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Forest performance during two consecutive drought periods: Diverging long-term trends and short-term responses along a climatic gradient

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ABSTRACT

Forest decline, attributed to increased aridity under global climate change, has been observed with rising frequency worldwide. One of the knowledge gaps making its spatially explicit prediction difficult is the identification of the climatic settings that generate a significant change in the forest state. A relatively rare sequence of unfavourable climatic events – a short extreme drought followed by a prolonged moderate drought within one decade – has allowed us to examine how rainfall amount affects forest performance.

Large-scale monitoring, at high spatial and temporal resolutions, is required to study climatic effects on forest performance. Therefore, time-series of spatially interpolated rainfall maps, remote sensing images and tree growth data were used to estimate the environmental settings to which the forests are exposed, and the corresponding forest performance responses. Performance was estimated from Normalized Difference Vegetation Index (NDVI) values obtained from 32 Landsat satellite images for 1994–2011. To widen the study perspective we sampled forest performance along a rainfall gradient (250–750 mm) in the planted *Pinus halepensis* forests in Israel.

Performance response was not spatially homogeneous. Three response types could be identified along the rainfall gradient: stable performance with low correlation to rainfall pattern in the humid region (>500 mm), moderate performance decline with high correlation to rainfall in the intermediate region (350–500 mm), and steep performance decline with intermediate correlation to rainfall in the arid region (<350 mm). The response to the second drought differed among regions, unlike the response to the first drought, which was homogeneous.

The observed diverging performance trend along the climatic gradient can be attributed to the varied importance of water availability as a limiting factor. The reduced effect of rainfall on performance deviations, the steep performance decline, and the difference between responses to the first and second droughts at the most arid locations, imply to higher importance of multi-annual accumulated and carried-over drought stress effects at these locations.

1. Introduction

Large-scale forest decline, i.e. defoliation, reduced tree growth rate and increased mortality, attributed to increasing aridity under global climate change, have been observed with rising frequency worldwide (Allen et al., 2010). For example, widespread mortality of *Pinus edulis*, *Pinus ponderosa*, and other species was recorded in south-western USA in 2002–2003, following an extreme drought (Breshears et al., 2005; Shaw et al., 2005). This event was considered an ecosystem ''crash'' (Breshears et al., 2011; Breshears and Allen, 2002), since in semiarid environments it can take more than a century for tree cover to fully re-establish. The magnitude of these ecosystem functional changes, generated by forest mortality, could be revealed by remote sensing with multispectral sensors (Breshears et al., 2005; Huang et al., 2010; Rich et al., 2008; Yuhas and Scuderi, 2009).

The increased forest mortality raises concerns regarding the fate of forest cover and sustainability of stands if climate becomes drier. However, forest decline and mortality are not well understood processes, either on the individual tree level (McDowell et al., 2011) or on the whole-forest level (Allen et al., 2010). In particular, it is asserted that the link between forest decline and causal

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climatic drivers should be systematically examined to evaluate forest sensitivity to climatic changes in various environmental settings (Allen et al., 2010).

In water-limited ecosystems, decline in forest performance is generally expected to be greater at the arid edge of a species distribution, where water availability constraint on vegetation is highest (Allen et al., 2010; Babst et al., 2013; Linares et al., 2009). However, studies of forests arid distribution limits received smaller amount of attention among forest-related ecological studies until now (Hampe and Petit, 2005; Matyas, 2010; but see Vicente-Serrano, 2007). For example, Carnicer et al. (2011) studied crown defoliation rates in European forests. The authors have found that a significant increase in defoliation rates occurred during 1987–2007 only in southern Europe, in contrast to the stable state observed in northern and central Europe over the same period. A divergent trend between the arid forest border and more humid locations with *Pinus halepensis* forests was also recently reported from Spain (Vicente-Serrano et al., 2010c).

Both abovementioned studies (Carnicer et al., 2011; Vicente-Serrano et al., 2010c) examined long-term performance trends with respect to the location along climatic gradients (i.e., average rainfall amount), but not to the temporally explicit trajectory of annual rainfall at each location. However, the way in which climatic events, such as droughts, translate into short-term deviations of forest performance from their long-term trend holds information on forest resilience when facing climatic deviations. For example, a significant long-term trend may indicate steady growth in areas which are not water-limited (in the case of a positive trend) or steady decline in locations irreversibly damaged by drought (in the case of a negative trend). No significant long-term performance changes, accompanied by short-term deviations of performance in response to rainfall amount variation, however, may indicate limits of a species distribution. Those are the locations where the role of rainfall as a limiting factor to performance is strongest, although no pronounced growth or decline has yet been observed. Drying trends have been observed around the Mediterranean (e.g. Kafle and Bruins, 2009; Sarris et al., 2007), while global climate change models predict further desertification in the region (Giorgi and Lionello, 2008). Therefore, it is particularly important to acknowledge how sequences of climatic deviations, such as recurrent drought, affect forest performance (Girard et al., 2012; Sanchez-Salguero et al., 2012; Sarris et al., 2011).

In forest science, remote sensing is a modern and efficient tool to obtain high temporal and spatial resolution data on vegetation performance and physiology (Pettorelli et al., 2005; Zhu et al., 2012). Indices summarizing reflectance patterns obtained from multispectral sensors (such as TM and ETM+ on Landsat satellites) were developed for these purposes. The most commonly used index in ecological studies, the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973; Tucker, 1979), is used to quantify green biomass (Pettorelli et al., 2005; Wang et al., 2011). NDVI was used to assess forest structural and physiological responses to climatic change in numerous studies, including studies on *P. halepensis* forests (Lloret et al., 2007; Vicente-Serrano et al., 2010c; Volcani et al., 2005) as well as on forests in other ecosystems (Verbyla, 2008). In the present study, NDVI is a measure of forest performance, reflecting green biomass quantity and state (Pettorelli et al., 2005; Wang et al., 2011), of the forested area in a given location, at a given year.

P. halepensis grows naturally in the Mediterranean region, mainly in the western part but a few isolated populations have been located in the eastern part, including Israel (Schiller, 2000). Its natural distribution is limited by minimum annual precipitation of 450 mm (Liphschitz and Biger, 2001; Schiller, 2000). However *P. halepensis* was planted under a wide range of climatic conditions in Israel, including regions with annual rainfall ranging between 200 and 850 mm, thus extending beyond the climatic envelope of the species' natural distribution. Planted forests cover about 8% of the Mediterranean climatic zone in Israel (Osem et al., 2008) and are dominated (~75%) by conifers, of which *P. halepensis* is the most common species (Perevolotsky and Sheffer, 2009). The majority of the forests are monocultures of even-aged trees (Osem et al., 2009), planted during a relatively short time period (1961–1970; Israel Forest Service GIS layer, 2011).

Recently, increased mortality of *P. halepensis* in the planted forests of Israel was reported in the southernmost locations (Schiller et al., 2005, 2009; Ungar et al., 2013), following a sequence of two drought periods: a short extreme drought (1998–2000) and a prolonged moderate drought (2005–2011). This has provided a unique opportunity to examine forest performance response to recurrent drought events.

In the present study we examine the response of *P. halepensis* forests planted along a rainfall gradient of 250–750 mm in Israel, to two consecutive drought periods during 1994–2011, as related to annual rainfall amount.

The principal questions that this study aims to tackle are:

1. How did forest performance response to two consecutive drought periods vary along a wide rainfall gradient, extending from the arid forest border towards the more humid Mediterranean zone?
2. Did the response to a second drought period differ from that of the first drought period, and how did this difference vary along the rainfall gradient?

2. Materials and methods

2.1. Study area

The study area encompasses 46 forests (see Figs. S1 and S2 in Supporting information) located in central and northern Israel, amounting to a total sampled area of 31.7 km^2. The forests are spread across a climatic gradient extending from semi-arid to Mediterranean conditions, i.e., annual rainfall ranging from 236 to 746 mm. The climate in the region is characterized by winter rains occurring mainly between December and March, and a relatively long, dry, hot summer (Osem et al., 2009).

Three forests along the rainfall gradient were chosen for dendrochronological sampling (Fig. S2). All sites were located on southern aspects and were of comparable age (planting year of 1969, 1965 and 1960 for the arid, intermediate and humid sites, respectively). Since growth declines with age (Sarris et al., 2007, 2011), the slight age increase towards the humid edge of the gradient in fact makes the comparison more conservative. The sites are hereafter referred to as "arid site", "intermediate site" and "humid site". Note that we do not refer to climatic regions; these labels are used to enable easier reference to relative position along the rainfall gradient (the same applies when referring to "arid", "intermediate" and "humid" parts of the rainfall gradient, see below).

2.2. Remote sensing data

To estimate forest structural responses on a large spatial scale, 30 Landsat-5 TM and 2 Landsat-7 ETM+ images from the period 1994–2011 were used. Two adjacent Landsat scenes (path 174, rows 37 and 38) from the same date were merged to cover the area of interest; sample sizes were 15 and 17 images for the northern and southern parts of the area, respectively. Images were selected from a relatively short time period during the end of the dry season (8 September–16 October) for two reasons (Vicente-Serrano et al., 2010c). First, during the dry season there is lower variation in