_c; C_e; D_b) and vegetation with higher water availability where winter to summer changes in photosynthetic activity are contrasting (Figure 3: C_d; D_e). There are phenological patterns which are almost symmetrical (Figure 3: A_d; B_d; C_c) and others distinctly asymmetrical which reflect their peak vegetative growth at the beginning (Figure 3: A_a) or end of summer (Figure 3: B_a; C-b). Phenological patterns can also reflect a certain bimodality resulting from the two times in the year where vegetative growth is higher (Figure 3: A_b; B_c); explained the last pattern (a peak in October and a high value in April) by northern Paramillo climate model (18) that indicates a cold, humid winter in June-July and a humid summer in late February-March; these are special situations in the context of the patterns for Mendoza where only one peak per year predominates.

The variety of phenological patterns shows that phenological characterization of vegetation units is not univocal, for the same unit may display several phenological patterns as in units 41 and 47 (Figure 3 D_a-d). The vegetation units established for Mendoza (14) were defined by their physiognomy and dominant floristic composition, showing variations from topography, soil, use, etc., that is, they present heterogeneity (internal variability). The phenological pattern expresses year-round changes in plant cover, for this reason the same vegetation unit can be dynamically described by more than one phenological pattern, depending on its geographical location. In this sense, the phenological pattern could be used to characterize gradual changes in plant cover along a humidity gradient or a gradient of use. In this manner, the phenological pattern, and the phenological behaviour map, provides supplement information to the map of vegetation units.

Fast Fourier Transform enables a simple and clear analysis of the time series of vegetation index images. Periods of 9 and 3 years gather information about inter-annual variability and the one-year period explains intra-annual variability or seasonality. Depending on the area, periods of 4.5 and 0.5 years may also be important.

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