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Seasonal patterns of Mediterranean evergreen woodlands (Montado) are explained by long-term precipitation

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ABSTRACT

In temperate areas, vegetation seasonality and phenology have been mostly associated with temperature changes both in space and time. In drylands, where water is the most limiting factor, we expect that they strongly respond to water availability. The degree to what that response depends more on precipitation that occurred when vegetation seasonality and phenology were measured, or on the long-term precipitation, is not fully known. We hypothesize that in drylands, long-term precipitation better explains the patterns of seasonality and phenology metrics than concurrent one, due to constrains imposed by ecosystem legacy. We correlated long-term precipitation (30 years normal) and concurrent precipitation (12 years) to several seasonal metrics (MODIS, average of 12 years) measured in a savannah-like system, Mediterranean evergreen woodlands, located in southwest Europe (Portugal). We observed that seasonal metrics of productivity and phenology were more significantly related with long-term precipitation than with concurrent precipitation. Comparing the extremes of our gradient we found that drier areas (c. 496 mm long-term annual precipitation) showed average growth cycles of annual plants 25 days shorter and ended 16 days sooner than more rainy regions (c. 739 mm). Evergreen vegetation productivity was shown to be c. 30% lower in drier areas. Moreover, productivity and phenology metrics were non-linearly related to the long-term precipitation, suggesting both are particularly constrained below 600–650 mm. These results suggest a memory effect in the response of vegetation to climate, most probably associated to legacies on soil characteristics and on plant community. It also indicates the existence of ecosystem response thresholds in vegetation's response to precipitation along ecosystem transitions. Overall, this method can be used to track ecosystem services over space in drylands and for managing ecosystems for both mitigation and adaptation to climate change.

1. Introduction

Vegetation in drylands, i.e., tropical and temperate land areas with an aridity index lower than 0.65 (UNEP, 1992), is responsible for most ecosystem services related to agriculture, including grazing and cultivation (Millennium Ecosystem Assessment, 2005). Vegetation in drylands is also responsible for other services such as land protection from desertification and land degradation (Garcia-Fayos and Bochet, 2009), which already affects ~20% of worldwide drylands (Reynolds et al., 2007). Water scarcity controls spatial and temporal vegetation patterns in drylands (Hoepfner and Scherer, 2011). This effect will be exacerbated due to increasing frequency and intensity of drought events associated with ongoing climate change forecasts (IPCC, 2007; Maestre et al., 2012).

Many drylands are occupied by woodlands or savannahs, where scattered trees and shrubs are mingled with pastures. In drylands, interaction between environmental drivers (Maestre et al., 2012) and complex temporal patterns of vegetation in response to meteorology (Le Houerou, 2001) prevents a straightforward prediction of climate change effects on vegetation. This is even more problematic due to the co-existence of evergreen vegetation and annual plants (Higgins et al., 2011). Under such conditions, the use of seasonal metrics can be more adequate than NDVI alone. Seasonal metrics (Zhang et al., 2003) characterize recurring events in vegetation and

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can be used as a proxy of vegetation phenology and productivity cycles (Joffre et al., 1999; Pumo et al., 2010). The annual response of vegetation to annual changes in water availability has already been addressed in many works (De La Maza et al., 2009; Knapp et al., 2008; Miranda et al., 2011; Peñuelas et al., 2004; Reynolds et al., 2004; Shinoda et al., 2010). However, to predict the response of vegetation to climate change, a long-term analysis, both of vegetation response and climate, is required. The need for long-term studies arises from the fact that vegetation in drylands is physiologically very well adapted to drought events (Li et al., 2009). Drylands species are known to be resilient to droughts events regarding phenology and productivity (Ivits et al., 2014). Moreover, vegetation in drylands often exhibits persistent seed banks (Peco et al., 2003), i.e., seeds that persist in the soil for a few years, only germinating with favourable conditions. This resilience to drought and persistent seed bank may delay vegetation response to recent climate changes. Moreover, long-term seasonal metrics were successfully used to map the distribution of biomes in South-Africa (Wessels et al., 2011), highlighting the importance of these metrics to study the long-time patterns of vegetation and its relationship to climate. The study of the long-term responses of this vegetation to climate is also important to understand its resilience and resistance to the advance of the desertification and land-degradation processes, a long-term process (Brandt and Thornes, 1996).

Here we focused on the response of drylands vegetation seasonal metrics (12 years average) to precipitation. More specifically, we tested if long-term precipitation (30 years average) explains better the spatial patterns of productivity and phenology metrics than concurrent precipitation (12 years average). This was evaluated over a spatial precipitation gradient on drylands, between semi-arid and dry-sub-humid climates, in southwest Europe, an area occupied by Mediterranean evergreen woodlands.

Table 1
Vegetation seasonal metrics (Jönsson and Eklundh, 2004; Wessels et al., 2009), calculated from the analysis of NDVI variation over time, and their ecological interpretation.

Seasonal metrics	Ecological interpretation
Phenology metrics	
Season-start	Date of the beginning of growing season (Julian days)
Season-end	Date of the end of growing season (Julian days)
Season-length	Duration of growing season (number of days)
Mid-season time	Date for which the peak of the growth (i.e., max NDVI) occurs
Productivity metrics	
Rate-growth	Maximum growth rate (NDVI value per day).
Rate-senescence	Maximum senescence rate (NDVI value per day).
Amount of evergreen vegetation	Minimum annual NDVI values, a proxy of the amount of the evergreen vegetation (NDVI values) (base-NDVI)
Annual-amplitude	Difference between base-NDVI and maximum-NDVI, a proxy of the amount of annual vegetation
Maximum-NDVI	Maximum NDVI of the season, a proxy of maximum amount of vegetation on the sampling point
Annual-productivity	Cumulative NDVI values throughout the growing season, proxy for all vegetation net primary productivity (small integral)
Overall-productivity	Same as annual productivity but with cumulative start at base-NDVI, proxy for annual vegetation net primary productivity (large integral)

2. Materials and methods

2.1. Study region and sampling design

This study was developed in southwest Europe (Alentejo, Portugal), under semi-arid and dry-sub-humid climate (1960–1990), where the effects of future climate alterations are expected to be strong (Arguez et al., 2007; Costa et al., 2008). One example of recent climate changes in the area is the occurrence of more events of extreme temperatures in spring and summer from 1976 to 2006 (Santo et al., 2014) and reduction in precipitation in February and March from 1961 to 2009 (Guerreiro et al., 2014). Mediterranean evergreen woodlands (*Montados*) in the area are dominated by holm-oak (*Quercus ilex* L. subsp. *rotundifolia*), a species with high resilience to drought events (Vaz et al., 2010) and a key species to prevent desertification and land-degradation (Príncipe et al., 2014).

The National Forest Inventory 2005/06 (AFN, 2010) was the basis for sampling point selection because (i) it is defined in a systematic way and (ii) the type of vegetation occupation for each point was verified. Sampling points were selected from the c.336,000 available, after homogenizing for a number of environmental variables, to avoid confounding effects of other environmental factors.

From all possible points available, the sampling points were chosen by several criteria: (1) "holm-oak woodland" land-use type (the focus of this work, because it is the dominant land-cover on the region); (2) within drylands (with semi-arid and dry-sub humid climate, 1960–1990), an altitude between 150 and 300 m and inclination smaller than 5° (to avoid the effects of a steep orography), with a luvisol soil type that is dominantly acidic (pH < 6.5) and dominated by sedimentary and metamorphic lithology (the dominant soil characteristics of the region); and for which there was no record of fire. This homogenization resulted in 2730 sampling points (Fig. 1). In these sampling points, we evaluated precipitation and phenology metrics (Table 1).

It is important to highlight that homogenization of the land-use type allowed the reduction of two effects: (i) the edge-effect; and (ii) land-use intensity effect. Edge effect could result from non-homogenous land-cover types on the edges of sampling sites.

This was avoided not only by ensuring a homogenous land-cover but also by using a circular sampling area smaller than the national forest inventory sampling area.

Regarding the effect of land-use intensity, caused mainly by grazing, was avoided by using the same type of land-use, because most holm-oak woodlands in the region have the same type of extensive, low-intensity grazing. Moreover, we further tested the possible influence of land-use intensity by calculating the density of livestock units at the civil parish level, using the national agriculture census (INE, 2011). We observed no significant correlations between the variables of interests (phenology and productivity metrics) and cattle density (for $p < 0.05$). Thus, we consider that the influence of land-use intensity on the results was similar for all sampling points.

2.2. NDVI data and precipitation

The NDVI data set was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) by NASA Land Processes Distributed Active Archive. The MODIS data were acquired between February 2000 and December 2012. The MODIS Terra Vegetation Indices (MOD13Q1) with 250 m spatial resolution are produced by NASA using multi-temporal composites generated using the maximum NDVI value every 16 days as previously described by (Huete et al., 2002). This procedure aims at minimizing the effects of clouds and other atmospheric interferences in order to produce more