DROUGHT IMPACTS ON VEGETATION ACTIVITY, GROWTH AND PRIMARY PRODUCTION IN HUMID AND ARID ECOSYSTEMS

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ABSTRACT

We have evaluated the response of the Earth biomes to drought using a new global dataset that captures drought effects on vegetation at various time scales. We show that arid and humid biomes are both affected by drought, and that the time scale on which droughts most intensively affects vegetation plays a key role in determining the sensitivity of biomes to drought. Arid biomes respond to drought at short time scales because plants have mechanisms allowing them to rapidly adapt to changing water availability. Humid biomes also respond to drought at short time scales, probably because there plant species show a poor adaptability to water shortage. Sub-humid biomes respond to drought at long time scales because plants are adapted to withstand water deficit, but they lack the rapid post-drought recovery observed in arid biomes.

Key words: Time-scales, Drought index, drought vulnerability, Standardized Precipitation Evapotranspiration Index.

RESUMEN

En este trabajo se evalúa la respuesta de los diferentes biomas terrestre a la sequía mediante una base de datos nueva que captura el efecto de la sequía sobre la vegetación a diferentes escalas temporales. Se ha comprobado que los biomas característicos de zonas áridas y húmedas se ven afectados por la sequía, y que la escala temporal de la sequía juega un papel clave al determinar la sensibilidad de los biomas a la sequía. Los biomas áridos responden a las sequías medidas a escalas temporales cortas, debido a que las plantas tienen mecanismos que les permitan adaptarse rápidamente a la disponibilidad de agua. Los biomas húmedos también responden a la sequía a escalas temporales cortas, probablemente debido a que las especies ubicadas allí muestran una mala adaptación a la escasez de agua. Los biomas subhúmedos responden a la sequía a escalas de tiempo más largas, porque las plantas están adaptadas para soportar el déficit de agua, pero carecen de la rápida recuperación observada tras la sequía en los biomas áridos.

1. INTRODUCTION

Drought is one of the main drivers of the reduction in terrestrial aboveground net primary production (ANPP) (Webb *et al*., 1983). World ecosystems differ in the sensitivity of aboveground activity and productivity as a response to drought variability (Knapp and Smith, 2001; Fang *et al*., 2005). However, the sensitivity of terrestrial vegetation to drought is largely unknown and the subject of scientific debate (Knapp and Smith, 2001; Meherali *et al*., 2004), particularly in humid regions (Samanta *et al*., 2010). Understanding the response of vegetation to drought is a crucial challenge, nevertheless, studies in this area are difficult because of the problems associated with drought quantification (Vicente-Serrano *et al*., 2011), the varied response of vegetation types to drought (Chaves *et al*., 2003; McDowell *et al*., 2008), and the synergistic effects of recent warming and drought on plant ecosystems (Breshears *et al*., 2005).

The quantification of drought severity is a very difficult task since we identify a drought by its effects on different systems (agriculture, water resources, ecosystem, etc.), but there is not a physical variable we can measure to quantify drought intensity. In addition, it is very difficult to identify the moment when a drought starts and ends, and to quantify its duration, magnitude and spatial extent (Wilhite, 2000). Furthermore, the intrinsic multiscalar nature of drought introduces another element of uncertainty to identify drought impacts on global biomes. In recent years the concept of time scales has been widely used by drought scientists (Hayes et al., 1999). Drought impacts on vegetation may be time-dependent given the fact that the period from the occurrence of a water shortage to the decrease of vegetation activity and growth differs noticeably as a function of the bioclimatic conditions and the vegetation types (Vicente-Serrano, 2007; Pasho *et al*., 2011).

In this study we focus on the analysis of the drought impact on worldwide vegetation stressing the importance of considering the drought time-scale to quantify the drought impacts on a variety of vegetation types and biomes. For this purpose, we used the recently developed Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010), which is a site specific probabilistic indicator of deviations from average moisture conditions summarized at various time scales. Then, we assessed at a global scale how the SPEI affected primary production, vegetation activity and tree growth by using three different sources of information: field ANPP, remote sensing images and tree-ring width series.

2. DATA AND METHODS

To quantify drought severity on different time-scales, we used monthly data of the SPEI at a spatial resolution of 0.5º and time scales ranging from 1 to 24 months obtained from the SPEIbase (Beguería *et al*., 2010) (http://sac.csic.es/spei/download.html). The quantification of the temporal variability of vegetation parameters related to the growth, activity and production is very difficult. Therefore, to give more robustness to our results we have used two different datasets, which provide information on leaf photosynthetic activity and tree radial growth across the world. The first dataset was based on annual tree-ring width data, obtained from the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html). We selected the tree-ring width series with at least

25 years of data within the period 1945-2009, in which the climate records have more quality. A total number of 1846 site chronologies were selected and analysed.

Finally, in order to obtain a wider spatial perspective over the entire earth, we have included time series of vegetation indices obtained from long term satellite imagery. We used the NOAA Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) (Tucker *et al.*, 2005) from July 1981 to December 2006, at a resolution of 0.1º, (www.glcf.umd.edu/data/gimms/). Improved vegetation indices from the Moderate Resolution Imaging Spectroradiometer (MODIS) were also used to replicate the GIMMS-NDVI data for the period of available information. Monthly composites of the Enhanced Vegetation Index (EVI) (Huete *et al*., 2002) and the NDVI were obtained from https://lpdaac.usgs.gov/content/view/full/6665. Finally, to characterize the spatial distribution of the world biomes we used the Holdridge classification systemand the Global Land Cover Map (GLOBCOVER) developed by the European Spatial Agency from the ENVISAT satellite mission (http://ionia1.esrin.esa.int/) was used with the purpose of masking the urban areas and irrigated lands from the analysis. The 0.5º SPEI data series were interpolated to 8 km for the 1981-2006 period to match the spatial resolution of the GIMMS-NDVI and to 5.6 km for the 2001-2009 to match the MODIS vegetation indices.

A pixel per pixel impact of the SPEI interannual variability on vegetation activity and tree growth was assessed by means of parametric correlations using the Pearson coefficient and considering a significance threshold of $\sigma < 0.05$. Twelve series of the GIMMS-NDVI (one per month) were obtained per pixel and each one was correlated (Pearson coefficient) to the monthly 1- to 24-month SPEI series of the pixel for the period 1981-2006. Therefore, for each grid cell of 8 km x 8 km, we obtained 288 correlation values (24 for each month of the year). Given that global phenology shows large seasonal variability and different regions present peaks of vegetation activity and growth in different months, the monthly correlations were summarised seasonally and annually. The same methodology was applied to the MODIS EVI and NDVI datasets. The influence of droughts on tree growth was assessed by means of the same procedure. Maximum correlations and corresponding time scales were mapped and retained for further analyses. Maximum annual and seasonal correlations between the GIMMS and MODIS vegetation indices and the SPEI, and maximum annual correlations between tree-ring width records and the SPEI were summarised according to the different biomes included in the Holdridge classification. For this purpose, a quantification of the average aridity conditions in each biome were summarised using precipitation and potential evapotranspiration.

3. RESULTS AND DISCUSSION

Drought influence on vegetation changed markedly with season and among regions. This is clearly illustrated in Figure 1, which is based on the analyses of the NDVI-GIMMS dataset. For instance, in the Canadian prairies drought determines, to a large extent, vegetation activity during the boreal summer, and the vegetation response seems to be insensitive to the drought time scale. However, in other areas (e.g. Argentina) the influence of drought is greatest at long time scales (> 8 months), while in the Sahel its effect mostly occurs at short ones (< 6 months).

In large areas of the world the vegetation activity is mainly driven by drought (Fig. 2). Associations between the SPEI and the GIMMS–NDVI data are particularly strong throughout large regions (e.g., eastern North America, southern and eastern South America, the Mediterranean Basin,

the Sahel, etc.). Overall, 72% of the vegetated areas of the world show significant correlations between the GIMMS-NDVI and the SPEI. These results were replicated using vegetation indices derived from data from the MODIS satellites (Fig. 3), and tree ring width series (results not shown), showing patterns similar to the one based on the GIMMS-NDVI dataset.
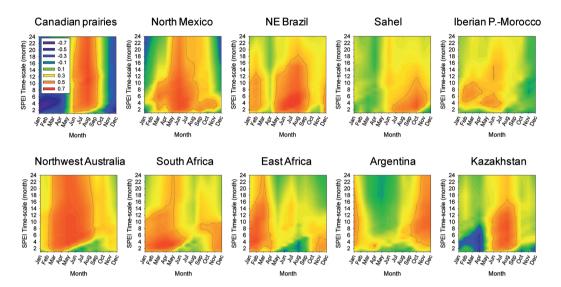

FIG. 1: *Correlations (Pearson coefficient) between the SPEI at time scales from 1 to and 24 months and the GIMMS-NDVI in different regions of the world for the period 1981-2006. Dotted lines frame statistically significant correlations (α < 0.05).*
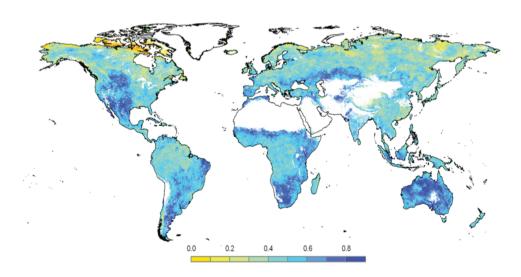

FIG. 2: *Spatial distribution of the correlations (Pearson coefficient, r) between SPEI and GIMMS-NDVI for the period 1981-2006. The values represent the maximum correlation recorded for each pixel, independently of the month of the year and the SPEI time scale. Significant correlations are set at r = 0.39 (α < 0.05).*
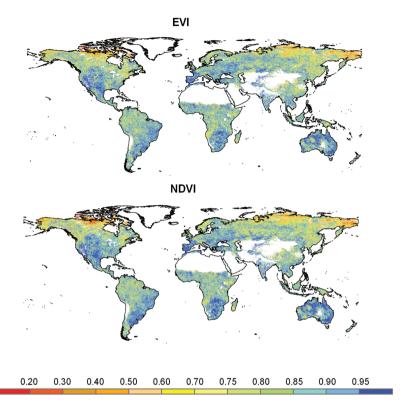
EVI

NDVI

FIG. 3: *Spatial distribution of the correlations (Pearson coefficient, r) between SPEI and MODIS-EVI AND -NDVI for the period 2001-2009. The values represent the maximum correlation recorded for each pixel, independently of the month of the year and the SPEI time scale. Significant correlations are set at r = 0.67 (α < 0.05). Desert and ice areas are masked and not included in the analyses.*

The influence of the SPEI is lower in zones characterized by humid conditions (including tropical rainforests and cool temperate areas of the northern hemisphere) than in those characterized by arid conditions. Although the vegetation activity in humid areas is less determined by drought than in arid areas, drought events in the former also cause a marked reduction of vegetation activity and ANPP (Huxman et al., 2004), as has been observed in the Amazon region, particularly during the droughts recorded in 2005 (Phillips et al., 2009) and 2010 (Xu et al., 2011). Accordingly, the GIMMS-NDVI analysis showed that 78% of tropical and subtropical rainforests are characterized by a significant correlation between the NDVI and the SPEI. This percentage was found to be even higher for the MODIS images obtained for the period 2001–2009 (90.7% for the EVI, and 90.9% for the NDVI). The percentage of surface area showing significant correlations was also high for boreal forests, cool temperate moist forests and rainforests (65.6% for the GIMMS-NDVI, and 85.5% and 84.4% for the MODIS-EVI and MODIS-NDVI datasets, respectively). It is noteworthy that the greater influence of drought on vegetation in arid areas does not imply that plant communities from those areas are more vulnerable to drought than those dominant in humid biomes, as the former are adapted to frequent periods of severe water deficits. Thus, drought vulnerability, i.e. the likelihood that drought permanently impairs plants, is much larger in humid biomes than in arid ones (Maherali et al., 2004).

There is a clear spatial relationship of the world biomes to the impacts of drought on: vegetation activity (Fig. 4a) and tree growth (Fig 4b). Thus, highly developed wet and moist forests of each ecoregion are located in areas with a positive water balance, where the control of vegetation activity by drought is low.
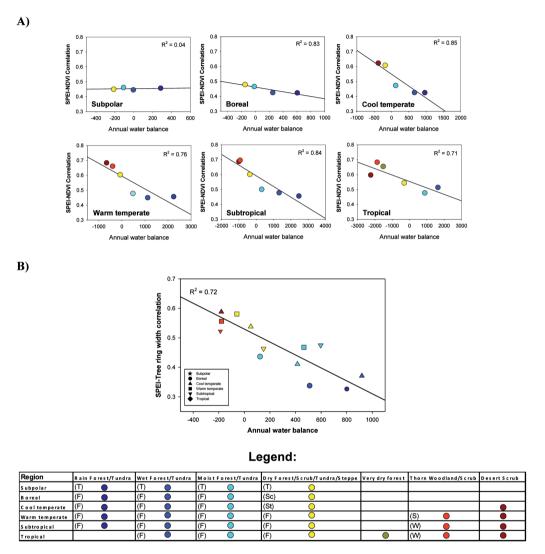
A)

B)

Legend:

Region	Rain Forest/Tundra		Wet Forest/Tundra		Moist Forest/Tundra		Dry Forest/Scrub/Tundra/Steppe		Very dry forest	Thorn Woodland/Scrub		Desert Scrub
Subpolar	(T)	●	(T)	●	(T)	○	(T)	○				
Boreal	(F)	●	(F)	●	(F)	○	(Sc)	○				
Cool temperate	(F)	●	(F)	●	(F)	○	(St)	○				●
Warm temperate	(F)	●	(F)	●	(F)	○	(F)	○		(S)	●	●
Subtropical	(F)	●	(F)	●	(F)	○	(F)	○		(W)	●	●
Tropical			(F)	●	(F)	○	(F)	○	●	(W)	●	●

Fig 4: *A) Relationships between SPEI/GIMMS-NDVI maximum Pearson correlation coefficients and the annual water balance (in mm) across eco-regions. B) Relationships between the average SPEI/tree-ring width correlations and the annual water balance in the world biomes. The biomes are grouped according to six eco-regions: Subpolar, Boreal, Cool temperate, Warm temperate, Subtropical and Tropical.*

The NDVI tend to respond to shorter drought time scales in arid areas than in humid areas (Fig. 5). This pattern is particularly evident in ecoregions that include the most arid biomes (Fig. 5a, red). In warm temperate, subtropical and tropical ecoregions the vegetation activity in the most arid biomes tends to respond to shorter time scales than occurs in more humid biomes. This pattern is likely to

be related to the physiological strategies of vegetation in arid and semiarid areas, which reduce the damage caused by water deficits.
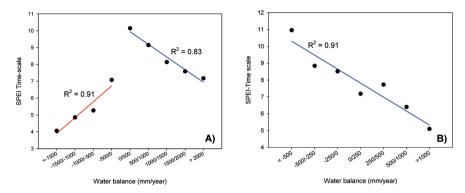

FIG. 5: *Average values of the time scales (in months) at which the GIMMS-NDVI/SPEI (A) and the tree-ring width/SPEI (B) and maximum correlations are recorded, summarized for different ranges of the annual water balance.*

Plants of arid regions are able to respond very rapidly to small droughts (which correspond to short SPEI time scales) by implementing physiological and functional strategies that reduce respiration costs, photosynthetic activity and growth rate (Chaves et al., 2003). When areas with positive water balance are analyzed independently it is found that as water availability increases the correlations of NDVI (Fig. 5a, blue) and tree growth (Fig. 5b) with the SPEI tend to occur at shorter time scales. This phenomenon is highly relevant because it provides evidence of the high vulnerability of the most humid biomes to drought. Forests and other vegetation communities living in semiarid and subhumid regions (e.g. between –500 and 500 mm year–1) regularly tolerate periods of water deficit, and have physiological mechanisms to respond to these conditions. Therefore, to be negatively affected by drought these communities must be exposed to water deficits that are sustained over time, which requires conditions that correspond to long time scales of the SPEI. Thus, in areas with water balance approaching zero the greatest correlations for the NDVI and tree ring width occur at similar time scales (8–10 months). Nevertheless, in areas with a positive water balance the time scales at which the greatest correlations are recorded decrease as water availability increases.

4. CONCLUSIONS

Our findings highlight the potential for using different drought time scales to identify global drought impacts on vegetation activity and plant growth. Knowledge of the dominant time scales over which droughts influence vegetation is critical in detecting the response of vegetation to departures from the mean water balance values, but is also useful in identifying vegetation drought response patterns that may reflect resistance and resilience to drought among diverse vegetation types and biomes. Thus, temporal scales should be included in analyses of drought impacts on vegetation, because of their substantial implications for plant activity and growth, thus affecting global carbon uptake and storage and the maintenance of plant biodiversity.

Global warming will almost certainly continue in the future (Solomon et al., 2007), increasing the frequency of negative water balances in arid areas (Gerten et al., 2008), which would imply more land

areas vulnerable to drought stress, including humid areas such as temperate, mountain, boreal and wet tropical forests. Vegetation in these areas is already subject to increased drought stress leading to die-off events because of warming-induced drought stress (Zhao and Running, 2010; Breshears et al., 2005). Increasing drought severity in humid areas may have unpredictable consequences for the biosphere and the global carbon cycle, because the main terrestrial carbon pool is stored in the humid world biomes (Nemani et al., 2003).

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