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Aridification determines changes in forest growth in *Pinus halepensis* forests under semiarid Mediterranean climate conditions

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ABSTRACT

Using a set of 16 Landsat TM and Landsat ETM+ images from 1984 to 2006, we tested whether climate trends in the last three decades differentially controlled the vegetal activity of eight *Pinus halepensis* forests located across a marked bioclimatic gradient. Our results show spatial differences in trends in the normalized difference vegetation index (NDVI) between 1984 and 2006, which were highly related to the spatial distribution of aridity. There was a strong correlation between the change in the NDVI values and the climatic water balance in each forest ($R = 0.86$, $p = 0.006$). A large increment of the NDVI was observed in forests located in the most humid areas, whereas those located in the most arid areas showed a slight decrease in the NDVI. We used a forest growth simulation model (GOTILWA+) to estimate the leaf area index (LAI) in each of the eight analyzed forests, and found similar results to those obtained for the NDVI. Significant correlation was found between the spatial pattern of NDVI and LAI trends between 1984 and 2006 ($R = 0.82$, $p = 0.01$). The climate evolution in the last four decades explains the observed and modeled changes in the NDVI and the LAI. In agreement with other studies, we showed that the general response of the forests to more favorable conditions (in terms of temperature increment and CO_2 fertilization) is increased leaf activity and biomass. Nevertheless, in forests located in the most arid areas the positive trend observed in the potential evapotranspiration rates increased water stress, and had a negative effect on forest growth. Given the future predictions of warming and declining precipitation from global climate models for the Mediterranean region, an increase in stress conditions affecting these forests is expected, which will affect their growth and survival, mainly in the most arid areas.

1. Introduction

Forest biomass is one of the major reservoirs of organic carbon (Wofsy et al., 1993; Dixon et al., 1994; Barford et al., 2001). Given the large dependence of carbon storage on the physiological status and activity of forests, a priority in environmental science is to assess the potential impacts of global change processes on the activity, health and growth of forest ecosystems (Saxe et al., 2001; Nemani et al., 2003; Boisvenue and Running, 2006), as they could markedly affect future rates of carbon storage.

Various studies have identified changes over recent decades in forest activity and growth at continental (e.g. Zhou et al., 2001; Slayback et al., 2003; Delbart et al., 2006) and local scales (e.g. Tardif et al., 2003; Andreu et al., 2007; Martínez-Villalta et al., 2008). Most of the changes have been caused by human activities, particularly deforestation (Achard et al., 2002; DeFries et al., 2002) and forest fires (Giglio et al., 2006; Riaño et al., 2007), but land marginalization and rural abandonment have contributed to natural revegetation processes in some regions (Zahawi and Augspurger, 1999; Vicente-Serrano et al., 2004; Sluiter and De Jong, 2007).

Some changes in vegetation cover are due to climate variability and change. At a global scale, net primary production of forests increased 6% in the last two decades, mainly in tropical ecosystems and driven by climatic factors including decreased cloud cover and the resulting increase in solar radiation (Nemani et al., 2003). In temperature-limited ecosystems, temperature increase is contributing to greater forest activity and growth. At high latitudes of the northern hemisphere, an increase in the rate of forest activity that is directly related to temperature increase has been reported (Myneni et al., 1998; Goetz et al., 2005), with implications for carbon sequestration by forests (Piao et al., 2008). Similarly, some studies have shown an increase during the 20th century in the upper altitudinal limit of trees in alpine mountain areas, mainly as a consequence of increased temperatures (e.g. Camarero and Gutiérrez, 2004; Lenoir et al., 2008).

In regions where the productivity and activity of forests is water-limited, variations in precipitation can markedly influence forest changes. Orwing and Abrams (1997) and Abrams et al.

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(1998) analyzed the effect of drought on radial growth of different tree species in Pennsylvania, USA, and showed that trees located in the most arid environments were more sensitive to droughts. In semiarid and subhumid regions, where climate variability is very high, the occurrence of droughts markedly reduces physiological processes, vegetation activity and leaf biomass (e.g. Borguetti et al., 1998; Bréda et al., 2006; Vicente-Serrano, 2007), and wood production and carbon storage by forests (e.g. Barber et al., 2000; Ogaya et al., 2003; Voronin et al., 2005).

Nevertheless, in water-limited environments including most of the Mediterranean region, changes in precipitation may not be the main factor driving changes to forests; temperature may also play a significant role, as it interacts with precipitation to determine water availability. Increased temperature commonly has a positive effect on the activity and growth of trees, but the effect can be negative if there is no corresponding increase in precipitation, as water stress may occur. In Spain, Andreu et al. (2007) have shown a progressive increase in the effect of temperature on tree growth during the second half of the 20th century and a decrease in the effect of precipitation. This suggests that in this period there were more years in which climate conditions limited tree growth as a consequence of induced temperature-related water stress. These results are consistent with those of Martínez-Villalta et al. (2008) for northeast Spain, who showed that increased annual temperature favored growth during humid years, and had the opposite effect in dry years. Some studies have shown reduced forest growth in Mediterranean ecosystems located near the distribution limit for some forest species. Sarris et al. (2007) reported a decline in the radial growth of *Pinus cembra* on the island of Samos (Greece), associated with a decline in precipitation. In Spain, Jump et al. (2006) found a decline since 1975 in *Fagus sylvatica* forests near the distribution limit for this species, related to increasing temperature and greater water stress. In Italy, Maselli (2004) noted a decrease of activity in coniferous and broadleaf forests between 1986 and 2000, associated with a decrease in winter rainfall.

Nevertheless, the spatial pattern of forest growth and decline can be very complex. Large variations in forest responses to climate are related to local climatic gradients. For example, Martínez-Villalta et al. (2008) showed that, in the driest parts of northeast Spain, the effect of increased temperature was always detrimental to growth, whereas the effect was positive in humid areas. Vicente-Serrano et al. (2006) showed a direct spatial relationship between vegetation activity and aridity in broadleaf and coniferous forests in Spain. Lloret et al. (2007) have also shown that the diversity–stability relationship between forest activity and drought in Spain follows a climatic gradient, with the driest localities being more affected; this finding is in agreement with the results of Vicente-Serrano (2007) in the center of the Ebro Valley (northeast Spain). The large spatial differences found at local scales in the response of forests to drought conditions suggests the importance of analyzing recent changes and trends in forest activity in relation to local climatic gradients, and the need to consider forests near their limit of distribution, as the first impacts of climate change processes are expected to be observed in ecotones (Neilson, 1993).

Although there have been some studies of trends in tree growth in European environments, based on tree ring analysis in a range of environmental and climatic gradients (e.g. Mäkinen et al., 2002; Dittmar et al., 2003; Martínez-Villalta et al., 2008), few studies have analyzed trends in other forest variables related to photosynthetic activity and leaf biomass production. Studies of this nature are very relevant to understanding the effects of global change on ecosystems, as there have been reports of marked variability in roots, and above ground wood and green parts of trees, related to changes in water availability (Lapenis et al., 2005). Changes in leaf biomass and leaf activity are more difficult to identify than changes in tree growth, where tree ring analysis is commonly used. However, while analysis of leaf-related processes poses some difficulties, remote sensing can be used to measure the activity and trends in leaf biomass over large areas and varying climatic gradients. Moreover, the availability of long time-series archives of satellite images provides the opportunity for analysis of trends and changes over recent decades.

Few studies have analysed the possible evolution of the *P. halepensis* forest under future climate projections. Gaucherel et al. (2008) have expected an increase of the *P. halepensis* growth in South France during the 21st century as a response to CO_2 increase. The results agree with the outputs of a biogeochemistry model in Provence considering both temperature and precipitation changes (Rathgeber et al., 2003). Nevertheless, there are no analyses focussed on the impacts of climate change processes on the *P. halepenesis* forests located near the distribution limits. Sabaté et al. (2002) suggested that in these areas the growth could be reduced as a consequence of water constraints associated to precipitation decrease and temperature increase in Mediterranean areas.

In the present study, we analyzed trends in vegetation activity over a climate gradient (346–626 mm average annual precipitation) in the central Ebro Valley (northeast Spain), which is in the northernmost semiarid region of Europe. We focused on *Pinus halepensis*, a forest species that is highly adapted to aridity. It is able to withstand drought periods and soil drying because it rapidly responds to decreasing predawn water potential by stomatal closure, which reduces transpiration (Borguetti et al., 1998) and prevents severe tissue dehydration and foliage dieback (Chaves et al., 1993). Consequently, a decline in the photosynthetic activity of *P. halepensis* forests would be a sign of widespread aridification in the region, given the high degree of adaptation of this species to common water stress conditions.

The aims of the study were to investigate: (i) changes in leaf activity in *P. halepensis* forests, (ii) spatial differences in leaf activity trends over the past three decades, (iii) the likely climatic drivers of temperature and precipitation trends, and spatial patterns of aridity and (iv) the predicted changes in the leaf activity according to the climate change projections. We addressed these aims using: (i) an exploratory step based on high resolution remote sensing data, and (ii) a confirmatory step using a forest growth model to simulate the leaf area index (LAI) for the period covered by the remote sensing data, and to project LAI for the entire 21st century according to different climate change scenarios. We tested the hypothesis that trends in forest activity and LAI are controlled in contrasting ways in the most arid and humid areas by recent temperature trends, and with a strong influence of aridity. The study was highly relevant as Mediterranean forests are highly sensitive and vulnerable to change as a consequence of: (i) centuries of human use and modification of the land (e.g. fires) that have affected the resilience of forests to climate perturbations (e.g. drought); (ii) the high temporal variability of climate, characterized by frequent and severe drought periods; and (iii) the increased water stress predicted for the region by current climate change models for the end of the 21st century, resulting from a large decrease in precipitation and increased evapotranspiration rates (Giorgi and Lionello, 2008). Thus, temperature in the study region increased markedly (about 2 °C) during the 20th century (Brunet et al., 2006), aridity is very pronounced (Vicente-Serrano et al., 2006), and there is low precipitation (Cuadrat et al., 2007) and high rates of evapotranspiration during summer (Vicente-Serrano et al., 2007).

2. Study area

The study area corresponds to the 199/31 Landsat scene located in the middle Ebro Valley, which is one of the most arid regions of the Iberian Peninsula. Relief determines the climate, as the valley is